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Autonomy is the answer, what was the question again?

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Synopsis

In recent years aspirations regarding the implementation of autonomous systems have rapidly matured. Consequently, establishing the assurance and certification processes necessary for ensuring their safe deployment, across various industries, is critical. In the United Kingdom Ministry of Defence distinctive duty holder structures - formed since the publication of the Haddon Cave report in 2009 - are central to risk management. The objective of this research is to evaluate the duty holder constructs suitability to cater for the unique merits of artificial intelligence-based technology that is the beating heart of highly autonomous systems.

A comprehensive literature review examined the duty holder structure and underpinning processes that form two established concepts: i) confirming the safety of individual equipment and platforms (safe to operate); and ii) the safe operation of equipment by humans to complete the human-machine team (operate safely). Both traditional and emerging autonomous assurance methods from various domains were compared, including within wider fields, such as space, medical technology, automotive, software, and controls engineering. These methods were analysed, adapted, and amalgamated to formulate recommendations for a single military application.

A knowledge gap was identified where autonomous systems were proposed but could not be adequately assured. Exploration of this knowledge gap revealed a notable intersection between the two operating concepts when autonomous systems were considered. This overlap formed the development of a third concept, *safe to operate itself safely*, envisioned as a novel means to certify the safe usage of autonomous systems within the UK's military operations.

A hypothetical through-life assurance model is proposed to underpin the concept of *safe to operate itself safely*. At the time of writing the proposed model is undergoing validation through a series of qualitative interviews with key stakeholders; duty holders, commanding officers, industry leaders, technology accelerator organisation leaders, requirements managers, system designers, Artificial Intelligence developers and other specialist technical experts from within the Ministry of Defence, academia, and industry.

Preliminary analysis queries whether a capability necessitates the use of autonomy at all. Recognising that some autonomous systems will *never* be certified as safe to operate themselves safely, voiding ambitious development aspirations. This highlights that autonomy is simply one of many tools available to a developer, to be used sparingly alongside traditional technology, and not a panacea to replace human resource as originally thought.

This paper provides a comprehensive account of the convergence between *safe to operate* and *operate safely*, enabling the creation of the *safe to operate itself safely* concept for autonomous systems. Furthermore, it outlines the methodology employed to establish this concept and makes recommendations for its integration within the duty holder construct.

Keywords: LAWS; AI; Autonomy; MoD; RN; Duty Holder; Safe to Operate; Operate Safely

1. Introduction: How Do You Trust a Robot?

Preliminary research was conducted to analyse Lethal Autonomous Weapon Systems (LAWS) and aimed to develop a model for building trust among stakeholders integrating new autonomous technologies. However, research quickly revealed a significant knowledge gap requiring investigation that forced a change of direction towards human-machine teaming and artificial intelligence (AI). The initial literature surveys concluded early that established assurance mechanisms designed to ensure that human operators *operate safely* and that conventional machines are *safe to operate* are not fit for purpose when applied to the assurance of AI based autonomous systems. Therefore, a new method to account for technology able to *operate itself* was devised.

Authors' Biographies

WO2 Peter Spayne is a Weapon Engineer in the RN, majoring on mine disposal systems. He studied Autonomous systems at BEng and explored weaponising high powered ultrasound to agitate submerged explosives at MSc with Staffs Uni. He is a PhD student researching the assurance of lethal autonomous weapon systems at Cranfield University.

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This study focuses on risk management and assurance methods used by the British Royal Navy (RN), covering LAWS within a broader spectrum of autonomous systems. Given the RN's operations across various domains, LAWS is understood here as a self-sufficient weapon, capable of learning to independently performing target acquisition, discrimination, and engagement in compliance with International Humanitarian Law (IHL). The emphasis on LAWS, as opposed to general Autonomous Systems, arises from their potential to make life-or-death decisions, necessitating a deeper exploration of an AI's role in making judgments. LAWS can be static, part of a larger system, or attached to conventional vehicles, including advanced targeting and guidance systems capable of selecting targets for engagement post-human intervention. Henceforth, 'autonomous system' will encompass all forms of autonomy, including LAWS.

2. Literature Review: Automatic, Automated and Autonomous

Kenneth Payne's 'I-Warbot' (Payne, 2021) highlighted that the WWII V2 rocket was considered as the first autonomous weapon by earlier standards. Its analogue mechanics - altimeters, barometers, fuel float switches, and gyroscope - allowed it to adjust its flight based on environmental feedback, without AI or complex computing. Today, such systems are classified as automatic or automated, not autonomous.

To investigate further the research protocol was given a favourable opinion by the Ministry of Defence Research Ethics Committee (MODREC) ref: 2265/MODREC/23. Twenty interviews with MOD and industry personnel identified a significant gap in the understanding of autonomy. Despite detailed knowledge of systems such as the Outfit DLH decoy launcher, Phalanx, and Seawolf, the majority of participants confused *automated* capabilities with *autonomy*. This confusion is partly due to a large number of misleading 'autonomy scales' in circulation, such as the IMO's 'Degrees of Autonomy' (IMO, 2019), which focuses on variations of remote control rather than any true autonomy.

Today the concept of autonomy in technology remains vaguely defined. While the Oxford English Dictionary (2010) defines it as 'self-governance', applying this to technology implies the need for intelligence. However, true autonomy, suggesting free will, or unpredictable actions due to unforeseeable inputs, poses safety concerns in technology applications. This distinction is crucial, as understanding the difference between manual, automatic, automated, and autonomous systems - illustrated in Table 1 using fire detection systems – is the foundation of the challenge in defining and safely integrating true AI based autonomy into technology.

Table 1: Distinctions of Autonomy

Statement	Example	Description
Manual	A person witnesses a fire, raises the alarm by shouting and fights the fire with a handheld extinguisher	A Manual Process of detecting and responding to a fire
Automatic	Smoke from a fire is sensed by a detector triggering an audible alarm	An environmental change automatically triggers an electro-mechanical process
Automated	Indications of a potential fire (Smoke and Heat) is detected to different degrees by multiple sensors causing software within an alarm system to *logically* conclude there is a fire. This triggers a predefined output from a Boolean table, such as an audible alarm, text message, or the activation of a spray system	An environmental change is noted by multiple sensors. An appropriate output is concluded by the system based on the logical sum of defined inputs. For example; Heat NOT Smoke = Investigation Warning, Heat AND Smoke = Alarm and Spray, Smoke NOT Heat = Alarm Only
Autonomous	The AI model central to a ships autonomous platform management system becomes aware of a fire in a machinery space, concluded from data received through inputs from an extensive array of sensors distributed throughout the ship and connected externally. This system gathers data on the location of the human crew, the state of machinery and fuel tanks, etc. Additional information about the ship's current tasking, the task group's situation, enemy activities, and broader mission	An Artificial Intelligence trained from the data of millions of human examples is central to a platform management system. It analyses complex data from a vast array of input sources and makes a complex decision that cannot be mapped to a single input, nor plotted in a Boolean table. The resultant output may need to be justified in a court of law. In this example the system replaced the cognitive reasoning, critical thinking and judgement required of a chief engineer, who may have acted in a similar fashion or made different decisions on a

https://doi.org/10.24868/11162

Statement	Example	Description
	objectives provides essential situational context for decision-making. Upon assessing the situation, the AI probabilistically assesses that the human engineers in the compartment would not be able to effectively combat the fire or evacuate the area before it spreads to a nearby fuel sampling valve, which was already compromised due to a minor leak - being temporarily managed with rags and buckets as recorded in the digital maintenance logs. The resultant output is that the AI opts to activate mechanical ventilation valves to hermetically seal the compartment, trapping the engineers inside. Following this, it triggers a gas suppression system to extinguish the fire by removing oxygen from the compartment. Although this action results in the death of the engineers, it prevents a larger catastrophe, prioritising the ship's overall safety. Should any aspect of input data or situational context been different, the AI might have selected from an infinite array of other potential actions.	case-by-case basis, were a human in command of the control room during this incident.

Degrees of Autonomy

Table 1 suggested that a fire protection system's autonomy status - be it manual, automatic, automated, or autonomous - is fixed by design. Yet, autonomy is better understood as a state rather than a fixed capability. Interviews revealed a common misconception among technology developers from various sectors, including those working on autonomous ships and cars, who initially attempted to develop systems under the assumption that they would not require any form of manual control. This approach often led to the elimination of human-machine interfaces, comfort, and life-support systems, resulting in the need for retrofitting or the abandonment of trials (PSN9876, 4567, 0123, *Personal Communication (Anonymised Research Interview)*, 2024) (Lee and Wu, 2023).

Interviewees agreed that autonomy should be adjustable, analogous to a volume control, allowing for modulation as necessary (All Participants, *Personal Communication (Anonymised Research Interview)*, 2023/24). This concept aligns with the Yerkes-Dodson Law (Cohen, 2011) (Figure 1), which correlates performance with operator attention. Linking a need for an operator to remain alert to exercise the ability to dial up and down autonomy in line with the complexity of a situation. Building on this, Table 2 proposes an adjustable autonomy scale, and Table 3 introduces examples of degrees of autonomy within the hypothetical scenario of a minor warship, building on established crewing states (Navy Lookout, 2024). This demonstrates that a vessel can operate under various automation levels depending on the required task, suggesting that autonomy can and should be fine-tuned at both the system and subsystem levels for optimal performance and safety.

Table 2: Degrees of Automation

Degree	Definition	Description
M	Manual	Human operated manual control
R	Remote Control	System is manually operated from a remote location
1	Assisted	Very low-level automation for operator assistance. For example, cruise control aiding a driver may be considered automatic

2	Partial	Increased automation with more complex input, for example adaptive cruise control where a RADAR aided cruise control device monitors vehicle speed and distance from the vehicle ahead, causing the vehicle to accelerate or decelerate in response to sensed inputs. May be considered automated
3	Conditional	An autonomous system operating independently within a defined environment. For example, a driverless car on a racetrack. Complex examples may include geofencing via GPS when referring to ships or aircraft. Human override is available remotely or by an onboard operator who is monitoring the system *hands off*
4	High	As degree 3 but operating in an unrestricted (or less prescribed) environment. The ability for human override remains available but would be very rarely used
5	Full	As degree 4 but with no human override capability indicating that the system would never need human intervention. *Degree 5 autonomy, sometimes known as General AI is not yet technologically possible

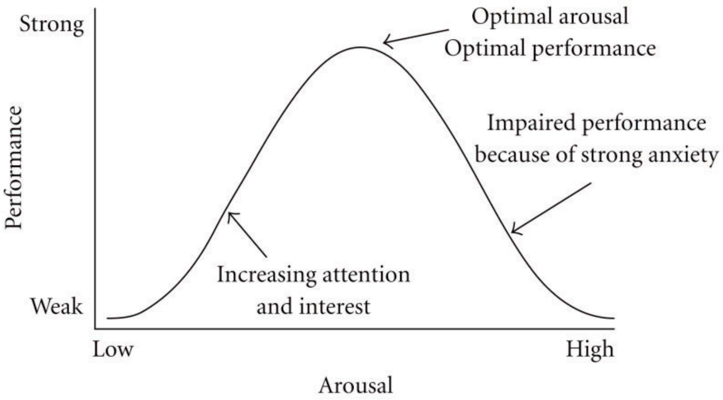

Figure 1: Yerkes-Dodson Law, Cohen (2011)

Table 3: Crew States

Crew State	Definition	Description
0	Action (Uncrewed)	In operations deemed extremely high risk, verging on suicidal, where crew safety is significantly compromised, the ship is transitioned to a state of full autonomy. Following crew evacuation, an integrated network of platform and combat management systems takes over, autonomously controlling all internal machinery, navigation, and combat operations. To minimise risks such as fire, life-support systems are deactivated, and some compartments may be depleted of oxygen. Operations proceed unattended, though the option to monitor and exercise remote control from an off-ship command centre remains, allowing for strategic oversight while prioritising human safety
1	Action (Crewed)	The ship is at action stations with all positions locally crewed ready to respond to enemy action. This posture is only maintained for short periods when an engagement is imminent. All weapons are readied
2	Defence (Crewed)	The ship's crew is keeping defence watches operating in a high-threat area where enemy engagement is possible, but not imminent. 50% of the crew are *on watch* operating weapons and sensors and

		contributing to the day-to-day running of the ship's routine. The other 50% are resting
3	Cruising (Crewed)	The ship is running a normal daytime routine akin to a merchant vessel, there is no risk of enemy engagement, and the crew are undertaking routine business in normal working hours
4	Cruising (Uncrewed)	For low-risk, routine tasks not requiring crew presence, the ship autonomously navigates to a set destination with life support and combat systems off, showcasing the efficiency of autonomous technology for benign operations.

* For tasks that are monotonous yet hazardous (mine hunting), a mix of State's 4 and 0 might be necessary. The ship methodically scans areas at slow speeds with SONAR. It is crucial to understand that autonomy is a state, not a fixed capability, and thus, the autonomy level should be adjustable to regain control as operational risks or environmental conditions change.

3. Safe to Operate and Operating Safely (The Duty Holder Construct)

The RN manages risks associated with the operation of technology by aligning with legislation from the UK's Health and Safety Executive (HSE) and wider bodies. Compliance is optional but mandated where possible by the Secretary of State. Procedures for adhering to this guidance (including deviations for military gain) when operating warships, weapons and equipment are detailed in Defence Safety Authority Book 2 - Defence Maritime Regulations (DSA02-DMR) (Defence Maritime Regulator, 2023). Specific guidance is then percolated through subordinate internal publications. The approval to depart from legislation and take risks for military gain, once thoroughly identified, is owned and authorised by Duty Holders, whose seniority dictates the severity of risk to life that may be tolerated.

Risk management involves a network of HSE, IMO and specific International Standards Organisation (ISO) regulations, tailored to equipment, scenarios, and environments. Military operations often require deviations from standard guidelines; therefore, deviations are managed internally by duty holders who strive to keep risks 'as low as reasonably practicable' (ALARP) (Defence Maritime Regulator, 2016).

Duty holder facing organisations throughout defence (Defence Maritime Regulator, 2018) administer safety management and ensure equipment and services meet safety standards, reporting non-compliance as required. They also curate policy for the safe use of equipment that does not fall under civil regulation, such as weapons and bespoke submarine operations. Specifically, platform and equipment authorities ensure equipment is *safe to operate* by defending safety compliance arguments in safety cases, achieving certification from the Naval Authority, which sets maritime compliance rules and standards by translating civil regulations to policy and accrediting curated policy where civil regulations do not exist.

Training authorities ensure personnel are well-trained, equipped and vetted to undertake the safe operation (*Operating Safely*) of equipment, with unit or platform Commanding Officers (COs) ensuring adherence to training and legislation, making their platform a human-machine team under a single command.

This model, pairing humans and machines in two distinct silos parallels civilian systems, in the United Kingdom (UK) vehicles in use on public roads are regulated by design standards and Ministry of Transport (MOT) testing, resulting in an MOT Certificate, and drivers are trained, examined and accredited by the Driver and Vehicle Licencing Agency (DVLA), resulting in a driving licence, to form human-machine teams as road users, safety assured by their combined certification.

For military gain, exceptionally, platforms may operate non-compliant with COs managing minor risks. Major risks escalate up the duty holder chain of more senior risk holders for approval. Immediate, unconsented, deliberate but justifiable breaches may be taken, but fall under the CO's accountability no matter the risk to life.

While effective for conventional technology and human resource management, this system struggles with autonomous systems due to unpredictable AI model behaviours that are akin to human unpredictability. An Autonomous systems' model training and outputs, comparable to human actions, require analysis from data scientists which is beyond the capabilities of training authorities optimised to train humans and not validate training data. A third concept must therefore be created.

4. Conclusions: Operating Itself Safely – The Third State

As the degrees of autonomy that were detailed in Table 2 increase the two statements of *safe to operate* and *operate safely* begin to converge, as depicted in Figures 2, 3 and 4. Figure 4 depicts a system that has been tuned up to fourth degree autonomy. It therefore requires specialist assurance to ascertain its ability to *operate itself safely*.

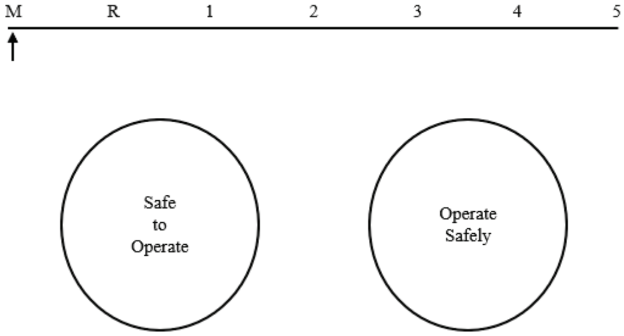

Figure 2: A manual system with separate agencies defining the assurance of machine aspects and human aspects. (x-Axis scale as per Table 2)

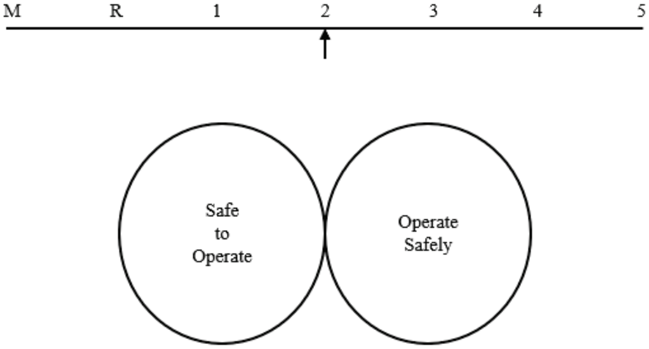

Figure 3: A second degree system (partial autonomy – automated) utilises separate agencies defining the assurance of mechanical aspects and human aspects but working much closer together.

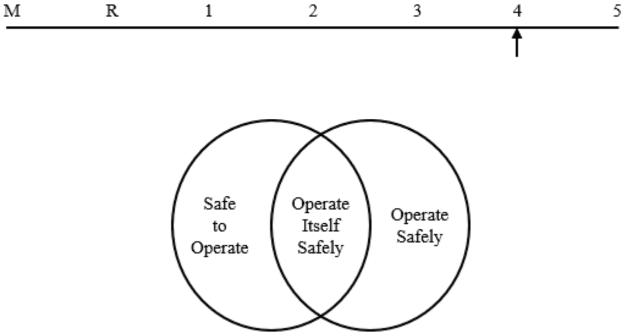

Figure 4: A fourth degree system (high autonomy), the two statements have converged and created a third in the overlap. This third space deals with the unique data science aspects of autonomy and AI model training data, outside of the scope of traditional equipment authorities or training agencies.

Autonomy is the sum of AI, Machine Learning (ML), and Data Science (DS) (Ministry Of Defence, 2022) This research has concluded that AI and ML demand specific assurance beyond the standard practices of training people and risk assessing to certify machinery. ML's reliance on training data necessitates extensive validation via DS, a process far removed from traditional human operator training scopes. Given the unpredictable nature of decision-making in ML and AI, traditional equipment authorities cannot assess these systems using the usual Software Integrity Level (SIL) certification (International Standards Organisation, 2023).

However, the new third concept is not a replacement, a fundamental need for assurance of traditional hardware and software remains as an AI model sitting within an autonomous system consisting of normal hardware and software complements, rather than replaces, these components.

Additionally, even if a system achieved full autonomy, eliminating the need for constant human operation, personnel involved in the systems infrastructure or potential emergency intervention would still require training through established human training methods.

5. Output: Assuring a System is Safe to Operate Itself Safely

Assuring an autonomous system is a thorough and expensive process, which has previously deterred development progress beyond the conceptual stage (Thomas, 2022). Typically, unless a critical safety function necessitates autonomy – something unachievable by human or automated means – the system is unlikely to reach production or prove its viability past testing (Thomas, 2022). Autonomous systems, as decision-making entities mimicking human cognition, often become far more expensive than the human alternative. Continuous investment in autonomy must acknowledge the inherent safety limitations; achieving an acceptable ALARP safety level is challenging, given the absence of human-like accountability mechanisms.

Autonomous systems span three levels, as outlined in Table 4. This tiered structure introduces further complexity, as each level might function independently as an autonomous entity, necessitating individual assurance at each level, further multiplying the effort required to complete the assurance process (Safety of Autonomous Systems Working Group, 2022).

Table 4: Autonomous System Levels

Level	Definition	Description
3	System	The ‘platform’ representing the final autonomous system as a product. Directly interacts with the environment
2	Architecture	System software that hosts the AI model(s), operating software, and hardware at component level
1	Computation	Individual processes that translate inputs into outputs. Complex systems typically contain billions of computations across multiple architectures

The National Institute of Standards and Technology (NIST) (2023) study informed the AI Risk Management Framework (RMF) and underscored the need to consider AI-specific risks alongside conventional ones, due to their potential to affect a wider audience with more significant implications. In 2020, The Artificial Intelligence High Level Expert Group created the Assessment List of Trustworthy AI (ALTA) framework; allowing developers to self-assess their products during development, focusing on wider social and political aspects. ALTA addresses seven areas to assure a system is *operating itself safely*; these include human agency, analysing AI's impact on human behaviour; oversight, defining human interaction and training requirements; technical robustness, enhancing system resilience against unforeseen events and threats; privacy, ensuring data collection complies with human rights laws; explainability, clarifying the reasoning behind unusual decisions; and also addresses diversity, societal & environmental wellbeing, and accountability to ensure broad, responsible AI application (High Level Expert Group on Artificial Intelligence, 2022).

An autonomous system's integration within an organisation involves scrutinising every aspect of the TEPIDOIL[1] framework across the three levels detailed in Table 4. This comprehensive assessment encompasses the implications of AI-specific risk factors and the traditional assurance processes for human and non-AI system elements (Ministry of Defence, 2009). This ensures a holistic evaluation of the system's operation, highlighting the need for a coordinated approach to manage both conventional and AI-related risks effectively.

Assurance for deployment in specific environments initially permits only interim accreditation. Full *operating itself safely* status follows extensive operational use, with reliability proven through consistent documentation and the verification of expected outcomes.

Whilst deployed, autonomous systems can be comparatively assured to humans. Both process inputs; training, experience and judgement for humans is similar to programming and environmental interaction for an autonomous system. Inputs inform outputs that are subject to scrutiny. Therefore, the unpredictability of unknown responses

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[1] 'Training, Equipment, Personnel, Information, Doctrine, Organisation, Infrastructure and Logistics

to novel situations means *full* safety assurances are unattainable. However, through repeated satisfactory performance, a basis for *reliability trust* may be established.

Assurance efforts should therefore focus on verifying training data and monitoring real-time responses to ensure the expected results. This approach can be delivered by way of a multilayer assurance model (Table 5) that encapsulates the system within its components, the organisation, and the wider operational context.

Table 5: Assurance Layers of Autonomous Systems

Layer	**Definition**	**Description**
-2	Computation	Identify and assure all computations, where reasonably practicable.
-1	Architecture	Define the system architecture, assure traditional hardware and software using established methods.
0	Platform (System)	Establish system boundaries, set requirements for operators and interacting agents to ensure they operate and interact with the system safely, conduct risk analysis for traditional system aspects to ensure traditional hardware and software components are safe to operate.
1	System of Systems	Identify the intended and unintended nodes in the wider system of systems, including other autonomous systems, traditional systems, and humans that may interact with this platform within the operational environment.
2	Operating Environment	Define the operating environment, identify sources of live data, potential sources of shared live data, and actively feed this back to training data creators for curation and reissue, to optimise the system for operations in a specific environment.
2a	Data	Assure and validate training data, secondary sources and third-party (shared) validation data, ensure data validation and curation tools are reliable. Assure the integrity of the simulated training environment.
3	Deployment	Implement live monitoring of operations, analyse returned data, and update assurance activities based on continuous feedback.
4	Real World Impact	Evaluate the system's impact on real-world communities, considering social, political, and economic influences in the operating environment.

This broad assurance model illustrates the extensive scope of examination required to assert system safety. Extending across the system's lifecycle (Table 6), this new approach diverges from the traditional CADMID[2] cycle and reflects a requirement to assure wider than typical system boundaries.

Table 6: Through Life Assurance of Autonomous Systems

Step	**Definition**	**Description**
1	Prepare	Prepare the organisation to receive an Autonomous System prior to procurement by setting the highest-level capability requirements, terminology, and definitions. Engage stakeholders to outline required governance before embarking on a typical engineering procurement cycle
2	Cartography	Map requirements and broader considerations for the entire system of systems, considering the intended operating environment and context
3	Global Risk Assessment	Assess known and predicted risks in 3-dimensions, factoring controllability and orientation of an operator during a state change. An appropriately instructed Generative Pre-Trained Transformer (GPT) may be used to risk assess a vast combination of scenarios and environmental variables

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[2] Concept, Acceptance, Design, Manufacture, In-Service, Disposal

4	Go/No Go	Answer a series of Go/No-Go questions to determine the costs and feasibility of continuation of the project. What is also considered is whether the system (and which aspects) needs to be autonomous given the cost
5	In Service Monitoring	Active monitoring during systems development, model training, and deployment
6	Disposal	Outline a disposal and emergency withdrawal plan that adheres to ethical guidelines and considers data security aspects

The impact and influence of each layer must be considered within every step. When the system initially deploys with *interim* accreditation as *safe to operate itself safely*, Step 5 shall enact a feedback loop to Step 2 to enable the system to work towards full accreditation. This accreditation is based on the consistent safe performance of the system and may be withdrawn at any time.

Disposal at Step 6 is more complex than simply shutting the system down and dismantling it for disposal. The data must be sanitised for security and recycled into training data stock to inform the next generation of systems that will operate in the environment.

6. Summary

Autonomous systems fall outside the traditional UK MOD categorisations of being either 'safe to operate' or 'operating safely' due to AI's distinctive characteristics. They necessitate a third categorisation, *operating itself safely*, to meet their unique requirements. Despite the buzz around autonomy as a solution to global industry challenges, the complexity, and costs of integrating AI into LAWS or safety-critical systems have been underestimated. The expense of rigorous and widespread risk management and the additional costs for curating and validating training data greatly surpass those of existing manual or automated systems. Care should be taken to avoid the creation of an autonomous assurance cottage industry where it is not required.

Autonomy – misunderstood and often confused with automation – has been ambitiously presented as a complete solution, which has misled stakeholders regarding the capabilities of new systems. It is crucial to recognise autonomy as a *state* rather than a *capability*, ideally employed as a safety mechanism, battle override or emergency sub-system, activated only in critical situations, such as the incapacitation of an operator. These states require assurance of their safe self-operation outside of the scope of traditional agencies, demanding further development of the methodologies proposed in this paper for their readiness.

Whilst further research and development into autonomous systems is vital for technological progress, procurement of systems intended to be autonomous as the rule and not the exception, for widespread application and implementation today, is deemed unviable at this time.

7. Acknowledgement

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8. References

Cohen, R.A., 2011. Yerkes–Dodson Law, in: Encyclopaedia of Clinical Neuropsychology. Springer New York, New York, NY, pp. 2737–2738. https://doi.org/10.1007/978-0-387-79948-3_1340

Defence Maritime Regulator, 2023. DSA02 Defence Maritime Regulations for Health, Safety and Environmental Protection.

Defence Maritime Regulator, 2018. DSA01.2.

Defence Maritime Regulator, 2016. DSA01.1 Defence Policy for Health, Safety and Environmental Protection.

High Level Expert Group on Artificial Intelligence, 2022. Assessment list for trustworthy Artificial Intelligence (ALTAI) for self-assessment. https://doi.org/10.2759/791819

IMO, 2019. Autonomous shipping [WWW Document]. URL https://www.imo.org/en/MediaCentre/HotTopics/Pages/Autonomous-shipping.aspx (accessed 3.8.24).

International Standards Organisation, 2023. ISO/IEC/IEEE 15026-3:2023, Systems and software engineering: System integrity levels.

Lee, C.K.H., Wu, K.Y.K., 2023. Making autonomous vehicle systems human-like: lessons learned from accident experiences in traffic. Enterp Inf Syst 17. https://doi.org/10.1080/17517575.2021.1998641
Ministry of Defence, 2009. Defence lines of development analysis with MODAF.
Navy Lookout, 2024. After action report – Royal Navy's busiest air defence activity since 1982.
NIST, 2023. AI RMF PLAYBOOK.
Oxford English Dictionary, 2010. Autonomy.
Payne K, 2021. I Warbot.
Safety of Autonomous Systems Working Group, 2022. Safety Assurance Objectives for Autonomous Systems.
Thomas, 2022. Swatting of Mosquito latest UK uncrewed dead end [WWW Document]. Airforce Technology.com. URL https://www.airforce-technology.com/features/mosquito-swat-becomes-the-latest-in-a-long-line-of-uk-uncrewed-dead-ends/ (accessed 3.9.24).

From Cruise Ships to Combat - Evaluating Power and Propulsion Technologies for a Lean Warship.

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Synopsis

This paper examines technologies around Power and Propulsion (P&P) systems including design requirements, training, maintenance, and operations exploring how recent advances in these systems can help facilitate a lean crewed warship. The paper draws on the authors experience in the cruise industry and how crewing challenges have been addressed commercially with existing and emerging technologies. The paper challenges the current techniques of P&P analysis and proposes alternative processes for analysing conflicting requirements such as equipment acquisition costs, lean crew objectives, redundancy, and systems efficiencies. Associated risks, opportunities and regulatory framework of a lean crew are investigated. The role of automation, remote condition monitoring and virtual reality is explored. Some recommendations are made for how these technologies can be adopted while still maintaining safety, resilience, and capability.

Keywords: Lean crew, power and propulsion, design out maintenance, equipment health management, virtual reality,

1. Introduction

Over its history, the maritime industry has undergone many significant technological transitions that have impacted the size of the crew onboard. The transition from wood to iron hulls allowed for the accommodation of steam engines. The transition from coal to oil then cut the engineering department and gave improvements through higher energy density. The adoption of a standardised container has dramatically reduced shipping costs through reduced loading times (Stopford, 2008). These, amongst more recent changes such as implementing integrated automated control systems, have led to highly efficient crew levels per cargo carried. In 2003, the world's largest cruise ship was the Queen Mary 2 at 148,527GT. In 2023, the largest cruise ship has ballooned to 248,663GT (Wikipedia, 2024). Despite the 67% surge in tonnage, the technical crew has remained a similar size. Cruise ships share many similarities with modern warships such as complicated survivability requirements, sustaining hundreds of seafarers onboard, high power demands and objectives of balancing capability with an efficiently sized crew. Valuable insights can be obtained from examining how commercial strategies have facilitated an efficiently sized technical crew on cruise ships.

Further radical transformations in the maritime industry are currently leading to an upheaval in crewing training and numbers. 2022 to 2027 looks to introduce disruptive commercial emission policies such as the IMO's introduction of the Carbon Intensity Indicator rating (IMO, 2023) and the EU's Emission Trading Scheme expanding to shipping (European Commission, 2024). Decisions made because of this legislation will have a direct effect in interconnected sectors, such as defence, where commercial shipping will start to coalesce around alternative fuels and prime movers. These decisions and technologies will not only influence the design of the ship but also require an upheaval in maintenance and operations potentially requiring an overhaul of crew skill sets. Disruptive technologies pull crewing requirements in the opposite direction in the form of automation and digitisation. There have been many digital technologies adopted in adjacent sectors to defence such as predictive maintenance through remote equipment health management, virtual reality-based training, and remote-controlled fluid systems.

The methods of enabling a lean crew explored in this paper do not aim to compete with or replace seafarers. Instead, the paper aims to outline some technologies around the P&P systems to move duties ashore, increase reliability of equipment and reduce repetitive tasks to maintain capabilities with a shrinking pool of seafarers.

Authors biography

Edward Penn is a Marine Engineer specialising in Naval power and propulsion systems for Rolls-Royce PLC where he provides systems engineering support for the business development team. He has a decade of engineering experience in the maritime sector and holds an STCW unlimited chief engineers CoC. Before joining Rolls-Royce, Edward spent several years as a seafarer working on new build cruise ship projects, one of which was optimising and verifying the Integrated platform management system on behalf of the owner. He also spent several years operating and maintaining cruise ships power and propulsion equipment.

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2. The Requirements, Opportunities, and Risks of a Lean Crew

2.1. The Requirements

Minimum crewing levels are determined by the flag state of a merchant vessel. All UK flagged commercial vessels above 500GT are required to hold a safe manning certificate which specifies the crewing requirements. The IMO issues guidance for flag states and the capabilities they should consider such as the capacity to train personnel onboard, ensure safe navigational or engineering watches and provide medical care (IMO, 2011). Some principles are applied to naval vessels where a minimum level of crew is determined by a countries naval command. These requirements give forward thinking navies the opportunity to lead lean crewing technologies as the decisions are made in house and not subject to an external party such as a classification society or flag state.

2.2. The Opportunities

Reducing the crew onboard will reduce the number of personnel exposed to a high threat environment. Conflict in the red sea at the beginning of 2024 has illustrated the serious risk to life for seafarers in commercial shipping and defence maintaining these critical corridors. A reduction in crew need not necessarily result in a reduction in capability if balanced with adequate risk assessment and thoroughly tested technologies.

Another major advantage of reducing crew numbers are reductions in operational costs (OpEx). A reduced crew not only reduces the salary associated costs but also the travel relating to boarding and repatriation, hiring costs and training costs. The accommodation spaces and life supporting equipment, such as freshwater generators, can be reduced which leads to reductions in fuel and maintenance associated expenses. The reduction of food further reduces storage space and refrigeration capacity. Ships can allocate the space gained from accommodation and supporting equipment to additional cargo, additional mission critical systems or a reduction in size of the vessel. The reduction in size can lead to a positive design spiral where smaller ships have a lower power requirement further reducing the total size of P&P equipment and crew required to maintain them.

While not directly explored in this paper, some of the discussed P&P technologies may be viable for enabling fully uncrewed autonomous ships. A lean warship could act as a gateway to assessing the feasibility of the technologies more novel to Navies such as remote equipment health management and the associated obstacles when transmitting large amounts of data from ship to shore.

2.3. The Risks

A lean crew also presents several risks. Sufficient crew to conduct on the job training and crew turn over should be factored into the minimum crew numbers. Failure to properly analyse crewing requirements can lead to increased risks of a major incident. An example of this is the HNoMS Helge Ingstad which had adopted a Lean Crewing Concept (LCC) with a high reliance on automation. In November 2018, the frigate was involved in an incident with an oil tanker where mistakes eventually led to a collision and sinking of the Helge Ingstad. The consequent Norwegian Safety Investigation Authority Report (NSIA) detailed a high crew turn over before the incident leading to a lack of sufficient training and an over reliance on automation (NSIA, 2021). When the LCC was introduced, a doctrine was created to reduce the associated risks of a lean crew. Training was a key factor in the doctrine. The successful implementation of the LCC concept on other Norwegian vessels demonstrates that the LCC can be successful if procedures are strictly followed.

Risks of a lean crew have more recently become evident in the red sea as the French navy has announced its intention of increasing crew sizes by almost 20% likely due to the fatigue induced by a continuous elevated threat state (Meta-Defense, 2024). However experienced and motivated the crew, if overloaded, fatigue can lead to compromising on safety and dissatisfaction. If sustained over long periods, an overloaded crew can lower retention rates and result in workload redistributions (Academy of Management Journal, 2023).

In terms of P&P equipment, historic data can be used to optimise and estimate the maintenance tasks and workloads. Time outside of planned maintenance and fixed emergency drills will be allocated to training, ship improvements, or unplanned maintenance. Repeated unplanned maintenance through untested or unreliable equipment contributes to an increased workload and in some cases can reduce planned maintenance, decrease time available for training, and overload crew.

One method of reducing crew is relying on automation to conduct repetitive and analytical tasks. Depending on the system security, automation systems can be subject to external interference and disruption. Commercial shipping companies have opened automation and control systems remotely to allow for system updates, real time data analysis and remote trouble shooting. This brings risks associated with malicious actors manipulating the systems to cause damage, gaining unauthorised access to demand ransom, or stealing confidential data. Systems must have sufficient security and redundancy built in to mitigate cyber security risks. The UK MoD has engaged with industry under the Defence Cyber Protection Partnership (DCPP) and releasing DEFSTAN 05-138. This standard incorporates a risk assessment, risk profiles and associated controls for suppliers. (MoD, 2019). Automation and control systems with numerous interfacing networks and thousands of data points also bring incredibly complex IT systems. The rate of adoption has meant the seafarers onboard are sometimes not equipped with the necessary training to troubleshoot and rectify issues.

3. Design Considerations

3.1. P&P Systems Lifecycle and Viability Analysis

When selecting the P&P equipment for a vessel, both naval and cruise ship design teams carry out a life cycle and viability assessment. Priority is often given to the amount of fuel various systems will use and the capital expenditure (CapEx) of the system. Data from operational profiles or itineraries are combined with power speed curves to determine the most efficient propulsion system. The volume and mass of equipment are analysed to determine if integration is viable. Redundancy and additional capability such as underwater signatures for naval vessels or engine vibration for cruise ships are factored into the P&P system analysis. The future resilience of the system should be considered, particularly with the introduction of direct energy weapons and compatibility with future fuels. Consideration is sometimes given to running hours and associated planned maintenance tasks. It can be difficult to quantify unplanned maintenance even if an operator has experience with the equipment and extensive historic maintenance records.

There are various techniques for selection of the equipment through multi-criteria decision making. The analytical hierarchical process has proven successful in the past but great care must be taken to avoid any bias. Another method of assessment, where possible, is to assign monetary values to the options over the predicted lifetime of the vessel. When calculating the total expenditure, a monetary value can be assigned for fuel costs, spare parts, maintenance hours, capital costs and even physical space. If using a financial basis for the multi-criteria decision making, historical data should be used to estimate the inflation rates of the OpEx. It is important to estimate the actual cost of a seafarer including the potential cost reductions discussed in section 2.2.

In the cruise industry, a financial value can be assigned to a specific volume through the additional revenue of added passenger cabins. In the past, cost modelling has been carried out comparing power dense, P&P equipment which enables additional passenger cabins. In defence, the value of additional volume gained by selection of power dense equipment can be difficult to determine – either facilitating additional mission systems or a reduction in vessel size.

3.2. Redundancy

There are several methods of achieving the survivability requirements to sustain propulsion in a modern warship. Spatial redundancy has been adopted and proven effective in hybrid or Integrated Full Electric Propulsion (IFEP) vessels. Mechanical systems can also adopt some spatial redundancy by offsetting gearboxes and main engines in different machinery spaces. Redundancy can also be achieved by duplicating P&P equipment. The US Navies optionally crewed ghost overlord fleet are fitted with five mechanically driven water jets and three gensets – a total of eight engines. Engines have been adapted to increase the operational unmanned periods at sea such as installing three oil filters instead of one (Seapower magazine, 2022). While these measures increase the unmanned period, the maintenance burden during refit is increased with a larger number of components to overhaul.

To reduce the maintenance burden, operators in the cruise industry, have opted for a redundancy of power instead of a redundancy of components. Here the total number of diesel engines are reduced often from six to four opting for a higher cylinder output and reduction in total number of cylinders. In these setups, the maximum power of all engines outstrips the maximum propulsive and service loads. Operators of this redundancy philosophy normally use 25% to 50% of the vessels power generating equipment. Peak demands from the propulsion and service loads cannot exceed 75% by design. This allows for one engine to be overhauled in service and still gives capacity in the form of breakdown of another engine for most operations and itineraries. A more traditional P&P arrangement would have six smaller engines installed, still achieving normal operations with the allowance for two out of service engines. The six-engine design when compared to the four-engine design equated to a significant increase in the maintenance burden as the total running hours were higher and number of components were higher. Further benefits were also realised as supporting systems such as cooling water and fuel delivery were optimised for four engines further reducing the maintenance burden. Despite the larger individual volumes and mass, the cumulative size of all engines and associated systems was reduced, facilitating a reduction in overall size of the vessel or additional passenger cabins.

3.3. Prime Mover Selection

One method of reducing onboard maintenance to enable a lean warship is to consider the maintenance philosophy of the equipment. Equipment employing the design out philosophy aims to reduce failures to a minimum and eliminate the need for maintenance. Equipment achieves this by observing failure patterns and eliminating them where possible, reducing repairability and employing advanced materials. Electrical systems such as moulded case circuit breakers or variable frequency drives have proven a successful example of employing this philosophy as in the unlikely event of failure, they are designed to be replaceable. Removing the option to overhaul this equipment onboard increases the reliability, reduces repetitive tasks for the technical team and creates a safer environment as the opportunity for mistakes are reduced. Some equipment can be offloaded and overhauled in specialist facilities.

This maintenance philosophy can also be applied to P&P equipment through modular removal and replacement. One example of this is the major overhaul of the MT30 gas turbine core where the maintenance philosophy differs dramatically from a traditional marine engine. At the major overhaul periods, the 6.5 tonne engine core is removed from the ship either through the inlet down take or via the enclosure side. The core can then be shipped to an overhaul facility with the entire removal process taking between 48 and 36 hours (Rolls-Royce, 2019). Many in service maintenance tasks such as balancing, and blade redressing can therefore be designed out of the engine equating to an average of less than two hours of planned maintenance a week. This is enabled through a twin spool design where the resultant reduction in shaft length, reduces the amount of shaft sag and allows for reduced blade clearance.

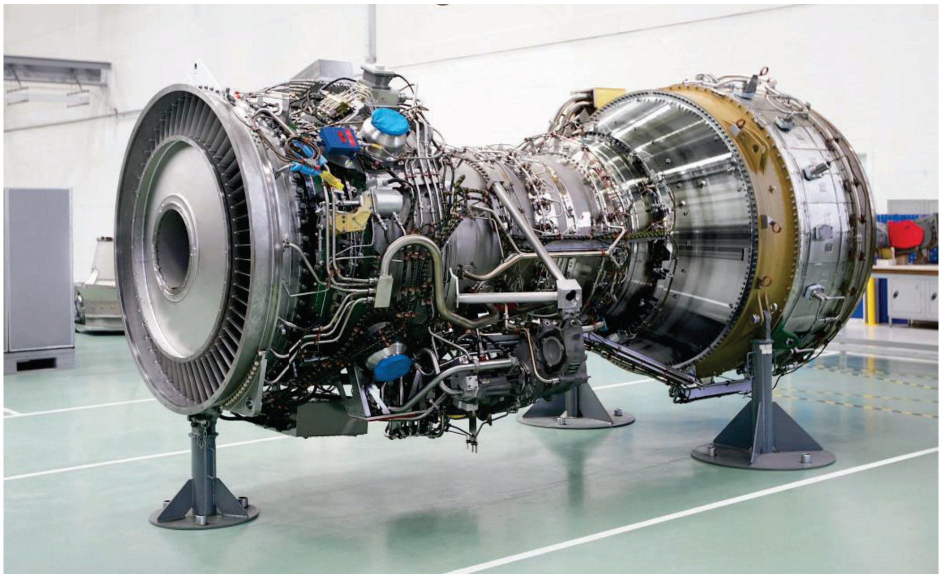


Figure 1 - MT30 core

3.4. Environmental Supporting Systems

The number of supporting and additional systems interacting with diesel engines exhaust systems have grown dramatically over the past decade. To meet MARPOL annex six legislation, NOx abatement Selective Catalytic Reduction (SCR) systems have been installed in the engines uptakes. Merchant navy operators look to waste heat recovery to improve efficiency and ships associated EEDI rating. To prolong the use of cost-efficient high sulphur fuels but still comply with 2020 sulphur legislation, some commercial shipping operators have opted for exhaust gas SOx abatement equipment. The latest exhaust gas treatment to be mooted is Onboard Carbon Capture (OCC) (DNV, 2023). These technologies, while having emissions benefits, also bring dramatic CapEx and OpEx increases. Crew must have adequate training to operate, maintain and manage the chemicals consumed by the systems. The added complexity increases maintenance tasks and the burden for engine room watchkeepers.

While MARPOL legislation does not directly apply to naval vessels, navies often adopt commercially required pollution prevention technologies. Taking NOx abatement as an example, the type 26 P&P system has opted for SCR systems to be installed on the MTU series 4000 diesel engines (Navy lookout, 2019). The cruise industry has opted to mitigate use of the SCR systems through adoption of LNG. In LNG's current form, it is unlikely this fuel will be adopted in next generation warships. To avoid certain exhaust treatment systems, Navies could look to alternative prime mover technologies such as relying on batteries for low loads and gas turbines for boost as the levels of NOx allows exemption from abatement systems.

4. Control and Monitoring

4.1. Integrated Platform Management System (IPMS) Integration

If a holistic approach is adopted when designing the IPMS, automatic planned maintenance can be integrated which can yield huge benefits for reducing maintainers interaction with equipment. One example is implementing remote controlled, automatic cleaning cycles for power generating equipment. Systems which interface with exhaust gases such as heat recovery heat exchangers, SOx abatement systems and turbo chargers often require some form of chemical or water cleaning system. The level of automation adopted in the cleaning system can vary from, complete manual control, a mixture of human input and automation or a completely automatic and remote system. The latter will present risks of introducing more equipment and the complexity of these systems with additional CapEx. By eliminating the number of manual operations, technical crew will be able to conduct maintenance more frequently, remotely and carry out multiple maintenance tasks in parallel. A reduction in maintenance is one of the many benefits of a close cooperation between equipment suppliers, IPMS integrators and the end user.

An IPMS system can also be used to reduce maintenance tasks of the P&P subsystems. To reduce running hours, IPMS controlled ventilation fans, cooling water, and fuel pumps can be automatically started and stopped depending on if the P&P equipment is running. VFD seawater cooling pumps can be set to regulate on temperature which reduces flow rate and biofouling over strainers. Machinery space ventilation can regulate to pressure and temperature to ensure optimum equipment conditions. It is important to consider the threat state when designing an IPMS system. Stopping of P&P subsystems may give maintenance and fuel improvements but could potentially decrease the standby capability of the P&P equipment. Adoption of modes such as normal, low threat and high threat states would allow systems to operate either efficiently or with elevated redundancy through pre-starting subsystems or running numerous engines.

Due to advances in data storage, modern IPMS systems can record vast amounts of information assisting with troubleshooting and watchkeeping. Users can create automatic reports which can replace traditional manual paper logbooks. Observing the thousands of equipment sensors can quickly overload operators and over long, uneventful periods may cause operators to disengage. Some thought in the merchant sector has been given to gamification of the interfacing systems particularly around the aesthetics, ease of navigation and user interaction. This keeps operators engaged in lull periods but also familiar with the system so able to quickly react in emergency situations. CCTV systems can be integrated into IPMS systems and can be a useful tool to reduce watchkeeping teams. If for example, a main engine fuel leakage alarm is triggered, a tactically positioned CCTV camera can be used as a first response tool.

4.2. Condition Monitoring

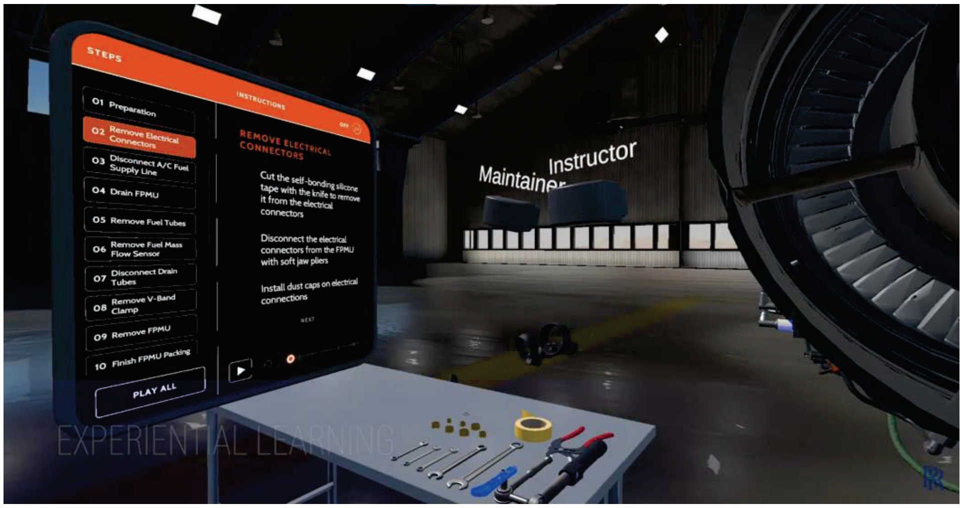
Monitoring of equipment can be further improved by transmitting data remotely in real time directly to equipment suppliers known as remote condition monitoring or equipment health management. These manufacturers can anonymise and collect data from many operators of equipment. The data pool can be used to create a proactive rather than reactive approach to maintenance. Civil aerospace has been using real time engine condition monitoring where data is transmitted from air to ground since the mid-1980s (Aviation today, 2022) . The maritime industry has been slower to adopt these technologies mostly because the nature of a ship allows for reactive maintenance to be conducted in service.

Adopting real time condition monitoring technologies could yield huge benefits to naval operators. If remote transmission systems are utilised, equipment suppliers can use the various data points to detect trends and malfunctions. The data can be used to inform the ship to apply load limits or carry out preventative maintenance. This can yield reliability increases through preventing downtime or damage to equipment. The data can also be used to accurately predict overhaul periods decreasing unnecessary time-based maintenance. The remote transmission element will eliminate the need for on-site data retrieval. If data collection frequency is increased, it is more likely underlying issues will go undetected. Training of naval staff to analyse condition monitoring data can also be considered. This can result in a compromise reducing the frequency of collection but mitigating some of the cyber security concerns around transmitting data to external parties.

The cruise industry is beginning to adopt some remote communication and condition monitoring technologies. One example being the novel exhaust treatment systems where Suitably Qualified and Experienced Personnel (SQEP) onboard remains low. To advance the SQEP onboard, system specific, instant messaging communication tools have been created in collaboration with equipment suppliers to encourage conversation between vessels which share the same equipment and the suppliers. As well as offering troubleshooting and training, these systems can bridge the knowledge gap which can be created between vessels of the same class.

5. Training Considerations

Some of the most comprehensive and effective training for technical crew is practical on-the-job experience. There are several reasons for why this kind of training is not always possible or unfavourable. A pool of SQEP must be sustained onboard with relevant experience of all equipment. The SQEP pool must be given adequate time to pass on experience through on-the-job training. Varying operational requirements and staff turnover can lead to situations where experienced personnel are unavailable. Vessel operators are also responsible for accommodation, living conditions, travel, repatriation, health, and safety for all seafarers onboard the vessel. These additional costs create an expensive training environment.



- 01 Preparation
- 02 Remove Electrical Connectors
- 03 Disconnect A/C Fuel Supply Line
- 04 Drain FPMU
- 05 Remove Fuel Tubes
- 06 Remove Fuel Mass Flow Sensor
- 07 Disconnect Drain Tubes
- 08 Remove V-Band Clamp
- 09 Remove FPMU
- 10 Finish FPMU Packing

REMOVE ELECTRICAL CONNECTORS

Cut the self-bonding silicone tape with the knife to remove it from the electrical connectors

Disconnect the electrical connectors from the FPMU with soft jaw pliers

Install dust caps on electrical connections

Figure 2 – Virtual reality training – tooling and maintenance instruction

One method of reducing crew onboard is making more training available in shoreside facilities. Advances in virtual reality have allowed training facilities to provide complex engine space and control room simulators such as the facilities in HMS Collingwood (Royal Navy, 2023). An advantage of this type of training facility is the virtual reality environment can be adapted as systems develop such as the adoption of alternative fuels or propulsion systems. Equipment suppliers are also developing solutions. Rolls-Royce for example has developed virtual reality maintenance training software (Rolls-Royce, 2023). The training method has some advantages over traditional on-the-job training as it allows for advanced visualisation of the engine internals, limiting downtime of equipment, and experimentation without the risk of damage. Traditional skills such as the familiarisation with specialised and standard tooling has been considered.

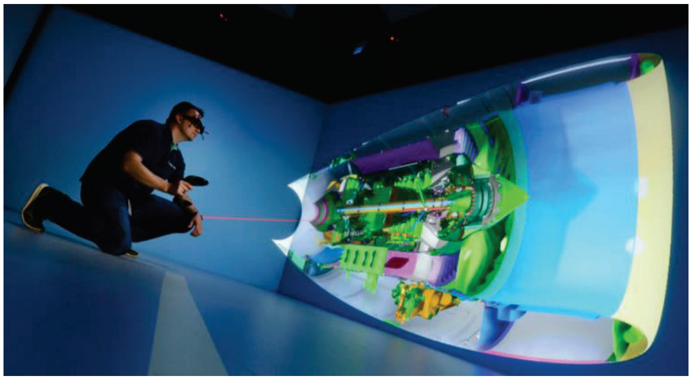


Figure 3 – Virtual reality training – visualisation of engine internals

6. Conclusions

This paper suggests many methods of reducing crew onboard however a holistic approach is required to ensure future warships can operate safely and effectively. Crewing doctrines must be updated frequently with changing technologies and abided by strictly to ensure the associated risks are mitigated. The objective for a lean crew will compete with other priorities but if vessel operators are committed to the objective, it should take priority as early as possible in the design phase. Lean crewed P&P systems favour minimal and reliable equipment, reducing the planned and unplanned maintenance burdens. While this may seem to contradict some survivability requirements, warships could embrace P&P designs adopted in the commercial sector such as a redundancy of power concept. Adoption of remote condition monitoring and autonomous systems remains a viable and established way of reducing technical crew but there are still concerns to alleviate around cyber security.

The aim to reduce crew requirements is a common goal shared between the defence and the commercial sectors. Reducing human error, crew salaries and increasing the space for cargo or mission equipment are driving investment into research. There are advantages for defence to lead this change as personnel exposed to high threat states are reduced and Navies have more autonomy from classification societies and international legislation. There is still room for collaboration between industry, commercial shipping, and defence to ensure knowledge is shared, systems are better integrated and common goals can be achieved safely.

References

Academy of Management Journal, 2023. *Who is leaving and why? The dynamics of high quality human capital outflows..* [Online]
Available at:
https://www.researchgate.net/publication/367566724_Who_Is_Leaving_and_Why_The_Dynamics_of_High-Quality_Human_Capital_Outflows

Aviation today, 2022. *ACARS Over IP and its Impact on Airline Operations.* [Online]
Available at: https://connectedaviationtoday.com/acars-over-ip-and-its-impact-on-airline-operations/

DNV, 2023. *Onboard carbon capture and storage on ships.* [Online]
Available at: ONBOARD CARBON CAPTURE AND STORAGE ON SHIPS

European Commision, 2024. *Reducing emissions from the shipping sector.* [Online]
Available at: https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en

IMO, 2011. *Principles of minimum safe manning. Resolution A1047(27),* s.l.: IMO.

IMO, 2023. *2023 IMO Strategy on reduction of GHG emissions from ships.* [Online]
Available at: https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

Meta-Defense, 2024. [Online]
Available at: https://meta-defense.fr/en/2024/05/01/national-navy-crew-fremm-20/

MoD, 2019. *Defence Cyber Protection Partnership.* [Online]
Available at: https://www.gov.uk/guidance/defence-cyber-protection-partnership

Navy lookout, 2019. [Online]
Available at: https://www.navylookout.com/powering-the-stealthy-submarine-hunter-type-26-frigate-propulsion-system-in-focus/

NSIA, N. S. I. A., 2021. *REPORT ON THE COLLISION BETWEEN THE FRIGATE HNOMS 'HELGE INGSTAD' AND THE OIL TANK SOLA TS,* s.l.: s.n.

Rolls-Royce, 2019. *MT30 brochure.* [Online]
Available at: https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/defence-aerospace/MT30-brochure_REFVCOMB3258.pdf

Rolls-Royce, 2023. *Virtual reality maintenance training software.* [Online]
Available at: https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/defence/virtual-reality-maintenance-training-software.pdf

Royal Navy, 2023. *Royal navy enters the metaverse with new virtual reality simulators.* [Online]
Available at: https://www.royalnavy.mod.uk/news-and-latest-activity/news/2023/february/14/20231402-vr-bridge-sims

Seapower magazine, 2022. *Navy Ready to Christen New Overlord USV ‘Mariner’.* [Online]
Available at: https://seapowermagazine.org/navy-ready-to-christen-new-overlord-usv-mariner/

Stopford, M., 2008. *Maritime Economics.* Third ed. s.l.:s.n.

Wikipedia, 2024. [Online]
Available at: https://en.wikipedia.org/wiki/Timeline_of_largest_passenger_ships

Certifying for Operate Safely – Building Trust in Naval USVs

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Abstract

Autonomy and autonomous platforms are not just coming; they are here, and Defence isn't ready. Regulators are beginning to issue rules to certify autonomous vessels against; however, many rules do set empirically defined values that are to be achieved in support of a safe claim of compliance with goal-based certification. The Goal-based regulations for fully crewed platforms have centuries of empirical data demonstrating safe and unsafe practices and engineering. This has led to an inherent level of trust that Naval Vessels are Safe to Operate and can be Operated Safely. This breakdown of the Safe Claim, Argument, and Evidence is well understood within the defence's safety construct. Safe to Operate is the side of the argument provided and maintained by the Platform Authority (PA). Where Operating Safely is dependent on the Operating Organisation (Royal Navy (RN)), the separation between is unclear when certifying a vessel to operate at IMO Level 3 & 4 Autonomy. This is leading to platform teams being asked to demonstrate Operate Safely arguments on behalf of the operating bodies while the goal-based rules of Safe Operations remain undefined. Whilst there is some experience and commercial regulatory frameworks in place to provide an acceptable means of compliance, naval certification challenges remain. This is in part due to the need to assure a platform is Safe and Legal without limiting capability of the complex service vessels for broad scopes of operations. This paper aims to share the challenges, risks and opportunities identified through the lived experience of NavyX with the Autonomous Pacific 24 (APAC) Autonomy demonstrator.

Key Words: Autonomy; Naval Certification Safe to Operate; Trust in Autonomy

1. Introduction

Technological innovations are rapidly advancing, enabling Uncrewed Surface Vessels (USVs) to perform operations that were previously exclusive to crewed assets. These advancements are paving the way for Autonomous vessels, capable of making independent decisions and executing actions without human intervention, to complete their own Observe-Orient-Decide-Act (OODA) loop. The International Maritime Organisation (IMO) is in the process of developing a non-mandatory Goal-based Maritime Autonomous Surface System (MASS) code, set to be finalized by 2025, with a mandatory code to follow in 2028.

In the regulatory scoping exercise for this code, the IMO has defined 'degrees' of autonomy as:

- Degree one: ship with automated processes and decision support;
- Degree two: remotely controlled ship with seafarers on board;
- Degree three: remotely controlled ship with no seafarers on board;
- Degree four: Fully Autonomous ship.

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Crewed Naval vessels demonstrate their safety through a safety argument that outlines the vessel's scope of use and is certified against it. This argument is divided into Safe to Operate and Operate Safely. The Platform Authority (PA), the Technical Authority for ships operating within the Ministry of Defence (MOD), provides the Safe to Operate argument. The operating organisation, the Royal Navy (RN), provides the Operate Safely argument. This clear division of responsibility works well for crewed vessels, however as vessels transition to higher levels of autonomy this division becomes less apparent. Regulators are now having to assure both the vessel and the Autonomy Package, presenting new challenges in the certification process.

To better understand Autonomy the RN tasked NavyX to certify and experiment with APAC. This is a standard Pacific 24 Mk4 boat modified with an Autonomous package and has been used as an Unmanned Surface Vessel (USV) operational demonstrator for the Royal Navy. Early in October 2023 APAC was certified by the Naval Authority Technical Group (NATG) to operate to Degree 3 within limited areas for experimentation. This was one of the first boats NATG had certified to Degree 3 autonomy and consequentially identified that the means of acceptable compliance with their goal-based standards had not been fully explored. The PA found, at the time of the submission, that both sides of the safety argument were under subjective criticism having to comply with an as yet fully defined goal-based standard and limited trust in operators.

Figure 1- APAC24 in HMNB Portsmouth

This paper challenges the subjective setting of high and potentially inappropriate standards for autonomous systems. It explores the differences between certifying a degree one platform and an autonomous platform in a naval environment and how these differences impact the required evidence base and the balance between simulation and demonstration. The paper ultimately poses the question, 'Are standards for autonomous systems being set above and beyond what would be accepted for a crewed vessel because of a lack of trust?'. This paper critically examines the balancing act that this question poses.

2. The Autonomy Certification Delta

Certifying autonomous vessels, in theory, should have the same goals and aims as certifying a crewed vessel: that a vessel is safe to operate within a set of defined limits. Lived experience though shows a significant difference in attitude when determining the safe operational limits of autonomous vessels versus their crewed equivalent. This section will explore the differences required in evidence to demonstrate an autonomous vessel is safe to operate, the impacts created by these deltas, and the positives and negatives of the current naval USV certification process.

2.1 Concept of Use

A Concept of Use (CONUSE) “describes the intended ways in which a specified capability is to be employed in a range of activities, operations, or scenarios” (Ministry of Defence, 2013). From a certification perspective, a good CONUSE will define what a vessel is intended to do and, equally, what it is intended not to do. A crewed vessel is assumed to not conduct an activity unless it is implicitly stated within the CONUSE. The emphasis on what the vessel will not do substantially increases with autonomous vessels.

Certification bodies are only prepared to certify USVs to perform specific tasks at pre-determined speeds and ranges. A crewed surface vessel could be permitted to carry a maximum number of souls up varying designated speeds, sea states and conditions. To perform additional tasks such as aviation operations or carriage of Weapons, Munitions and Explosives (WOME), additions to the certificate can be applied. For example, a Type 23 Frigate can carry 120+ people at 20+ knots in Sea States up to and including Sea State 9 to perform military operations.

However, a USV is not given the same level of flexibility. USVs will only be certified to perform designated tasks. For example, APAC24 can only operate at Level 3 autonomy for the purpose of experimenting with autonomous systems within a predefined area of operation.

2.2 *Safe Operating Procedures and Crewing Policy*

Safe Operating Procedures (SOPs) and Crewing Policies typically serve very different purposes. SOPs detail how the crew operate the ship safely whereas Crewing Policies dictate the number of crew required to perform SOPs. They contribute significantly to the Operate Safely argument and are often interlinked, but with USVs, they are almost the same document, particularly on smaller USVs.

Why is this? Fundamentally a USV’s operation changes dependant on the degree of autonomy in operation. In fact, most, if not all, Level 4 USVs will still maintain a level of oversight except for “fire and forget” items. An example of this can be seen with the US Navy’s Ghost Fleet Overlord programme where a LUSV completed a 4,421 nautical mile voyage at 98% Level 4 autonomy (Shelbourne & Lagorne, 2024). However, 6 crew members were still accommodated on board. Yes, there is an argument that this is because of the experimental nature of the vessels but even still, there are some areas where crew are still needed or preferred.

There is the argument of manned vs crewed. it is a topic worthy of discussion in its own right, but within this paper, crew are defined as Suitably Qualified and Experienced Personnel (SQEP). SQEP varies from platform to platform and very quickly the qualification and crewing burden becomes rather large to, in theory, to act as supervisor to an autonomous vessel. APAC24 is designed to be operated remotely with or without crew on board, the Degree 2 SOPs dictate there must be someone on board to physically hit the emergency stop and operate the boat. For safety reasons there then also needs to be a second person on board in case of a Man Overboard or injury expanding the crewing burden to just supervise.

As a result, whilst the technology might be operating at Level 3 or 4, in practice, SOPs prevent Level 4 operations in the true sense. However, this reliability on the human ability to intervene when increased levels of autonomy are in place is questionable. Several papers have shown that simply using crew to supervise instead of operate (Chan, et al., 2022a) (Chan, et al., 2022b) (Chan, et al., 2023), can increase risk due to behavioural changes, reduced practical experience, and complacency. All this raises the question, are crew still able to intervene as well as they could on a Level 1 or 2 platform? SOPs are designed to enforce best practices and safe operation, but is current regulatory hesitancy actually risking safe operation? Ultimately, USVs are designed to be cheaper alternatives to existing crewed platforms that reduce the risk to human life.

2.2 Hazard Log

A Hazard Log is a way of articulating a system’s risk to harm to As Low As Reasonably Practicable (ALARP). A log can be generated through a variety of means. It involves a SQEP panel reviewing a system and identifying all credible events that could cause harm to personnel, equipment, or the environment. These events have an initiating Cause that could be safeguarded against occurring in the first instance and controlled before a situation or 'Hazard' becomes present. This 'Hazard' could lead to harm or accident. Once a Hazard is present mitigations can be implemented to reduce the severity or probability of the consequential accident occurring. This construct of events can appear as a Bow Tie with several Causes leading to a singular Hazard that could present a series of credible accidents, as shown in Figure 2.

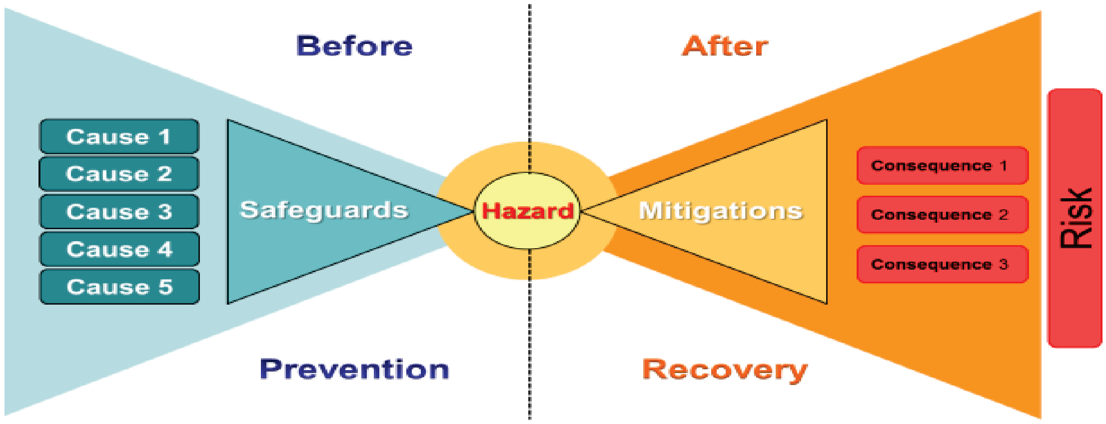

Figure 2 - Indicative Bow Tie Structure (DE&S, 2020)

The role of a SQEP panel is crucial in identifying and grading the risk of each accident against a standardised matrix. With its Subject Matter Experts (SME), this panel meticulously examines the elements that could lead to an accident. The highest risks to harm are then identified and prioritised for mitigation. This process involves identifying the design features, processes, or limits that must be present to satisfy the argument that a system's risk to harm is Tolerable and ALARP.

When considering autonomous vessels, many hazards and accidents must be reviewed for every degree of autonomous operation. Consequently, the harm to personnel focus moves from involved personnel to 3rd parties throughout the HAZID. For example, in the case of a collision, there will be harm to people, equipment, and the environment. When uncrewed, the personnel harm will only be to third-party personnel; this risk to 3rd parties was not scrutinised when crewed operations were examined. In the case when APAC was operating as a USV at Degrees 1 & 2, the responsibility fell within the operating organisation's safety construct; however, at Degree 3, the argument fell to the PA to satisfy.

This risk of harming 3rd parties can only be mitigated so far by systems and design; however, the accident's probability can only be mitigated by processes. i.e., operating within a safe space. This can be implemented by operating within controlled areas and using a geofence to set bounds for the autonomous system. The operating organisation must maintain this safe space outside the Safe to Operate scope. Within the Aviation space, this risk to 'uninvolved persons' from a Remotely Piloted Air System (RPAS) has many similar factors to USVs covering: Mass, dimensions, speed, quality of training and duration of exposure. Exposure is a function of the number of third parties at risk and the period that they are at risk. This risk is managed within the operating side of the safety checklist section of an RPAS's categorisation argument.

However, this argument was being asked to be made by the PA when certifying APAC within the Safe to Operate argument in which this enforced system would act as failsafe in case of loss of control of the system or connection failure. These are embodied within an emergency stop function that turns off the boat's automation if the connection is lost or under the operator's command. This is the extent of the PA's control of the operation, providing an assured system to a suitable Safety Integrity level. It remains for the operators to know to activate or manage connection links to not endanger uninvolved persons, equipment and the environment.

2.3 Class Certificates

Unlike certificates of class issued to crewed vessels, certificates of class for USVs are not as advanced. Using the example of a Lloyds Register (LR) Unmanned Marine Systems (UMS) Certificate it is clear that the main focus of LR is on the basic functionality of the systems that make the vessel autonomous, i.e., does the vessel start and stop when told to. It does not cover issues such as stopping distances or positive identification distances of other objects. This can be problematic as the level of assurance provided to naval certification bodies is reduced. The other basic functions of the boat and items, such as structures and stability, would still have to be covered by the crewed vessel equivalent. With APAC24 this requires a Work Boat Code certificate and an UMS certificate.

As a result, many naval certification bodies would not accept UMS certificates as significant evidence. The evidence would still prove useful but if the scope of certification covered items such as stopping distances, the UMS certificate would carry far more weight.

In defence of class societies, generating an UMS code that fits all USVs is challenging. Crewed vessels have been operating for hundreds of years, and codes have been derived from reviewing thousands of safety incidents to establish best practices. For USVs, this bank of experience does not exist. This means that the knowledge base is predominantly theoretical and experimental in comparison.

Further compounding the issue is that attitudes to risk have changed significantly. In the early 1700s safety was an afterthought to capability. Now, safety is an integral part of everything the Royal Navy designs and operates. Risk also now extends to reputational damage. Using the examples of historical incidents that have redefined what is believed safe have in the long-term bettered industry. The damage that an incident could cause however, has led to an increasingly risk averse approach. This is problematic because fundamentally to fully develop a UMS code fit for purpose, mistakes are going to occur and must be learnt from.

The key difference with USVs, and where there is scope to expand the pace and risk appetite of certification bodies, is that systems can be proven with a vastly reduced risk to humans, even if that comes at a cost to the asset. If stakeholders are willing to accept an increased risk to experimental assets in a controlled environment, then the pace of development could increase drastically. Combining this with the ability to run preliminary testing in simulated environments will massively speed up the rate of development of UMS codes.

However, UMS codes will also need to be broken down further. A UMS code for a work boat will not be appropriate for a 300m container ship. The knowledge and experience base is not available to be drawn from, but codes must clearly state safe separation, identification distances and other minimums of navigational safety.

2.4 Safety and Environmental Case Report

Safety and Environmental Case Reports (SECRs) are a fundamental part of certifying any vessel, no different from USVs. The basic structure of a SECR remains the same in that to prove a vessel is Safe, it must be Safe to Operate and can be Operated Safely. Broadly, the evidence and criteria are the same as those for crewed vessels, but with one key difference: cyber security.

For naval vessels, cyber security is becoming a priority. The ability to safeguard sensitive and operational information has never been more paramount when the capability of Signals Intelligence (SIGINT) has evolved rapidly. As a result, far more detail and evidence are required that USVs can a) prevent intrusion on systems, b) prevent a hostile takeover of control systems, and c) be rendered harmless in the event of an unrecoverable hostile takeover.

Whilst this is undeniably a critical safety aspect, there is one problem: what do naval architects, marine engineers, and safety managers – typically tasked with conducting certification activities know about cyber security? Inevitably, this will force the adoption of cyber security experts into the certification process, both within class societies and project teams. This presents opportunities, most obviously, to offer upskilling to existing engineers within the industry, which can only be a good thing in an increasingly digital and cyber-contested world. Operationally however, it represents the ability to place maritime cyber security firmly in the mindset of vessel designers and drive the adoption of improved practices and growth of capabilities

2.5 Trust

The main theme throughout the autonomy deltas is trust. Naval certification bodies do not yet trust USVs to do their jobs and therefore require a far higher level of evidence to achieve the same operating capability compared to a crewed equivalent. The primary reason for this, as seen in the deltas of CONUSE, SOPs and Class Certificates is that the knowledge and experience base is severely lacking. Humans are risk averse and creatures of habit, two things which do not go well with rapidly deploying autonomous systems.

3. Building Trust in Autonomous Systems

In naval environments trust is built within the equipment and the combination of equipment and operators. Modern navies use institutes such as Flag Officer Sea Training (FOST) to assure that a ship and its crew can deliver capabilities safely and effectively. Remove the crew and replace them with a machine -how do you then conduct FOST? This section will explore the challenges presented by this and what can be done to fill this gap in assurance so that trust can be built in USVs.

3.1 Demonstration

As with most new technologies, demonstration is the best and most effective way of building trust. The demonstration allows authorities and parties to see and gauge risk for themselves. However, demonstrations are seen as more of an exam when it comes to certification, and unlike an exam, autonomy demonstrations rarely have fixed objectives. Using example of an APAC demonstration, the experiments team had a set trial to develop evidence to inform the NavyX Autonomy Programme. This Trial Plan had set evolutions to be conducted with success criteria, whereas the regulators witnessing the demonstration did not have specific criteria to satisfy them APAC was Safe to Operate or Operate Safely.

3.2 Simulations and LUSVs

Demonstrations for smaller vessels such as APAC can be frustrating but achievable. With comparatively low running costs and support requirements USVs can be trialled several times until the certifying body is content. For LUSVs this is not a feasible approach. The support requirements, operating costs, and operational pressure to deliver new capabilities at pace would make certification unrealistic. The Operate Safely argument then strays rapidly from crew to platform authorities.

There is a solution to this problem. Simulations allow for hundreds or even thousands of pre-determined trials as requested by a certification body. This gives the flexibility to establish a baseline relatively quickly for the vessel against which a potential demonstration could be held. For example, the certification strategy will request a speed and operating envelope. The simulations can be used to establish if a demonstration at the full extent of the operating envelope is useful or whether sufficient concerns exist that further enhancements are required.

However, simulations can present an insufficient representation of the realities of the maritime environment. They can only represent a simplified maritime environment, while more complex simulations can represent the chaotic physical of the natural environment. Depending on the level of chaotic variation permitted in the simulated environment, hundreds of the same events could be simulated yet lead to the production of varying resulting states. It may infer a predictive behaviour, although the probability of system hallucinations remains.

Due to this simulation can only suggest that an automated system will behave in a predictive manner to a degree of certainty within the simulation environment. It cannot be a final answer as only live trials will expose the OODA loop system to the chaotic reality of the maritime environment and therefore there remains the issue of trusting its decisions.

The benefits of this are sizeable. It allows certification bodies time to develop the tools, knowledge, and subsequent rules set to objectively certify USVs without significantly increasing the trial burden. It also allows the pace of in-service dates for USVs to be accelerated. This would be akin to using the simulations to replace FOST before sea trials. Sea trials could then be expanded by a day or two to conduct the final phase of FOST, thus not creating potential days' worth of extra trials. This also would allow the utilisation of a key part of USVs. Every time a ship is docked the Ships Company is required to conduct an extensive workup period for the sake of the equipment post such intrinsic maintenance, and for the crew to regain confidence in their SQEP.

4. Finding the Balance between Objective and Subjective

So far, this paper has focused on evidence to persuade certification bodies of Safe to Operate and the theme of trust, but this goes beyond evidence. As lived experiences have demonstrated, multiple ways of producing evidence and building a safety argument exist. However, even if an objective rules-based approach does not exist the problem of certifying naval USVs will persist.

Before the discussion continues it is pertinent to make clear that this is not an advocation for a fully objective rules-based system. There still fundamentally exists a significant element of learning and operational experience to be fully content a USV is safe, and that can only be captured through a certain degree of engineering judgement. Indeed, this is common with crewed platforms where concessions are made to demonstrate that a platform is still safe but does not necessarily comply with every rule.

Nevertheless, there is an urgent need to establish a route to achieving a steady state similar to that of crewed platforms. Proposals of frameworks, which include introducing some minimum benchmarks based on vessel size and purpose, is a crucial step in this direction. This approach, like existing surface ship rules, will provide engineers with a clear objective to meet when designing these platforms. It will also reduce the excessive evidence pool required to get a certificate, freeing up valuable time, resources, and money. This will not only enable us to exploit the advantages of USVs best but to also ensure that the development of USVs can continue at pace with a greater degree of regulatory control.

5. Conclusion

Through the lived experience of attempting to certify APAC through the NATG, lessons have been identified by the NavyX PA and NATG to improve the requirements in order to certify an autonomous boat. However, hurdles remain to ensure consistent assurance for USVs and LUSVs.

The PA should continue to provide the Safe to Operate argument with the expanded responsibility of providing Claims, Arguments and Evidence to support assurance that an autonomous system will behave predictably when not under the direct control of an operator, and that operators have sufficient systems to ensure they can operate the system safely. I.e., a minimum standard of Situational Awareness proportional to the CONOPS of the USV or sufficient fail safes are present in case of a runaway system.

Operating organisations must remain responsible for the risk of harming equipment, environment and personnel (including third parties) when operating autonomous assets. As with crewed vessels, when within the bounds of their safety case the responsibility remains with the operators to know and understand the risks involved in using equipment. The assurance of this must be updated to reflect the evidence provided by the PA in the Operate Safely Argument.

Trust can only be built in these systems by enabling their function and enabling the iterative development of autonomous decision-making systems; however, in a controlled manner, accidents are expected to occur with all systems. Society will need to decide when it is comfortable operating around these systems, as with the autonomous automotive and aviation industry.

References

Chan, D. J., Norman, D. R. & Pazouki, D. K., 2022b. An Analytical Assessment of the Situational Awareness of Seafarers & Their Trust in Automated Systems. *International Naval Engineering Conference .*

Chan, D. J., Norman, D. R., Pazouki, D. K. & Golightly, D., 2022a. Autonomous Maritime Operations and the Influence of Situational Awareness Within Maritime Navigation. *WMU Journal of Maritime Affairs,* pp. 121-140.

Chan, D. J., Norman, D. R., Pazouki, D. K. & Golightly, D., 2023. Perception of Autonomy and the Role of Experience within the Maritime Industry. *Journal of Marine Science and Engineering.*

DE&S, 2020. *20201031-SHIPS_O_and_A-Leaflet_5-Issue_3-O.pdf,* Bristol: DE&S.

Military Aviation Authority, 2023. *Regulatory Article (RA) 1600: remotely piloted air systems (RPAS) Issue 9,* s.l.: Ministry of Defence.

Ministry of Defence, 2013. *Capability Management Practitioners' Guide.* 2.1 ed. s.l.:Ministry of Defence.

Shelbourne, M. & Lagorne, S., 2024. *US Naval Intelligence News.* [Online]
Available at: https://news.usni.org/2024/01/16/navy-wraps-first-unmanned-surface-deployment-to-westpac
[Accessed 13 May 2024].

Solid hydrogen carriers as an Alternative Fuel and Impact Damper

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Synopsis

The search for cleaner and more sustainable fuels extends to the maritime sector, including the navy. Naval vessels have additional requirements regarding survivability and safety, as compared to commercial ships. A promising type of alternative fuels are the boron-based solid hydrogen carriers, specifically ammonia borane and sodium borohydride. These powders react with water to release hydrogen, resulting in a higher energy density. However, spills in and contact with water in confined areas should thus be avoided for safety reasons. The powders also react to heat, possibly releasing toxic and explosive substances. Ammonia borane starts reacting at 110 °C and sodium borohydride at 450 °C. The spent fuels exhibit significant advantages. They are thermally stable and, in the case of ammonia borane's spent fuel, even act as a flame retardant. These spent fuels may thus enhance the safety and survivability of the ship upon impact from a heat source. The significant differences between the fuels and their spent fuels require careful consideration of onboard storage locations and appropriate containment measures. Addressing these storage challenges will help pave the way for the safe and efficient adoption of solid hydrogen carriers, ultimately enhancing the environmental sustainability and survivability of naval vessels.

Keywords: Alternative fuel; Solid hydrogen carrier; Sodium borohydride; Ammonia borane; Hydrogen

1 Introduction

New, alternative maritime fuels are required to reduce or eliminate the use of fossil fuels in shipping. This need extends across all shipping industry sectors, including the Navy. However, Navy vessels comply with unique requirements compared to vessels within the general shipping industry. Increased safety and survivability is paramount for naval vessels. Alternative fuels like ammonia and hydrogen may not meet these safety standards. Ammonia is toxic, and hydrogen is extremely flammable. Other alternative fuels, such as methanol, require additional mitigating measures like cofferdams. However, solid hydrogen carriers seem to be a safe option despite requiring additional research (van Rheenen et al., 2023a).

These solid hydrogen carriers can store and release hydrogen when needed. Pure hydrogen gas is not present in large quantities, resulting in an increase in safety. Many substances are available to store hydrogen, ranging from metal hydrides to ice (van Rheenen et al., 2023b). The authors previously identified a set of three solid hydrogen carriers that show promising characteristics for use onboard ships: sodium borohydride, ammonia borane and potassium borohydride (van Rheenen et al., 2023b). These hydrogen carriers have relatively high energy densities, are generally considered safe, have medium to high technology readiness levels, and can be regenerated on shore to avoid unnecessary waste. Sodium borohydride, ammonia borane, and potassium borohydride are solids in the form of granulates or powders. As potassium borohydride has similar characteristics but lower energy density than sodium borohydride, it is not considered in this paper. However, the powder-like nature of these hydrogen carriers will give rise to new challenges. Additionally, to allow for on-shore regeneration, the spent fuels need to be stored somewhere onboard. It is currently believed these spent fuels may be stored in empty fuel tanks. Thus, bunkering, storage and distribution of the fuels and spent fuels onboard must change entirely, as powders behave differently from liquids and nowadays, nothing has to be taken back to shore. On the other hand, these powders may also give rise to new opportunities, enhancing the safety of ships as compared to current fuels.

Maritime safety is a broad topic, but the main focus of maritime safety is to protect human life at sea (e.g., SOLAS), the environment (e.g., MARPOL) and the integrity of the vessel itself and its cargo. These three pillars are all relevant when considering alternative fuels, each having its own specific connection. Crucially, the integrity of

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the vessel itself will directly influence the other two pillars if the (alternative) fuel is released. This release may influence life on board as well as the environment. This is not a concern limited to naval ships; commercial vessels are equally vulnerable. Recent developments have seen a rise in attacks on civilian ships. Examples are MSC Sky II, which was hit by a missile on the 4th of March 2024. The missile caused a small fire (Bahtic, 2024). On the 6th of March, True Confidence was also hit by a missile. This missile set the ship ablaze, and 3 seafarers were killed (Bahtic, 2024). Next to deliberate attacks, commercial ships face a constant risk of collisions, both with other vessels and with natural objects like icebergs. Even though ships colliding with icebergs may feel as far away, the YONG XING 56 sank on March 1st 2023, after her hull was breached with ice, and the MS Explorer sank on 23rd November 2007 after striking an iceberg (Van den Bovenkamp, 2023; The Associated Press, 2007).

While solid hydrogen carriers themselves cannot prevent ships from sinking, their properties may offer potential safety advantages in the event of collisions. When stored within a ship's hull, these carriers may dampen the impact of a collision. The powdery nature of the hydrogen carrier could potentially solidify and even plug any resulting holes, reducing the release of the fuel through the hole. Additionally, some of these chemicals may have flame-retardant properties, potentially reducing large-scale fires. Finally, solid hydrogen carriers could minimize fuel loss compared to liquid alternatives. These characteristics suggest that solid hydrogen carriers may offer improved safety compared to conventional fuels like diesel or other liquid alternatives like methanol.

Thus, this research aims to investigate the consequences of storing solid hydrogen carriers as fuel in the ship's hull. Both impact with and without heat will be taken into account. The research will follow a conceptual approach based on chemistry and chemical reactions. This approach allows for the evaluation of alternative fuels for various ship types.

2 Method

An approach based on chemical reactions is proposed to investigate the possible usage of hydrogen carriers as impact dampeners. The influence of heat, water and a combination of heat and water on the hydrogen carriers is investigated. The likelihood of reaching relevant temperatures depends on possible environmental conditions and is not taken into account in this paper. However, the likely consequences of these impacts on hydrogen carriers are investigated. The mentioned hydrogen carriers are all circular in nature. Their empty fuel, called spent fuel, has to be stored on board and discharged and regenerated at a shore facility to enable renewable use. Thus, the ship will additionally carry the spent fuel of each of the carriers. This spent fuel depends on the reaction required to release the hydrogen. Both hydrogen carriers will release hydrogen through hydrolysis. For ammonia borane, the reaction is as follows:

$$\mathrm{NH_3BH_3} + 3\mathrm{H_2O} \rightarrow 3\mathrm{H_2} + \mathrm{B(OH)_3} + \mathrm{NH_3} \tag{1}$$

The spent fuel will thus be $B(OH)_3$, which can possibly be stored in the same tanks as the original fuels. Thus, the spent fuel must also be investigated. For sodium borohydride, a similar reaction is regarded:

$$\mathrm{NaBH_4} + (2+x)\mathrm{H_2O} \rightarrow 4\mathrm{H_2} + \mathrm{NaBO_2}.x\mathrm{H_2O} \tag{2}$$

In this case, the spent fuel thus consists of $NaBO_2.xH_2O$. The x here depends on the temperature at which the reaction occurs and the temperature at which the spent fuel is stored (Andrieux et al., 2012). To reduce weight, the x should be as small as possible. The resulting calculated weights of the spent fuel are given in table 1.

Table 1: Relation of x in equation 2 and weight of spent fuel

x	Weight of spent fuel [kg] per kg sodium borohydride
0	1.73
1	2.69
2	3.64

Thus, both the original fuel and the spent fuel will be investigated as to their chemical reaction to heat, water and a combination of heat and water. For this last scenario, the authors assume that the heat is a flash heat source, after which water will touch the products. What would happen without heat and water, with just a lack of confinement from the fuel tank, is not part of this research. Figure 1 shows the pathway of the chemical reaction paths that will be investigated in this study.

This research will focus on the chemical reactions, and the results of these reactions. Many of these chemical processes are step-wise processes. Some of these steps are exothermic and thus self-sustaining. This can potentially cause unwanted runaway reactions. Endothermic reactions, on the other hand, absorb energy and will stop once the initial energy source disappears. When considering products derived from these reactions, it's important to factor in their corrosive properties and typical applications. These substances may have undesired properties, such as high toxicity or flammability. Gasses are also less desirable than solids, as gasses can distribute themselves easily,

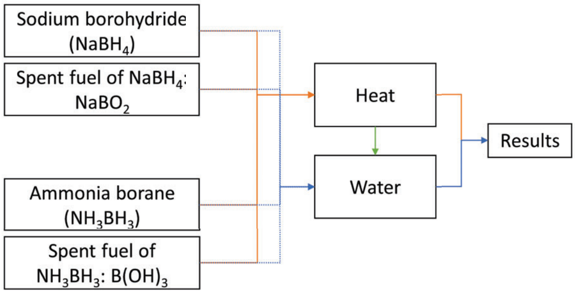


Figure 1: Overview of pathway to gain resulting chemical products for analysis in results

resulting in them coming to unwanted locations.

The substances formed will be evaluated based on their subsequent influence on the ship itself and the impact on the passengers and the environment. It is hard to quantify dangers exactly, especially as consequences depend greatly on the amount of substances produced and their location. However, a first overview of these dangers can be used to qualify whether they are large issues or can be overcome. Estimating these dangers is possible this way (van Rheenen et al., 2023a). The results can be used to determine the storage location of these hydrogen carriers based on whether they can or cannot be used as impact dampeners.

3 Results

This section discusses the reaction equations, the temperature at which they occur, whether they are endothermic or exothermic and the resulting products. Pure hydrogen is often a byproduct of the reactions and is discussed separately.

3.1 Ammonia borane

Ammonia borane reacts strongly with water and heat, releasing hydrogen and other substances during these processes.

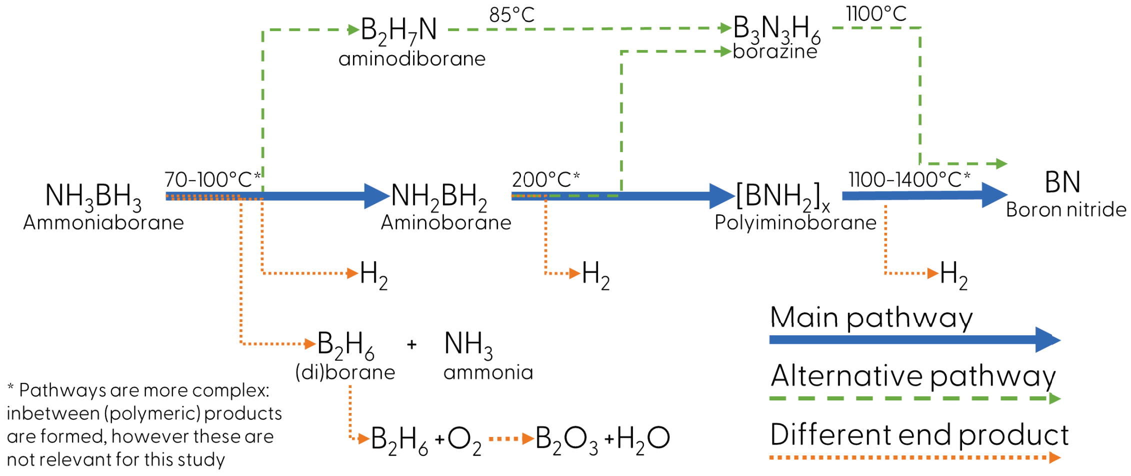
3.1.1 Reaction with heat

Figure 2 shows the resulting reactions when ammonia borane is heated. This figure is a simplified version, as the actual reactions are more complicated, see for example Demirci (2020); Al-Kukhun et al. (2013). The figure omits many intermediate steps with the same outcome, involving different but short-lived products. These in-between products, often polymeric, usually decompose to the products as visible in figure 2. The only exception is polyiminoborane, which is thermodynamically stable and only releases hydrogen upon heating at higher (over 1000 °C) temperatures. Figure 2 shows multiple end products and several in-between products that are stable within rather large temperature windows.

Figure 2 shows a three-step process for the main pathway. The first step in this three-step process is an endothermic process, with a reaction energy of approximately 115 to 145 kJ/mol, producing aminoborane (Kumar et al., 2019). When aminoborane is heated to about 200 °C, it decomposes into hydrogen and polyiminoborane. This second step is an exothermic reaction, releasing approximately 21 kJ/mol (Demirci, 2020). It is thus self-sustaining, making aminoborane as an intermediate product less likely. The exact enthalpy of reaction, however, depends on the heating rate (Baumann et al., 2005), especially as aminoborane is only stable until about 115 °C, after which it slowly decomposes (Baumann et al., 2005). The result, iminoborane (BNH_2), is illusive and highly reactive (Baitalow et al., 2002). It quickly oligomerizes or polymerizes. Polyiminoborane is rather stable (Hu et al., 1978). However, it slowly releases hydrogen upon heating (Hu et al., 1978). When iminoborane oligomerizes, it is transformed into borazine.

Only at much higher temperatures, of around 1100 to 1400 °C, boron nitride is formed (Frueh et al., 2011). When borazine is heated, it also forms boron nitride. Boron nitride is a highly stable nitride, subliming at 2500 °C (Demirci, 2020; Patnaik, 2003).

During each of the steps, additional byproducts occur. Higher heating rates result in more volatile, unwanted byproducts like diborane and borazine (Baitalow et al., 2002; Karkamkar et al., 2007). During the first step, diborane and aminodiborane are produced. Diborane (B_2H_4) is produced at a ratio of 0.02 to 0.04 mol per mol of ammonia borane (Baitalow et al., 2002). Diborane, also known as borane, will readily oxidize (at temperatures lower than 54 °C) to B_2O_3 (boron trioxide) (House, 2020). Boron trioxide is a stable solid substance, vaporizing at 1500 °C (Patnaik, 2003). Boron trioxide is an ingredient in flame retardant (NCBI, 2024f), and is non-combustible.



* Pathways are more complex: inbetween (polymeric) products are formed, however these are not relevant for this study

Figure 2: Reactions of ammonia borane in heat

Next to diborane, ammonia is produced. Ammonia is a toxic gas and is lighter than air. Ammonia has a flash point of 132 °C.

Next to diborane, aminodiborane can be produced simultaneously during the first step (Demirci et al., 2011; Al-Kukhun et al., 2013). Aminodiborane transforms later into borazine; this reaction happens at temperatures as low as 75 °C (Al-Kukhun et al., 2013). However, it takes time to produce amino diborane; the reaction is relatively slow (Al-Kukhun et al., 2013). Aminodiborane is generally hard to produce, resulting in very limited information available (Chen et al., 2010). It is reported as highly sensitive to air and moisture as it decomposes (Nair et al., 2023). However, it is likely to react with an in-between product of the main pathway, diammoniate of diborane, resulting in an alternative but slower path to produce borazine (Al-Kukhun et al., 2013).

Borazine is created during the second step as well. Approximately 0.03 to 0.06 moles of borazine per mol of ammonia borane are created during this process (Baitalow et al., 2002). Borazine is a dangerous liquid, which is highly flammable and causes severe damage to the eyes and skin (NCBI, 2024b). In water, it hydrolysis to ammonia, boric acid and hydrogen.

3.1.2 Reaction with water

Ammonia borane reacts with water in a process called hydrolysis. Equation 1 gives an overview of what happens during this process (Demirci, 2020). There are no known side reactions or alternative pathways (Demirci, 2020). However, the reaction rate is considered to be slow, as there are no catalysts or acids (Demirci, 2020; Li et al., 2022). Acids act as catalysts during hydrolysis; lower pH will result in faster reactions (Li et al., 2022). For higher pH, of about 10, no reaction was observed for 8 minutes, after which the experiment was stopped (Li et al., 2022). Additionally, the substance will self-stabilise if nothing is done about the pH value of the solution. Regardless of the concentration, the pH will become 8.7 to 9.1, close to seawater's pH (7.5 to 8.5) (Brockman et al., 2010; Chandra and Xu, 2006; Marion et al., 2011). At these pH values, the solution is reported to be stable for 80 days in an inert atmosphere (Chandra and Xu, 2006). Brockman et al. (2010) confirms this, testing ammonia borane in different amounts of water, resulting in very low (maximum of 10% of the overall hydrogen available in ammonia borane) hydrogen loss over several (at most 75) days. Unfortunately, the authors could not find data on what happens in a normal atmosphere. Thus, ammonia borane is estimated to react extremely slowly in seawater. Regarding the produced products, $B(OH)_3$, the original spent fuel, will be discussed in section 3.3 and hydrogen in section 3.2.2. Ammonia is the main product specific to the hydrolysis of ammonia borane in water. Ammonia is highly soluble in water and will react with water and form a solution according to the following equation (Demirci, 2020):

$$NH_3 + H_2O \rightleftarrows NH_4^+ + OH^- \tag{3}$$

In this equation, ammonium (NH_4^+) and hydroxide (OH^-) combined are called ammonium hydroxide (Kass et al., 2021). The amount of ammonia dissolved in water depends on the amount of water and whether some of the ammonia can be lost in the gas phase (Demirci, 2020). It is unclear whether all ammonia is dissolved in seawater. Some sources believe that some ammonia will still be in the gas phase (Demirci, 2020), while others believe that all ammonia that contacts water will be dissolved (Kass et al., 2021). Thus, the assumption has to be made that

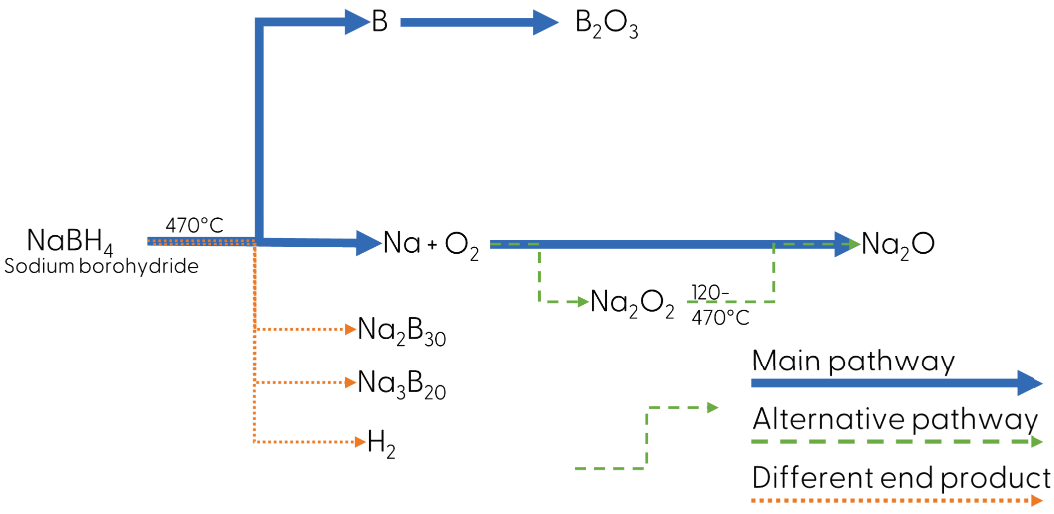


Figure 3: Reactions of sodium borohydride in heat

pure ammonia as a gas will be released, as well as ammonium hydroxide. Ammonium hydroxide is alkaline and corrosive. It will inhibit the reaction of ammonia borane with water and corrode materials nearby. It is also harmful to sealife (Kass et al., 2021).

3.1.3 Combined heat and water

Figure 2 shows several products resulting from heating ammonia borane. Ammonia itself was discussed in section 3.1.2. Borane/diborane has likely already changed into B_2O_3 (House, 2020), as visible in figure 2; however, if this does not happen, borane will react with water as follows:

$$B_2H_6 + H_2O \rightarrow 2B(OH)_3 + 6H_2 \tag{4}$$

In this equation, hydrogen and boric acid are produced. The reaction is strongly exothermic (Prosen et al., 1959). The authors refer to section 3.3.3 for the reaction of boric acid with water.
This leaves aminodiborane and borazine. As mentioned in section 3.1.1, aminodiborane decomposes in water (Nair et al., 2023). The authors cannot find the exact decomposition reaction. It will likely react similarly to borazine, forming hydrogen, ammonia and $B(OH)_3$ upon hydrolysis (Nagasawa, 1966; NCBI, 2024b; Nair et al., 2023). Generally, boron-nitrogen bonds are not stable in the presence of water (Nagasawa, 1966).

3.2 Sodium borohydride

Sodium borohydride is a salt and looks like a white powder. It can be thermolyzed and hydrolyzed to release hydrogen and will thus react with heat and water (Singh, 2021; Demirci et al., 2010).

3.2.1 Reaction with heat

Figure 3 gives an overview of the main and alternative pathways of thermal decomposition of sodium borohydride. Thermal decomposition starts at 470 °C and is in general as follows (Singh, 2021; Martelli et al., 2010; Kumar et al., 2017):

$$NaBH_4 \rightarrow B + Na + 2H_2 \tag{5}$$

All hydrogen is released at once when heated above 600 °C, although other sources estimate this to be 534 °C (Singh, 2021; Martelli et al., 2010). The process is exothermic and thus self-sustaining, releasing about 108 kJ/mol (Singh, 2021; Martelli et al., 2010; Kumar et al., 2017). The products formed are two solids (sodium and boron) as well as hydrogen.
Sodium is a well-known substance and is very volatile (Krolikowski, 1968; Lebel and Girault, 2018). Figure 3 shows the two main reaction pathways of sodium with oxygen, producing sodium oxide (Na_2O and sodium peroxide (Na_2O_2) (Krolikowski, 1968). This reaction occurs at temperatures at or below 105 °C and requires only 5% volumetric oxygen in the air (Krolikowski, 1968; Bulmer and Fire, 1972). The burning of sodium can reach temperatures of up to 3600 °C under ideal circumstances (Krolikowski, 1968).
Boron is a versatile material, and though it is generally categorized as interesting, there is still a lot unknown about

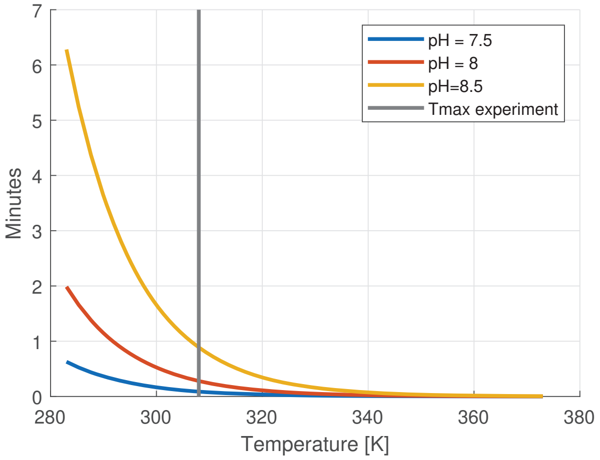


Figure 4: Release of half of the hydrogen from $NaBH_4$ during self-hydrolysis. Including the maximum temperature for which this equation, equation 6 has been validated, based on (Retnamma et al., 2011).

this material (van Setten et al., 2007). Boron generally does not react easily at room temperature and is not very volatile (van Setten et al., 2007). It is known, however, to burn readily and produce B_2O_3 (boron trioxide), which has been discussed previously in section 3.1.1 (House, 2020).

Next to these main products, also two combinations of boron and sodium are formed: Na_2B_{30} and Na_3B_{20}. Almost no data about Na_2B_{30} (Chang et al., 2021) is available and will thus not be discussed by the authors here. Na_3B_{20} is better studied. It is a pyrophoric substance if the particles are small, at larger particle size it is more stable (Albert, 1998; Albert and Hofmann, 1999). It is also possible that Na_3B_{20} only occurs at high temperatures (1050 °C) as it usually is synthesized at such high temperatures (Albert and Hofmann, 1999). It is thermodynamically stable, and likely only very small quantities are produced.

3.2.2 Reaction with water

The reaction of sodium borohydride with water is given in equation 2. No other pathways have been reported to the authors' knowledge. The reaction rate is strongly dependent on temperature and pH value. A higher pH value, indicating a more alkaline solution, will inhibit the reaction, while higher temperatures will result in a higher reaction rate (Sermiagin et al., 2022). A higher concentration will result in a faster reaction rate, too (Sermiagin et al., 2022). A temperature of 25 °C and pH of 7.4, lower than that of seawater, will result in approximately 67% of all hydrogen generated within 5 minutes and reaction rates of 2.05×10^{-3} s^{-1} have been reported for pH values of around 8.5 (Sermiagin et al., 2022; Marion et al., 2011). Another source cites a half-life of $NaBH_4$ of about 36.8 seconds when dissolved in a solution with a pH of 8. The reaction rate has been captured empirically as follows (Retnamma et al., 2011; Hoeppner et al., 2008):

$$log(t_{1/2}) = pH - (0.034T - 1.92) \tag{6}$$

with $t_{1/2}$ in minutes and T, the temperature, in Kelvins. Figure 4 visualises the different half-life times. Considering typical seawater temperatures of up to 30 °C (or 303K) (Kennedy, 2014), the shortest half-lifes lie under a minute. These reactions can be considered fast.

3.2.3 Combined heat and water

Sodium, known to be highly reactive with water, is part of many of the products in figure 3 (Bulmer and Fire, 1972). However, if there is no air, the reaction may be non-explosive (Bulmer and Fire, 1972). Figure 5 gives an overview of the resulting reactions. The reactions are all exothermic. One of the alternative endproducts, H_2O_2, is known to cause thermal runaways, as it decomposes at low temperatures, lower than 100 °C (Wu and Qian, 2018). NaOH, the main reaction product, will dissolve in water, releasing heat (NCBI, 2024d). This reaction can possibly ignite other substances, such as hydrogen peroxide. It splits into Na^+ and OH^- and is a salt. When not strongly diluted, it is extremely corrosive (NCBI, 2024d).

Boron is unlikely to react, as it is relatively stable and also present in seawater, with concentrations ranging from 0.5 to 9.6 mg/L (Kochkodan et al., 2015). This is both natural as well as due to human causes.

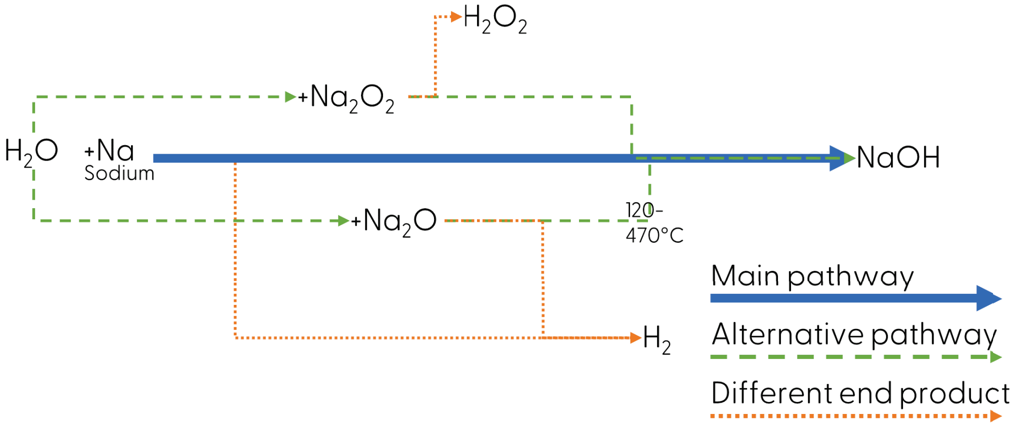


Figure 5: Reactions of products of sodium borohydride in heat, with water

3.3 Spent fuel

The spent fuel of sodium borohydride ($NaBO_2$) and that of ammonia borane ($B(OH)_3$ are very similar and composed of similar elements. Thus, they are considered both in this subsection. When dissolved in water, the spent fuel of sodium borohydride splits up in Na^+ and $B(OH)_4^-$, the latter which is also the spent fuel of ammonia borane.

Equations 1 and 2 give a high-over reaction overview. The exact composition of the spent fuel depends on temperature, whether and how the water is extracted and the pressure (Andrieux et al., 2012; Moussa et al., 2013).

3.3.1 Heating of boric acid

Boric acid, $B(OH)_3$, is a very weak acid and has been used as flame retardant (House, 2020; Sevim et al., 2006). Upon heating, boric acid releases its hydrogen and oxygen atoms in the form of water in a two-step reaction (Sevim et al., 2006; Kim and Hwang, 2021; Balci et al., 2012):

$$B(OH)_3 \leftrightarrow HBO_2 + H_2O \tag{7}$$

occurring at temperatures below 130 °C. The next step occurs at higher temperatures of around 200 °C, with a maximum of about 450 °C (Balci et al., 2012; Kim and Hwang, 2021). At temperatures higher than this, reactions will slow down. The second step is as follows:

$$2HBO_2 \rightarrow B_2O_3 + H_2O \tag{8}$$

It is possible that the second step already occurs before the first step is completed (Balci et al., 2012). The end result, B_2O_3, is called boron oxide. The first reaction, equation 7, is a slow reaction, taking up to 3 days for low temperatures (up to 100 °C) and 45 minutes for temperatures above 300 °C (Balci et al., 2012). The melting temperature of boron oxide depends on its structure. The exact structure of the end product of equation 8 is unclear, however the melting point will be around 450 to 500 °C (Sevim et al., 2006). Boron oxide is widely used, for example, in glass and ceramics, but it is also used as a fire retardant (Sevim et al., 2006). Boron oxide will evaporate at temperatures above 1025 °C (Lopatin et al., 2023).

3.3.2 Heating of Sodium metaborate

$NaBO_2$ is thermodynamically stable and does not react easily. It has a high melting and boiling point. The melting point lies at 966 °C and the boiling point at 1434 °C (NCBI, 2024c). On the contrary, it has also been stated to evaporate at temperatures above 800 °C (Lopatin et al., 2023).

3.3.3 Reaction with water

The reactions of water with the spent fuels are straightforward. These reactions also happen during the original dehydrogenation process, as both fuels are solved in water during the hydrolysis process. Sodium metaborate splits

Table 2: Resulting products of reactions of NH3BH3, NaBH4 and the spent fuels with heat, water and a combination of heat and water

	Heat	Water	Heat and water
Ammonia borane	NH_3(g), H_2(g), B_2H_6 (g), B_2H_7N (l), $B_3N_3H_6$ (l) T<1000 °C: $[BNH_2]_x$ T>1000 °C: BN	NH_4^+ (aq) + OH^- (aq) H_2 $B(OH)_3$ (aq) $\leftrightarrow$ $B(OH)_4^-$ (aq) + H^+ (aq)	H_2, NH_3, $B(OH)_3$
Sodium borohydride	Na (s), B (s), H_2 (g), Na_2O (s), Na_2B_30 (s), Na_3B_20 (s), B_2O_3 (s)	$NaBO_2$ (aq), H_2 (g)	H_2O_2 (l), NaOH (s/aq), H_2 (g)
Spent fuel	B_2O_3 (s) (NH_3BH_3) $NaBO_2$ (s) ($NaBH_4$)	$B(OH)_3$ (aq) $\leftrightarrow$ $B(OH)_4^-$(aq) + H^+(aq)	$B_2O_3 + H_2O \rightarrow B(OH)_3$(aq) Na^+ (aq), $B(OH)_4^-$ (aq)

into two ions, sodium and metaborate (Atiyeh and Davis, 2007):

$$NaBO_2 \xrightarrow{\text{Water}} Na^+ + B(OH)_4^- \tag{9}$$

As sodium ions are common in seawater, they are not of interest in this study. Thus, the authors will focus on the metaborate-ion, B(OH_4^-). This ion is unstable in water (House, 2020; Kochkodan et al., 2015; Kabay and Bryjak, 2015). It is the anion that is in balance with boric acid as follows:

$$B(OH)_3 + H_2O \leftrightarrow B(OH)_4^- + H^+ \tag{10}$$

The pH of the water strongly influences this balance. The balance lies at $B(OH)_3$ for low pH and switches to the right for pH levels higher than about 8.5; the exact pH value where the balance shifts depends strongly on the temperature (Kochkodan et al., 2015; Kabay and Bryjak, 2015). At seawater with a pH of 8.3, the balance in equation 10 shifts to the left, and most of the substance is in the form of boric acid (Kabay and Bryjak, 2015).

In the case of having first a heating reaction and then a water reaction, boron oxide reacts with water exothermically to reform boric acid (Rasmussen et al., 2003).

3.4 Hydrogen

Risks of hydrogen in its pure form have been widely covered in the literature (for example, but not limited to (Mjaavatten and Bjerketvedt, 2005; Makarov et al., 2021; Gerboni and Salvador, 2009; Dagdougui et al., 2018; Patel et al., 2023). The main issue with hydrogen explosions is not the heat source but the power resulting from the pressure of the explosion (Makarov et al., 2021; Mjaavatten and Bjerketvedt, 2005). Even relatively small hydrogen explosions, where about 3.5 to 7kg of hydrogen exploded, had destructive influences on nearby buildings (Mjaavatten and Bjerketvedt, 2005). As most explosions occur due to over-pressure (Patel et al., 2023), however, it is hard to estimate whether a breach of a ship tank will result in hydrogen explosions.

4 Discussion

The previous section has given an overview of the possible reactions occurring when the solid hydrogen carriers come into contact with heat, water or a combination of heat and water. This will have implications on how and where these fuels can be stored and whether they can be used as impact dampeners.

Table 2 gives an overview of all resulting products from each of the possible reactions. These products are not produced proportionally; some of the products only occur in very small quantities, making them less relevant. As the exact amounts of the products are unclear, they will all be taken into account in this analysis.

4.1 Heating

Both fuels produce dangerous substances upon heating. However, the products and the respective temperatures differ strongly.

4.1.1 Ammonia borane

Ammonia borane reacts at lower temperatures, of up to 200 °C already. During these reactions, the toxic gasses ammonia and diborane and the flammable gas hydrogen are formed. Heating of ammonia borane thus forms a danger to both the ship and the people on board. As these substances are all gasses, they are more dangerous but also more safe. Their gas-like nature will result in a faster distribution and, thus, lower overall concentrations of each gas. This will make the gasses safer, as lower concentrations are less likely to be dangerous.

Hydrogen has a lower flammability limit of 4% and is easily ignited. Thus, the release of hydrogen may cause an explosion and, thus, a secondary heat source. These types of reactions may become self-sustaining, resulting in more release of hydrogen and other dangerous gasses. Diborane (B_2H_6) is also easily ignited, igniting in moist air at room temperature without external triggers (NCBI, 2024a). The flammability and easy ignition of both hydrogen and diborane may influence the ship's integrity, as these are likely to ignite. Additionally, the spontaneous ignition of diborane, despite very low concentrations, may cause the ignition of hydrogen. Hydrogen is likely to be present in larger concentrations and can influence the integrity of the ship.

Ammonia is not easily ignited, but is extremely toxic, and concentrations as low as 2500 ppm are considered lethal (NCBI, 2024e). Diborane is even more toxic. It has a strong smell and can be smelled at low concentrations, as low as 1.8 ppm (NCBI, 2024a). It is extremely toxic and can be deadly at concentrations as low as 0.46 ppm if inhaled over longer amounts of time. At 7.3 ppm, it has immediate effects (NCBI, 2024a). Another danger of diborane, as opposed to ammonia and hydrogen, is that it is heavier than air and thus will accumulate. Ammonia, on the other hand, is lighter than air and will disperse more easily. The toxicity of ammonia and diborane, especially the heavy weight and high toxicity of diborane, will strongly influence the safety of the people on board.

Finally, ammonia may influence sealife, but only if it touches water. If it comes into contact with water, it may have large consequences for local sea life (Kass et al., 2021). As it is lighter than air, this is not necessarily likely. Diborane forms no environmental hazard according to the GHS standards, but as it is so toxic to people, it is likely to also influence sea life, and of these three gasses most likely to enter the ocean.

Two other substances that are formed are aminodiborane and borazine, both liquids. Borazine is a flammable and corrosive liquid with a clear smell and no colour (NCBI, 2024b). The corrosiveness of borazine applies to the skin, as it causes skin burns and eye damage (NCBI, 2024b). Aminodiborane is an unstable liquid, decomposing at room temperature, likely towards borazine (Demirci, 2017; Al-Kukhun et al., 2013). Release of these two liquids will likely result in contact with the environment. Aminodiborane will slowly hydrolyse, completing hydrolysis in 2 months at room temperature (Demirci, 2017). It is unknown if aminodiborane is toxic to the environment. However, it is not likely to influence the ship's integrity. Borazine will strongly influence the safety of the people on board, as it is a liquid that should not come into contact with people. It is flammable and reacts violently with water, which may influence the ship's integrity if this substance comes into contact with water (NCBI, 2024b).

4.1.2 Sodium borohydride

The resulting products of heating sodium borohydride are dangerous. However, these products occur after heating at much higher temperatures (around 470 °C for sodium borohydride, versus 200 °C for ammonia borane). In the case of sodium borohydride, runaway reactions are more probable.

When heating sodium borohydride, the structural integrity of the ship is likely influenced. A major product, sodium, is a dangerous solid due to its flammability and corrosivity. It burns violently and may also cause explosions. These explosions, in turn, can set off more explosions from hydrogen. The corrosivity of sodium may influence the metal the ship is made of. The other three substances (boron, sodium oxide (Na_2O) and boron oxide (B_2O_3)) are not likely to influence the ship itself.

Boron, sodium oxide (Na_2O) and boron oxide (B_2O_3) may all influence the safety of people on board. Boron is an irritant and should not be swallowed. Boron oxide is a typical boron-based product and only has a health hazard. This health hazard is typical for boron-based compounds, such as boric acid and boron oxide: these may influence fertility or the unborn child (Chapin and Ku, 1994). It is thus unlikely to influence the people onboard strongly. Like sodium oxide, it does not harm the environment or the ship. Sodium oxide is also dangerous for the people onboard as it is corrosive to the skin and thus can cause eye damage. All of these substances should thus not be touched. As they are solids, they are not easily distributed, enhancing their safety.

Even though some reports that boron compounds may cause long-lasting harmful effects on aquatic life, there is no consistency on this (NCBI, 2024g). Whether any of the products resulting from heating sodium borohydride will harm the environment is not known.

4.2 Water

Both substances will react with water. The most positive side is that no alternative substances are produced, only the substances that are known and well-studied. However, these substances are not necessarily safe.

Hydrolysis of ammonia borane will result in ammonia, hydrogen and boric acid. Ammonia will harm local wildlife and, if not dissolved in seawater, may harm the lives of people onboard the ship and in the surrounding area. and the possibility of hydrogen explosions.

The spent fuel of ammonia borane, boric acid, may damage fertility or the unborn child, resulting in a health hazard (NCBI, 2024f). However, no other dangers have been stated for this substance. When touching the water, it will sink and dissolve completely (NCBI, 2024f).

Sodium borohydride will only produce the possibly explosive hydrogen. Again, hydrogen explosions may influence the integrity of the ship.

Table 3: Resulting dangerous products of reactions of ammonia borane and sodium borohydride and their relative spent fuel with heat, water and a combination of heat and water

	Heat	Water	Heat and Water
Ammonia borane	Dangerous gasses and liquids, which will influence the ship’s integrity, life onboard and environment	Dangerous gasses, which may influence the ship’s integrity, life onboard and environment	Dangerous gasses and liquids, which may influence the ship’s integrity, life onboard and environment
Spent fuel: Boric acid	Flame retardant, will release water	May influence reproducibility of local wildlife	May influence reproducibility of local wildlife
Sodium borohydride	Dangerous gasses and solids which will influence the ship’s integrity, and possibly life onboard and environment	Dangerous gasses, which may influence the ship’s integrity	Dangerous gasses and solids which will influence the ship’s integrity, and possibly life onboard and environment
Spent fuel: Sodium metaborate	Unlikely to react	May influence reproducibility of local wildlife	May influence reproducibility of local wildlife

The spent fuel, sodium metaborate, may be a danger to human reproducibility and, thus, also likely to wildlife reproducibility. However, the exact effects are unknown.

4.3 Combined heat and water

When heating ammonia borane, many different substances are produced. However, almost all of these substances react in a very similar way with water. The reactions are usually exothermic (Prosen et al., 1959; Nagasawa, 1966; Nair et al., 2023), and the resulting products are likely to be ammonia, hydrogen and boric acid. These products will likely influence all three pillars: the integrity of the ship, the safety of the people onboard and the environment and are extensively discussed in previous sections.

As the spent fuel of ammonia borane, boric acid, releases water upon heating, it changes into boron oxide. Boron oxide will absorb water exothermically. This reaction forms boric acid again. Thus, the reaction of boric acid upon first experiencing heat and then water is unlikely to result in different reactions as compared to experiencing water only.

The main products from sodium borohydride, when heated, are sodium, boron and hydrogen, as well as sodium oxide and sodium peroxide. Some of these products are volatile. Sodium reacts strongly with water, forming sodium hydroxide (NaOH). This reaction is highly exothermic and may influence the integrity of the ship. NaOH is readily dissolved in water but is extremely corrosive and can thus influence the integrity of the ship. Similarly, sodium peroxide reacts with water, forming hydrogen peroxide. Hydrogen peroxide can cause thermal runaways (Wu and Qian, 2018). Thus, heating sodium borohydride, followed by adding water, may result in various explosions, resulting in additional heat sources and thus a chain reaction. This chain reaction will likely influence the integrity of the ship.

Of these products, only hydrogen peroxide is dangerous to the people onboard and the environment. It can cause severe skin burns and eye damage and harm aquatic life (NCBI, 2024h).

As sodium metaborate is thermodynamically relatively stable, no different reactions are expected upon a combination of heating and water as compared to releasing sodium metaborate directly in water.

4.4 Overview

Table 3 gives an overview of all the hazards accompanied by heating, adding water or a combination of both. It is clear that both ammonia borane and sodium borohydride release dangerous substances. Heating is the most dangerous for ammonia borane, as a chain reaction is likely. Heating of sodium borohydride results in similarly dangerous products. However, as the products of sodium borohydride are only released at much higher temperatures (over 500 °C), overall sodium borohydride is more safe than ammonia borane upon heating. Both spent fuels are the most safe. Boric acid is more safe than sodium metaborate. Boric acid is a flame retardant and will release water, possibly extinguishing the fire, while sodium metaborate likely will not react.

When adding water, ammonia borane produces the least safe products. However, as the reaction rate of ammonia borane with water is extremely slow, especially compared to sodium borohydride, it is difficult to say which one is safer. Both have different hazards. Again, the spent fuels are safer than the original fuels.

Finally, when first adding heat and then adding water, sodium borohydride appears to be less safe. Heating sodium borohydride produces, amongst others, sodium, which reacts violently with water. Heating ammonia borane produces mainly dangerous gasses, of which only one (diborane) is heavier than air. Diborane is also produced in less high quantities. The same applies to the liquids produced, which are mainly byproducts. Thus, ammonia borane is the safer fuel in this case. As before, both spent fuels are safer and likely will not release dangerous substances.

5 Conclusion

While the zero-emission nature of alternative fuels is a major advantage, their benefits may extend even further. Especially solid hydrogen carriers, such as sodium borohydride and ammonia borane, may offer advantages unknown to liquid alternative fuels. This research investigated the consequences of storing solid hydrogen carriers of boron-based fuels in the ship's hull.

This research regarded three main safety pillars: integrity of the ship, safety of the life onboard and environmental impact. Regardless of the type of impact, ammonia borane will likely influence all three pillars. As it reacts already with low heat sources (around 100 °C), heat is to be avoided at all times. Adding water to the heated ammonia borane is unlikely to make it worse. The gasses and liquids released are flammable and toxic to human life. As ammonia borane is a boron chemical compound, it may influence the reproducibility of sea life. A possible storage location, if stored in the hull, would, therefore, be below the water line.

Sodium borohydride, on the other hand, reacts only at much higher temperatures, starting decomposition at 450 °C. However, the reaction products are extremely volatile. Amongst others, sodium is produced, which reacts violently upon touching water. This can thus influence the ship's integrity. However, none of the products of heating sodium borohydride are toxic. Thus, if sodium borohydride were to be stored in the hull, a possible storage location would be above the waterline. This will also limit the possible influence of sodium borohydride on the reproducibility of local sea life.

Unlike the original fuels, spent fuels from sodium borohydride and ammonia borane offer potential benefits regarding safety. The spent fuel of sodium borohydride is thermodynamically stable and unlikely to produce toxic or flammable gasses upon heating. The spent fuel from ammonia borane is a known flame retardant, releasing water when heated. These properties suggest that spent fuels are unlikely to form hazardous substances upon impact and may even mitigate the effects of heat.

Ultimately, considerations must be made on where to locate the fuels and their spent fuels onboard the ship based on safety and the handling of the powders. By carefully addressing these storage and distribution challenges, the full potential of these alternative fuels for a cleaner and safer maritime future can be unlocked.

6 Future work and recommendations

This fuel research as an indicator for impact dampeners is still subject to active academic discussion. This statement applies to all reaction products discussed here and their corresponding maritime influences, as this is part of ongoing research. To fully assess the feasibility and safety of the storage of these two solid hydrogen carriers onboard ships, further research is crucial. This research can include but is not limited to, the following key areas. First of all, experimental validation of containment loss is required. In this case, no external factors (such as heat or water) are necessary; the focus should lie on what happens during the loss of containment of the fuel. Experimental data on the reaction rates during relevant conditions is also desired. This will give information on whether the size and volume of the alternative fuels and, thus, the tanks are relevant. All these experiments can provide insights into, for example, whether a double hull (such as used with oil tankers) is advisable. The optimal storage location for both the fuel and spent fuels also requires investigation. While using empty fuel tanks to store the spent fuel is currently considered the most efficient approach, the distinct properties of each type may necessitate alternative storage configurations for enhanced safety and performance. Besides this, a comparison with current rules and regulations set by the IMO and classification societies based on the storage of fuels would result in additional insights into the storage of these alternative fuels. Possible mitigation measures required when using hydrogen carriers should also be researched, however this will depend on the scale of exposure and consequently the relative ship design. By addressing these areas, a robust framework for the safe and efficient adoption of alternative fuels in the maritime industry can be established, paving the way for a cleaner and more sustainable future for maritime transportation.

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References

Al-Kukhun, A., Hwang, H.T., Varma, A., 2013. Mechanistic studies of ammonia borane dehydrogenation. International Journal of Hydrogen Energy 38, 169–179. doi:10.1016/J.IJHYDENE.2012.09.161.

Albert, B., 1998. A new ’old’ sodium boride: Linked pentagonal bipyramids and octahedra in na3b20. Angewandte Chemie - International Edition 37, 1117–1118. doi:10.1002/(SICI)1521-3773(19980504)37:8<1117::AID-ANIE1117>3.0.CO;2-X.

Albert, B., Hofmann, K., 1999. Synthesis, characterization, and crystal structure of na3b20, determined and refined from x-ray and neutron powder data. Zeitschrift für anorganische und allgemeine Chemie 625, 709–713. doi:10.1002/(SICI)1521-3749(199905)625:5<709::AID-ZAAC709>3.0.CO;2-L.

Andrieux, J., Laversenne, L., Krol, O., Chiriac, R., Bouajila, Z., Tenu, R., Counioux, J.J., Goutaudier, C., 2012. Revision of the nabo2–h2o phase diagram for optimized yield in the h2 generation through nabh4 hydrolysis. International Journal of Hydrogen Energy 37, 5798–5810. doi:10.1016/j.ijhydene.2011.12.106.

Atiyeh, H.K., Davis, B.R., 2007. Separation of sodium metaborate from sodium borohydride using nanofiltration membranes for hydrogen storage application. International Journal of Hydrogen Energy 32, 229–236. doi:10.1016/j.ijhydene.2006.06.003.

Bahtic, F., 2024. Missile attack kills three, injures four sailors on bulk carrier in gulf of aden. URL: https://www.offshore-energy.biz/missile-attack-kills-three-injures-four-sailors-on-bulk-carrier-in-gulf-of-aden/. retrieved May 23, 2024.

Baitalow, F., Baumann, J., Wolf, G., Jaenicke-Rößler, K., Leitner, G., 2002. Thermal decomposition of b–n–h compounds investigated by using combined thermoanalytical methods. Thermochimica Acta 391, 159–168. doi:10.1016/S0040-6031(02)00173-9.

Balci, S., Sezgi, N.A., Eren, E., 2012. Boron oxide production kinetics using boric acid as raw material. Industrial and Engineering Chemistry Research 51, 11091–11096. doi:https://doi.org/10.1021/ie300685x.

Baumann, J., Baitalow, F., Wolf, G., 2005. Thermal decomposition of polymeric aminoborane (h2bnh2)x under hydrogen release. Thermochimica Acta 430, 9–14. doi:10.1016/J.TCA.2004.12.002.

Brockman, A., Zheng, Y., Gore, J., 2010. A study of catalytic hydrolysis of concentrated ammonia borane solutions. International Journal of Hydrogen Energy 35, 7350–7356. doi:10.1016/j.ijhydene.2010.04.172.

Bulmer, G.H., Fire, A.M.I., 1972. Fire safety considerations related to the large scale usage of sodium. I.Chem.E. SYMPOSIUM SERIES 33.

Chandra, M., Xu, Q., 2006. Dissociation and hydrolysis of ammonia-borane with solid acids and carbon dioxide: An efficient hydrogen generation system. Journal of Power Sources 159, 855–860. doi:10.1016/J.JPOWSOUR.2005.12.033.

Chang, J., Zhang, T., Ge, N., 2021. Influence of pressure on the structure, mechanical and dynamic properties of boron-rich na2b30. Journal of Solid State Chemistry 296, 121962. doi:10.1016/J.JSSC.2021.121962.

Chapin, R.E., Ku, W.W., 1994. The reproductive toxicity of boric acid. Environmental Health Perspectives 102, 87–91. doi:10.1289/ehp.94102s787.

Chen, X., Zhao, J.C., Shore, S.G., 2010. Facile synthesis of aminodiborane and inorganic butane analogue nh3bh2nh2bh3. J Am Chem Soc 132, 17. doi:10.1021/ja104938v.

Dagdougui, H., Sacile, R., Bersani, C., Ouammi, A., 2018. Hydrogen logistics: Safety and risks issues. Hydrogen Infrastructure for Energy Applications , 127–148doi:10.1016/b978-0-12-812036-1.00007-x.

Demirci, U.B., 2017. Impact of h.i. schlesinger’s discoveries upon the course of modern chemistry on b-(n-)h hydrogen carriers. International Journal of Hydrogen Energy 42, 21048–21062. doi:10.1016/J.IJHYDENE.2017.07.066.

Demirci, U.B., 2020. Ammonia borane: An extensively studied, though not yet implemented, hydrogen carrier. Energies 13. doi:10.3390/en13123071.

Demirci, U.B., Akdim, O., Andrieux, J., Hannauer, J., Chamoun, R., Miele, P., 2010. Sodium borohydride hydrolysis as hydrogen generator: Issues, state of the art and applicability upstream froma fuel cell. Fuel Cells 10. doi:10.1002/fuce.200800171.

Demirci, U.B., Bernard, S., Chiriac, R., Toche, F., Miele, P., 2011. Hydrogen release by thermolysis of ammonia borane nh3bh3 and then hydrolysis of its by-product [bnhx]. Journal of Power Sources 196, 279–286. doi:10.1016/J.JPOWSOUR.2010.06.031.

Frueh, S., Kellett, R., Mallery, C., Molter, T., Willis, W.S., King’Ondu, C., Suib, S.L., 2011. Pyrolytic decomposition of ammonia borane to boron nitride. Inorganic Chemistry 50, 783–792. doi:https://doi.org/10.1021/ic101020k.

Gerboni, R., Salvador, E., 2009. Hydrogen transportation systems: Elements of risk analysis. Energy 34, 2223–2229. doi:10.1016/J.ENERGY.2008.12.018.

Hoeppner, K., Tanaka, S., Hahn, R., Reichl, H., Esashi, M., Tanaka, S., 2008. Nabh4 hydrogen microreactor fabricated by microsystem technology, in: Proceedings of PowerMEMS 2008+ microEMS 2008, pp. 84–88.

House, J.E., 2020. Chemistry of nonmetallic elements i. hydrogen, boron, oxygen, and carbon. Inorganic Chemistry , 465–516doi:`10.1016/B978-0-12-814369-8.00013-3`.

Hu, M.G., Geanangel, R.A., Wendlandt, A.W.W., 1978. The thermal deco,mposition of ammonia borane. thermochimica Acta , 249–255.

Kabay, N., Bryjak, M., 2015. Boron removal from seawater using reverse osmosis integrated processes. Boron Separation Processes , 219–235doi:`10.1016/B978-0-444-63454-2.00009-5`.

Karkamkar, A., Aardahl, C., Autrey, T., 2007. Recent Developments on Hydrogen Release from Ammonia-Borane. volume 2. doi:`10.1016/B978-0-12-385142-0.00015-5`.

Kass, M.D., Sluder, C.S., Kaul, B.C., 2021. Spill Behavior, Detection, and Mitigation for Emerging Nontraditional Marine Fuels. Technical Report. Oak Ridge National Laboratory. doi:`10.2172/2290266`.

Kennedy, J.J., 2014. A review of uncertainty in in situ measurements and data sets of sea surface temperature. Reviews of Geophysics 52, 1–32. doi:`https://doi.org/10.1002/2013RG000434`.

Kim, G.J., Hwang, H.T., 2021. Thermal hydrolysis of solid-state sodium borohydride for noncatalytic hydrogen generation. Chemical Engineering Journal 424, 130445. doi:`10.1016/J.CEJ.2021.130445`.

Kochkodan, V., Darwish, N.B., Hilal, N., 2015. The chemistry of boron in water. Boron Separation Processes , 35–63doi:`10.1016/B978-0-444-63454-2.00002-2`.

Krolikowski, T.S., 1968. Violently Sprayed Sodium-Air Reaction in an Enclosed Volume. Technical Report. Argonne National Laboratory.

Kumar, S., Jain, A., Miyaoka, H., Ichikawa, T., Kojima, Y., 2017. Study on the thermal decomposition of nabh4 catalyzed by zrcl4. International Journal of Hydrogen Energy 42, 22432–22437. doi:`10.1016/J.IJHYDENE.2017.02.060`.

Kumar, V., Roy, B., Sharma, P., 2019. Kinetics of borazine formation from ammonia borane dehydrocoupling reaction through ab initio analysis. International Journal of Hydrogen Energy 44, 22022–22031. doi:`10.1016/J.IJHYDENE.2019.06.172`.

Lebel, L.S., Girault, N., 2018. Aerosol generation from sodium pool fires: Learning from the 1980s-era emis experiments and modelling. Nuclear Engineering and Design 330, 36–50. URL: `10.1016/j.nucengdes.2018.01.030`, doi:`10.1016/j.nucengdes.2018.01.030`.

Li, H., Yao, Z., Zhu, Y., Wang, X., 2022. The effect of solvent properties on the hydrogen producing performance of catalytic liquid phase ammonia borane. Fuel 325, 124849. doi:`10.1016/j.fuel.2022.124849`.

Lopatin, S., Shugurov, S., Tyurnina, Z., Tyurnina, N., Polyakova, I., 2023. Thermodynamic properties of the na2o-bao-b2o3 glasses and melts. Journal of Non-Crystalline Solids 612, 122353. doi:`https://doi.org/10.1016/j.jnoncrysol.2023.122353`.

Makarov, D., Shentsov, V., Kuznetsov, M., Molkov, V., 2021. Hydrogen tank rupture in fire in the open atmosphere: Hazard distance defined by fireball. Hydrogen 2, 134–146. doi:`10.3390/hydrogen2010008`.

Marion, G.M., Millero, F.J., Camões, M.F., Spitzer, P., Feistel, R., Chen, C.T., 2011. ph of seawater. Marine Chemistry 126, 89–96. doi:`10.1016/J.MARCHEM.2011.04.002`.

Martelli, P., Caputo, R., Remhof, A., Mauron, P., Borgschulte, A., Zuttel, A., 2010. Stability and decomposition of nabh4. Journal of Physical Chemistry C 114. doi:`10.1021/jp909341z`.

Mjaavatten, A., Bjerketvedt, D.K., 2005. A hydrogen-air explosion in a process plant: A case history.

Moussa, G., Moury, R., Demirci, U.B., Miele, P., 2013. Borates in hydrolysis of ammonia borane. International Journal of Hydrogen Energy 38, 7888–7895. doi:`10.1016/J.IJHYDENE.2013.04.121`.

Nagasawa, K., 1966. Borazines stable to hydrolysis. Inorganic Chemistry 5, 442–445. doi:`https://doi.org/10.1021/ic50037a024`.

Nair, A., Tiwari, V., Verma, A., Saini, P., Elias, A.J., 2023. In situ generated aminodiborane as a reagent for deoxygenative reduction of carboxamides to amines. Organic Chemistry Frontiers 10, 327–334. doi:`10.1039/d2qo01717b`.

NCBI, 2024a. Pubchem compound summary for cid 12544637, cid 12544637. URL: `https://pubchem.ncbi.nlm.nih.gov/compound/12544637`. retrieved April 29, 2024.

NCBI, 2024b. Pubchem compound summary for cid 138768, borazine. URL: `https://pubchem.ncbi.nlm.nih.gov/compound/138768`. retrieved April 29, 2024.

NCBI, 2024c. Pubchem compound summary for cid 145326, sodium metaborate. URL: `https://pubchem.ncbi.nlm.nih.gov/compound/Sodium-metaborate`. retrieved April 29, 2024.

NCBI, 2024d. Pubchem compound summary for cid 14798, sodium hydroxide. URL: `https://pubchem.ncbi.nlm.nih.gov/compound/14798`. retrieved April 29, 2024.

NCBI, 2024e. Pubchem compound summary for cid 222, ammonia. URL: `https://pubchem.ncbi.nlm.nih.gov/compound/Ammonia`. retrieved April 29, 2024.

NCBI, 2024f. Pubchem compound summary for cid 518682, boric anhydride. URL: https://pubchem.ncbi.nlm.nih.gov/compound/Boric-anhydride. retrieved April 29, 2024.

NCBI, 2024g. Pubchem compound summary for cid 5462311, boron. URL: https://pubchem.ncbi.nlm.nih.gov/compound/Boron. retrieved April 29, 2024.

NCBI, 2024h. Pubchem compound summary for cid 784, hydrogen peroxide. URL: https://pubchem.ncbi.nlm.nih.gov/compound/Hydrogen-Peroxide. retrieved April 29, 2024.

Patel, P., Baalisampang, T., Arzaghi, E., Garaniya, V., Abbassi, R., Salehi, F., 2023. Computational analysis of the hydrogen dispersion in semi-confined spaces. Process Safety and Environmental Protection 176, 475–488. doi:https://doi.org/10.1016/j.psep.2023.06.019.

Patnaik, P., 2003. Handbook of Inorganic Chemicals. McGraw-Hill handbooks, McGraw-Hill.

Prosen, E.J., Johnson, W.H., Pergiel, F.Y., 1959. Heat of reaction of diborane with water and the heat of formation of boric oxide. Journal oCResearch of the National Bureau of Standar¡ 62.

Rasmussen, R.L., Morse, J.G., Morse, K.W., 2003. Main group elements, in: Meyers, R.A. (Ed.), Encyclopedia of Physical Science and Technology (Third Edition). third edition ed.. Academic Press, New York, pp. 1–30. doi:https://doi.org/10.1016/B0-12-227410-5/00398-7.

Retnamma, R., Novais, A.Q., Rangel, C., 2011. Kinetics of hydrolysis of sodium borohydride for hydrogen production in fuel cell applications: A review. International Journal of Hydrogen Energy 36, 9772–9790. doi:10.1016/j.ijhydene.2011.04.223. european Fuel Cell 2009.

Sermiagin, A., Meyerstein, D., Rolly, G.S., Mondal, T., Kornweitz, H., Zidki, T., 2022. Mechanistic implications of the solvent kinetic isotope effect in the hydrolysis of nabh4. International Journal of Hydrogen Energy 47. doi:10.1016/j.ijhydene.2021.11.040.

van Setten, M.J., Uijttewaal, M.A., de Wijs, G.A., de Groot, R.A., 2007. Thermodynamic stability of boron: The role of defects and zero point motion. Journal of the American Chemical Society 129, 2458–2465. doi:10.1021/ja0631246.

Sevim, F., Demir, F., Bilen, M., Okur, H., 2006. Kinetic analysis of thermal composition of boric acid from thermogravic data. Korean Journal of Chemical Engineering 23(5): 23, 736–740. doi:10.1007/BF02705920.

Singh, R., 2021. Reversible chemical hydrogen storage in borohydrides via thermolysis and hydrolysis: Recent advances, challenges, and perspectives. International Journal of Hydrogen Energy doi:10.1016/J.IJHYDENE.2021.10.022.

The Associated Press, 2007. Cruise ship goes down off antarctica. URL: https://www.nbcnews.com/id/wbna21935099. retrieved May 23, 2024.

Van den Bovenkamp, R., 2023. Chinees schip zinkt na dagenlang vastzitten in ijs voor russische kust. URL: https://www.schuttevaer.nl/nieuws/actueel/2023/03/02/chinees-schip-zinkt-na-dagenlange-stuurloze-drift-voor-russische-kust/?gdpr=accept. retrieved May 23, 2024.

van Rheenen, E., Scheffers, E., Zwaginga, J., Visser, K., 2023a. Hazard identification of hydrogen-based alternative fuels onboard ships. Sustainability 15. doi:10.3390/SU152416818.

van Rheenen, E.S., Padding, J.T., Slootweg, J.C., Visser, K., 2023b. Hydrogen carriers for zero-emission ship propulsion using pem fuel cells: an evaluation. Journal of Marine Engineering & Technology , 1–18doi:10.1080/20464177.2023.2282691.

Wu, D., Qian, X., 2018. Experimental study on the thermal runaway of hydrogen peroxide with in-/organic impurities by a batch reactor. Journal of Loss Prevention in the Process Industries 51, 200–207. doi:10.1016/j.jlp.2017.12.012.

Charting the Course: Navigating the Royal Navy's Autonomous Challenge with Synthetic Assurance.

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Synopsis

The Royal Navy (RN) has all but declared its hand that autonomous surface systems will form a significant part of its fleet as it moves into the Navy after next. The Maritime Operating Concept (MarOpC) signposts autonomy five times. The RN needs ships to deliver credible military effect, autonomy can help increase mass, reduce crewing and complete tasks ultimately with little or no oversight of most systems.

Small boats such as the Autonomous Pacific 24 (APAC24) are forming part of the answer, increasing capability for larger more conventional platforms. For the RN to enjoy the benefits of autonomy they will need to move away from remote control IMO Degree 3 and into the world of ship autonomy in IMO Degree 4. If this is possible, it is a win for defence, but how do, we get there? We are currently grappling with the challenges of small boats and degree 3.

Historically, naval ships are built to naval codes which stem from their commercial equivalents adding to the military delta. Nothing is expected from the International Maritime Organisation (IMO) in terms of legislation until at least 2025 and the Maritime and Coastguard Agency only just released a workboat code annexe to support the regulation of remote-operated systems less than 24 meters. The RN does not have the luxury of well-defined regulation and almost by accident, they have become the front line in the regulation space placing pressure on getting it right. These highly autonomous platforms have a significant amount invested in the sensor suite and ultimately the decision engine will likely be AI-based, so how can you regulate these?

Synthetic environments might be part of the answer and this paper looks at where synthetics have been used before to support regulatory outputs, the limitations of the current methods already implemented and how these might be optimised to install trust in the systems before going to sea. We already accept computer modelling for regulatory purposes in other areas, however, never with the stakes so high.

Many elements go into the validation of the synthetic model before this is even able to be useful to validate the autonomy system itself- this paper explores these and how the challenge might be tackled. It will also explore some of the interdependencies that will be required to make the synthetic testing credible.

Keywords: Autonomy, Naval Certification, Trust in Autonomy, Synthetic testing, Validation

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A chartered marine engineer employed as NavyX's experimentation and project delivery team lead. He has a MSc in marine engineering, he started as a seagoing merchant navy engineering officer before moving ashore with Wartsila. Later he moved to Lloyds Register as an engineering systems specialist. Areas of interest are marine autonomy, alternative fuels, and the use of novel technology with a maritime application.

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1. Introduction: The Problem

The Royal Navy has indicated its intention to use marine autonomy, as cited in the Maritime Operating Concept (MarOpC) (Royal Navy, 2022). The Navy also has several autonomy-related programmes, the Mine Hunting Capability Programme uses autonomous vessels to deliver its effect. (DE&S, n.d.). NavyX is the Royal Navy's Autonomy, Lethality and innovation accelerator and has seen the introduction of the Autonomous Pacific 24 and Maritime Demonstrator For Operational eXperimentation (MADFOX) both have enabled NavyX to learn how to operate autonomous assets (Royal Navy, 2024). Whilst these boats offer a good step towards autonomy, it is clear that large ship, human out of the loop autonomy is required to deliver the Navy's demands for the future. The Navy has a problem, whilst autonomy is a developing technology for the commercial sector, the RN will want to use it differently.

This report seeks to address some of the challenges around assuring the navigation element of the systems. Currently, there is a significant gap if we look at the whole platform: engine room watch keeping, machinery reliability and management of fuel, just a few areas that will see significant change.

2. Where Synthetic assurance has been used before

The use of synthetic assurance or computer-based modelling for the assurance of systems is not new, as demonstrated by the use of Computational Fluid Dynamics (CFD) being accepted in scaling ballast water treatment systems. The International Maritime Organisation (IMO) provide Guidance on the Scaling of Ballast Water Management Systems. It accepts mathematical modelling using CFD, however, it clearly states, that the modelling should be experimentally validated and that it should demonstrate the accuracy of the mathematical model (International Maritime Organisation, 2018).

Google's autonomous car Waymo Driver has done billions of simulation miles and then millions of actual driving, this is just an indication of the amount of data required (Waymo, 2024). Equally comparable is Ford's BlueCruise which is approved for hands-off supervised driving in the UK but only on very restricted routes and after significant simulation and real-world driving. This Level 2[1] the system is low in terms of 'quantity' of automation and there has been significant work to get there (Ford, 2024).

The use of synthetic assurance whilst commonplace is done with a good stakeholder engagement foundation where all parties (Developer, user and regulator) are aware of the assurance pathway and how the data sets have been obtained. Any deviation from this plan inserts dis-trust and therefore a loss in the credibility of the data. Keep in mind that George Box a British statistician stated, 'All models are wrong, but some are useful'.

3. The challenges of autonomy assurance vs normal assurance

Why do we need something different? Can autonomous systems be assured more conventionally? For the most part, they can, when there are well-founded methods, rules and regulations for elements such as emergency stops and computer hardware and for example environmental testing. We only need to pull out the novel parts and a whole system view.

Historically naval ships are built to naval codes which stem from their commercial equivalents adding in the military delta. With nothing expected from the International Maritime Organisation (IMO) in terms of autonomy legislation until at least 2025 and the Maritime and Coastguard Agency has only just released a workboat code annexe to support the regulation of remote-operated systems less than 24 meters. The RN does not have the luxury of well-defined regulation and has almost by accident become the front line in the regulation space, placing pressure on getting it right.

The challenging bit is the "autonomy delta" Figure 1 shows a simple autonomy system assurance needs to be placed on each area to be able to have an "assured" overall system,

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[1] Level 0: No Driving Automation, Level 1: Driver Assistance, Level 2: Partial Driving Automation, Level 3: Conditional Driving Automation, Level 4: High Driving Automation, Level 5: Full Driving Automation (Society of Automotive Engineers, 2021)

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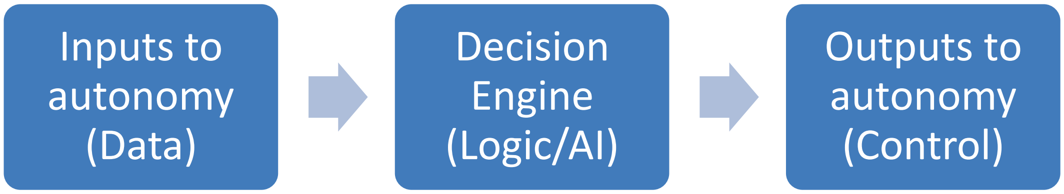


Figure 1- Autonomy System

This paper seeks to look at the decision engine element which in isolation is a dangerous focus as whilst it will assure an output, it is based on controlled inputs which may not replicate the real world. Equally these outputs will be used within a system but might not have the effect that is expected when integrated into a machinery system. A whole system view is critical to having a robustly assured solution, the sensors feeding into the decision engine are as important to fully understand, as the autonomy itself. This drives a significant amount of work in developing an understanding of the inputs before any relevant work can be done in the decision part. Neither box can be fully understood without an awareness of the other e.g. the decision drives a sensor demand. We often expect our operators to know or at least acknowledge if a sensor isn't reading right, so how do we have a computer that can do the same and then also deal with it?

You could run the platform in incrementally challenging operating environments over an extended period with people either, onboard or readily able to prevent a collision. However as the complexity of the systems increases, the rate of technology adoption increases, and the edge cases are realised this will fall over as an unsustainable proposition. This is where computer-based models and synthetics can help us.

Even significant other programmes are grappling with the problem, The Nippon Foundation MEGURI2040 Fully Autonomous Ship Program whilst ambitiously set a practical implementation by 2025 they also state 'there has been almost no development to date in the field of fully autonomous navigation for seagoing vessels.' (The Nippon Foundation, 2024). The Yara Birkeland programme is also not going as quickly as planned 'Yara Birkeland completed its first-fully autonomous voyage, under human supervision, from Yara Porsgrunn to a container terminal in Brevik in March 2023. However, owing to regulatory issues, the ship currently operates with a crew of three onboard who supervise and monitor the ship for safety reasons.' People are being removed from the platform but to undertake remote positions (Yara, 2024).

4. How computer modelling can be used

Computer modelling allows us to test software without having to install it into a wider system. As long as its context and limitations are known then this is a robust way of providing evidence to regulators. Some of the biggest benefits of this can be found in the ability to test edge cases and also the ability to do 1000s of runs faster than real time.

There is already the ability to test autonomy in real time, this is a service currently offered by BMT using the Marine Autonomous Surface Ships Synthetic Environment Assurance System (MASS SEAS) (BMT, 2024) but it could be seen as falling short, the REMBRANDT system SEAS employs is primarily designed to train human seafarers. Humans interpret the environment and take actions to influence the ship, the training simulators need to be representative of the real world in terms of time, there is an opportunity to model faster when we remove the need for human interaction, ultimately the aim of higher levels of automation.

Modelling faster than real time will enable the generation of significantly more data points in a time that is palatable to the demand of autonomy, it will enable the running of all the 'normal' cases but also the more novel edge cases. A V-model verification demands the requirements up front, compliance with the International Regulations for the Prevention of Collision at Sea (IRPCS) or 'COLREGs' would be a requirement but the measurement against this is incredibly challenging. Whilst measurable with several scenarios in a real time simulator there would be limited confidence in the edge cases. It also presents a challenge for real world validation as it is very unlikely that the same scenario can be replicated, getting the same targets, in the same location, in a similar operating environment, especially when compared to CFD validation where this is normally relatively easily replicated in a wind tunnel or piping system. Significant numbers of runs will also allow the implementation of other variables such as sensor degradation, increased sensor uncertainty and the failure of certain sensors all of which would be informed by the sensor work.

4.1. COLREGs

One of the main aims of autonomous navigation is compliance with COLREGs which defines how to prevent collisions with other ships as well as the means to do this. It states provisions e.g. the display of day shapes to support the decision making of other ships. In a fully autonomous ship, all of these rules will need to be applied by the machine and therefore scenarios where each of these rules is tested will be needed. Often the 'perfect' scenario is used, for example in Figure 3 a crossing scenario is shown where vessel B is the stand on and vessel A gives way, this could be one run in an autonomy validation however in the real world it could look more like Figure 2 or anything in-between this presents a challenge when later validating the simulation if only certain situations are simulated.

(International Maritime Organisation, 1972)

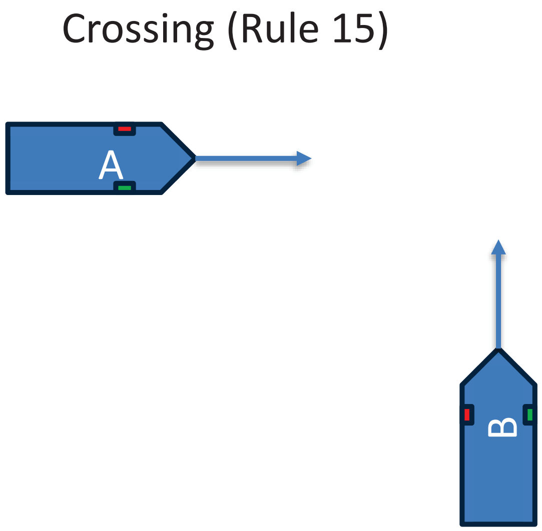


Figure 3- Simple Crossing scenario

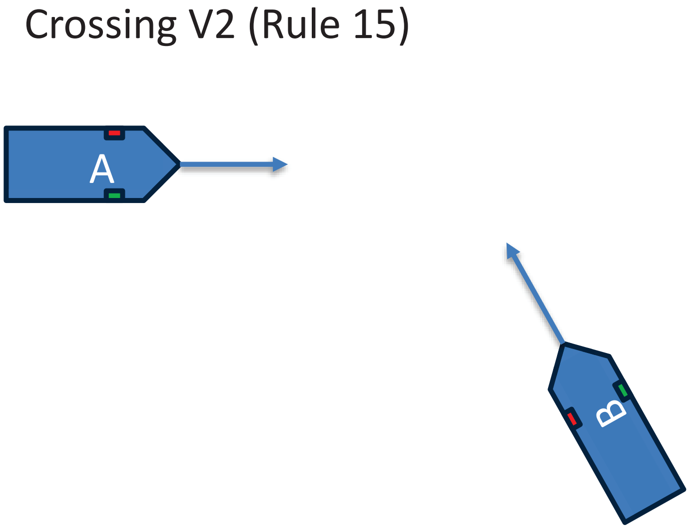


Figure 2- Variation on a simple crossing scenario

4.2. To what standard?

Watchkeepers who are entrusted to operate ships in complex water spaces are trained over a number of years gaining experience while completing numerous training courses. The proposal of navigation autonomy means there is an expectation that you can remove that person and put in a computer. However, there is an expectation that humans are not perfect, so does autonomy need to be?

A term often used is to 'be at least as good as a mariner', ships are normally operated by Officers of the watch who over 3 years learn how to operate ships before passing an exam with the relevant administration e.g. MCA before proceeding to sea. However, they are still accompanied on board by other more senior officers of the watch, a chief officer and a master. Complex water navigation is normally undertaken by the chief officer or the master these have more experience and have completed additional exams respectively Figure 4 shows this progression (Warsash Maritime Academy, 2024).

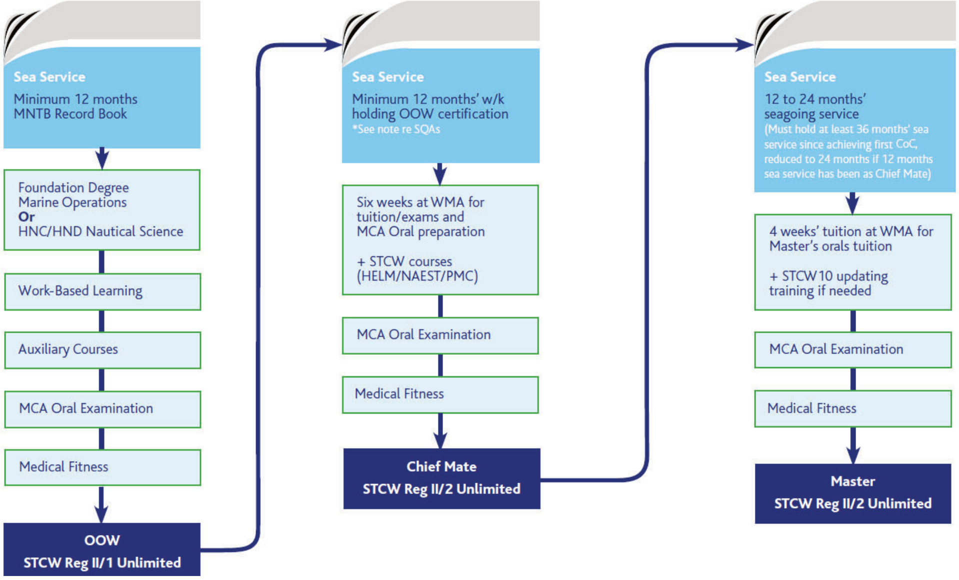
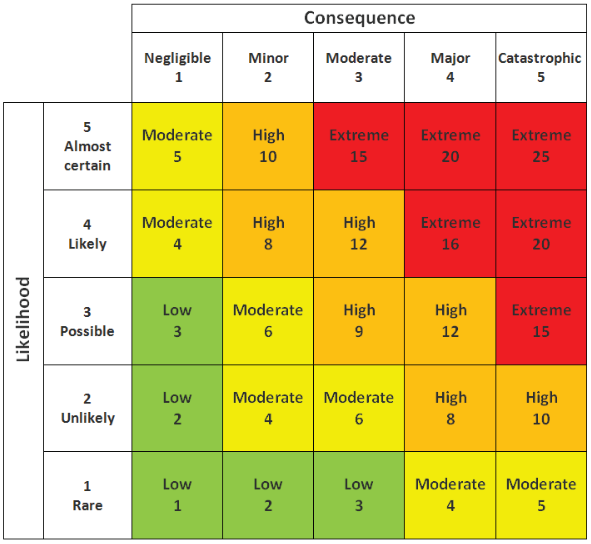


Figure 4- Progression Chart for Officer Cadet Routes (Warsash Maritime Academy, 2024).

The real challenge is that we would expect autonomy to be at least as good as a master, which is almost impossible to measure. The European Maritime Safety Agency (EMSA) issues an annual report each year on safety incidents on EU-flagged ships or incidents occurring in EU waters. The largest number of incidents occur in 'internal waters' which is considered the more complex operating space, 21% of maritime incidents in 2014-2022 were collisions with a range of root causes. Some are attributed to mechanical defects, whilst some are down to operator error (European Maritime Safety Agency, 2023) for example, the collision between Scot Explore and Happy Falcon on 24 October 2023 (Marine Accident Investigation Branch, 2024).

There is an expectation that by using artificial intelligence the software will improve as it learns, however, there is always a chance that it will perform to a lower standard than its initial installation point. Once a Master passes their certificate of competency there are no further checks on their ability to apply IRPCS. The MOD are different in that RN watchkeepers complete IRPCS tests at regular intervals. Given the reliance on software, it could be seen as reasonable that a periodic sample of the software is taken, which could be based on risk, this is then tested in the already validated synthetic environment with the expectation that it would continue to pass the runs.

For defence, a risk balance approach could unlock some of this challenge, currently ships in the MOD undergo a HAZID such that the level of risk the ship has can be held at the correct levels. There are many example risk matrices available, but the principle remains the same the combination of likelihood and consequence enables an understanding of a risk level and if it is tolerable for example Figure 5. Quantitative matrices allow mathematical calculations to influence the score e.g. a system might fail $1x10^{-6}$ times in a lifetime (Ministry of Defence, 2024)



		Consequence				
		Negligible 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
Likelihood	5 Almost certain	Moderate 5	High 10	Extreme 15	Extreme 20	Extreme 25
	4 Likely	Moderate 4	High 8	High 12	Extreme 16	Extreme 20
	3 Possible	Low 3	Moderate 6	High 9	High 12	Extreme 15
	2 Unlikely	Low 2	Moderate 4	Moderate 6	High 8	High 10
	1 Rare	Low 1	Low 2	Low 3	Moderate 4	Moderate 5

Figure 5- Example risk matrix (Kaya, Gulsum, 2018)

If the likelihood of collision could be understood via validated synthetic assurance and compared against severity, then a risk holding level can be obtained. It might be a case that results in collision occurs 1x10^{-6} times and the expected outcome in a 1-10 person fatality using the Common Risk Classification Matrix used by DE&S this would result in a Category C risk which can be considered tolerable if As Low As Reasonably Practicable (ALARP). It might be that additional mitigation is required in the early stages to make the risk tolerable, but the aim would be to bring the likelihood down to such a level that it can be held normally.

Using computer modelling is collecting a series of measurements generated from a digital model, the validation is comparing these with real-world measurements. There is a lot of measuring and therefore a good understanding of uncertainty is needed in terms of occurrence and magnitude. Given the current lack of defined standards to enable the autonomy software and the synthetic assurance system the software can be tested with, the use of claim argument and evidence will allow regulators to make a judgement based on well-presented evidence to make a decision. This will then enable understanding to grow until such time rules and legislation can be developed to be able to simply generate the required evidence in a known methodology. To ensure a robust case can be submitted there needs to be an element of geographic diversity in the testing. There is a need to operate the platform synthetically in a realistic validation environment e.g. the Solent. However, this only proves the platform can perform in this water space. Expanding the synthetic testing envelope to explore differing operating environments including location, changes in other vessels and weather is fundamental to understanding the actual performance level. A significant element of this is changing the sensor performance not only relative to the weather condition but also factoring in general degradation and lower than expected performance or even total loss.

Whilst currently there is aspiration for peacetime operation of these platforms and therefore compliance with commercial rules of the road is required, there will be times such as being in a task group or possibly times of War when the use case will change. This will mean that operating in a COLREG compliant way is no longer the goal and operational advantage is the key driver. This 'Wartonomy' function is beyond what will be offered by the commercial sector and will require a deep technical understanding of both performance and limitations to understand how the system will deal with these situations, these are much harder to validate in the real world beyond that of a normal task group or operational experimentation.

4.3. Data Points

A number of data points need to be collated within the simulation and the real-world validation testing. This will enable the validation and enable the levels of uncertainty to be understood. This is data that should be collated on the autonomous vessel but as much as possible should be collated from the target vessels. Table 1 gives an example of several data points but this list is unlikely to be exhaustive. Targets within the real world are expected to be a challenge, in the simulation they will be pre-defined, however, when trying to relate to a real world situation understanding their size, aspect and speed may be more challenging with a lower fidelity sensor suite.

Table 1- Data points

Data Point	**Sensor example**
Freedoms of movement (roll, pitch, sway, surge, heave and yaw)	Accelerometer
Speed through the water	Speed log
Speed over the ground	GPS
Heading	Directional GPS
Position	GPS, Inertial system
Time	
Tide	Predicted tide data, pressure and actual tide data.
Weather	
Sea State	Wave buoy or equivalent ship sensors.
Optical image	Electro-optics, infrared
Radar tracks	Radar
Water depth	Echosounder
AIS	AIS transceiver

All of the above sensors have a level of uncertainty, challenges are accuracy and repeatability that will all need to be understood and factored in both in terms of real-world measurement and simulated measurements.

4.4. Validation

A computer model is useless unless validated, there are a couple of areas that require validation some are well trodden, and others are new. The Society for Computer Simulation (SCS) have been the thought leaders in the validation of computer modelling. They have a few definitions that are still relevant today:

‘**Model Verification**: Substantiation that a computerized model represents a conceptual model within specified limits of accuracy.
Model Validation: Substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model.’

(Oberkampf and Trucano, 2002)

What is easy to observe is that the validation needs to meet the intended requirements which need to be carefully defined beforehand, referring to the need buy in from the relevant stakeholders early, ensuring both the modelling is robust and valid but not excessive.

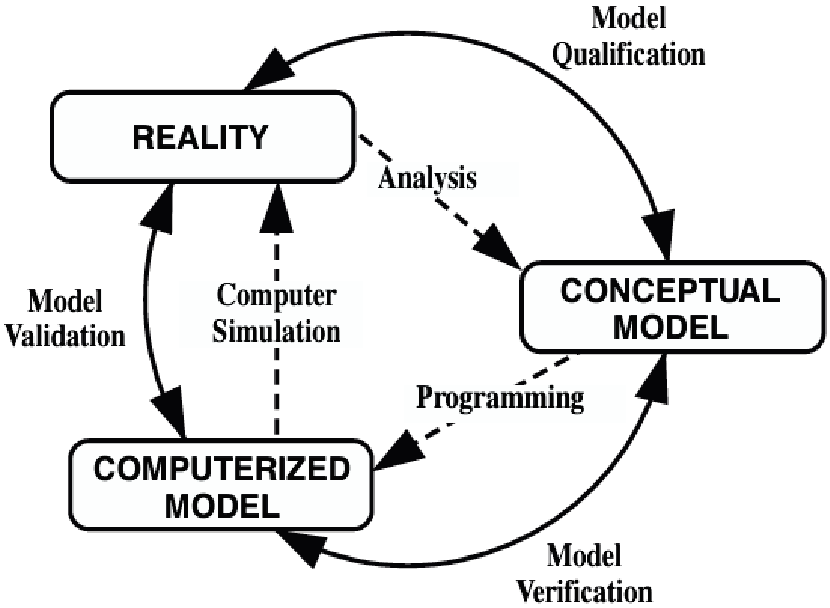


Figure 6- Phases of Modelling and Simulation and the Role of V&V

4.4.1. Simulation

The simulator used for the test runs needs to be assured, repeatable and accurate. Simulators are already used for the training of seafarers (Maritime and Coastguard Agency, 2020). The Standards of Training, Certification and Watchkeeping (STCW) gives guidance regarding the use of simulators. DNV-GL provide certification for simulators. One of the challenges of using simulation is the trust in the outputs, there needs to be a robust level of validation and assurance that the models are correct.

There are many classes of bridge simulators that can be used for training defined in Table 2, only class A or B will likely have enough functionality to test autonomous systems fully. There will be elements of the standard that might not be applicable due to the nature of the use case, this will likely be around the hardware in terms of bridge configuration (DNV-GL, 2023).

Table 2- Simulator classes for the function area bridge operation

Simulator Class	Description
Class A (NAV)	A full mission simulator capable of simulating a total shipboard bridge operation situation, including the capability for advanced manoeuvring in restricted waterways.
Class B (NAV)	A multitask simulator capable of simulating a total shipboard bridge operation situation but excluding the capability for advanced manoeuvring in restricted waterways.
Class C (NAV)	A limited task simulator capable of simulating a shipboard bridge operation situation for limited (instrumentation or blind) navigation and collision avoidance.
Class D (NAV)	A cloud based distant learning simulator capable of simulating a shipboard bridge operation for training through a remote desktop solution by enabling physical and operational realism through virtual reality.
Class S (NAV)	A special tasks simulator capable of simulating the operation and/or maintenance of particular bridge instruments, and/or defined navigation/manoeuvring scenarios

DNV has a recommended practice that directs the requirements for the validation of simulation models. This varies depending on the type of simulation used which is vast and a subject in its own right. It focuses on a risk-based assurance approach whereby risk is defined as the effect of uncertainty on objectives, requiring the uncertainty to be known. A lot of the uncertainty can be understood by knowing how the model was built. This places a lot of the assurance at the front end of the processes before any software can even be tested and there is currently no trusted method for quantifying the uncertainty in simulation models. However, we can make a good assessment by understanding the body of evidence presented to us. For example, the physical ship model can be measured against the real platform placing a relatively low risk in this space if the computer measurements can present a low uncertainty as well as the real-world measurements.

This qualitative assurance method requires a strong body of evidence for each element of the model be that the environment, ship or the physics before any use of the unknown ‘autonomy’ element can be applied. Ensuring that you’re able to provide a robust validated and high confidence simulation facility to the regulator is a key first stage to synthetic assurance of autonomy. (DNV-GL, 2021).

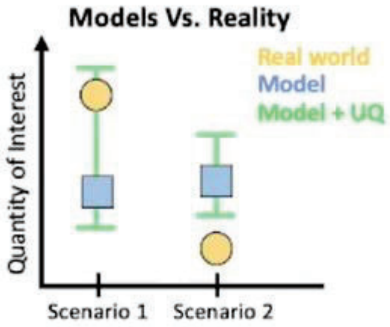


Figure 7- Models vs reality[2] (NASA, 2023)

Figure 7 shows that in scenario 1 there is a difference between the real world and the model the uncertainty covers that and therefore the limitations are known, when compared to scenario 2 where the real world and the model still don’t match but more importantly the uncertainty also doesn’t overlap meaning that the model is essentially useless.

One of the challenges that will face simulation is like that of CFD around mesh size or the level of detail, too much detail and the computer power required makes it disproportionate and expensive, too little and the data collected isn’t good enough to provide a robust body of evidence. This is common again in CFD where two mesh sizes are used to aid the compute demand vs detail required. One way to aid the introduction of uncertainty is to complete runs of scenarios a number of times such that a histogram of data can be generated and not only the average results taken but also the extremes are integrated.

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[2] UQ= Uncertainty Quantification

4.4.2. Modelling

Taking the benefit of 1000’s of runs there is an opportunity that the modelling can be validated with relative ease. Placing the software on representative scale models if considered especially risky or on full scale prototypes in controlled water targets and scenarios of opportunity can be taken to validate the model. Software that has been tested with a computer model that isn’t validated cannot be trusted as whilst it might have performed well in the synthetic environment there is no proof that this is representative of the real world.

The body of evidence generated through the validation coupled with the simulated runs will enable a suitable and safe operating envelope to be established. For the testing of the system on a ship, there will need to be robust safety measures in place and a safety case develop.The pathway could take all of the items in Figure 8 or chose the appropriate starting point depending on confidence.

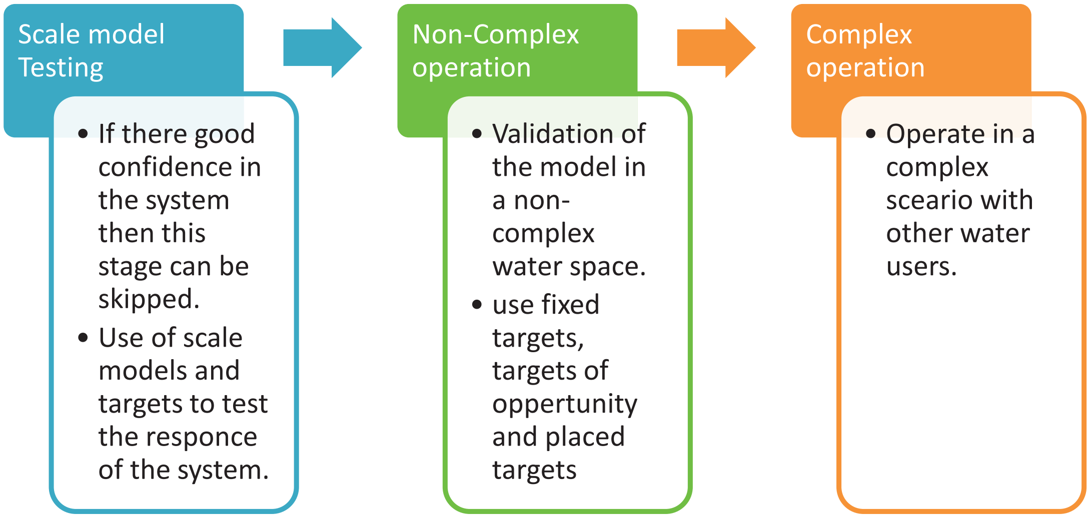

Figure 8- Testing areas

If scale model testing is planned, it is fundamental that the simulation testing of the same environment is conducted to support the validation. Equally, the use of scaling introduces another element of uncertainty into the validation, however, this might be required to reduce the risk to a tolerable level.

In the full-scale testing stages, a significant amount of data can be recorded and compared against the modelled scenarios to understand the model’s accuracy. Data collection for validation is key to enabling software to be validated and the methodology for collecting the data needs to be established with a clear understanding of the measurement uncertainty together with the context. This is likely to result in significant data being collated concurrently.

5. Conclusions

Full autonomy is likely to come and whilst currently there is a human in the loop, there is a level of attribution and control from the human operator, albeit remote and challenging. Passing this trust to a machine giving full autonomy will move the onus from the quality of training and experience to the equipment, putting regulators in a new and challenging place. The use of synthetic assurance offers a chance to test and collect data across a large number of cases including those edge cases that don't want to be tested in the real world. However, the data is only as good as the system that generated it. Validation is hard especially when so much work has to go into the system doing the modelling in the first place. Some lessons can be taken forward to ensure good stakeholder engagement upfront so everyone has a clear understanding of the plan and data to be collated allowing later integration. There is then the challenge of what is good enough especially when factoring in a changeable system. The use of tolerable risk is probably a good route to go down certainly for military applications but moving this to a commercial domain might be more challenging.

It will be easy for people to become complacent with the technology and forget its fallibility, reversionary methods of operation will need to be assured as much as the autonomy itself, this includes the impact on the human operators who suddenly find themselves in an unknown water space with an emergency on their hands but no or little contexts building up to it.

Using well evidenced synthetic assurance that has been validated by a number of runs in the real world to provide enough confidence of fit will enable a likelihood of collision to be understood, this can then be applied to a risk matric. There is then a choice of further mitigation perhaps by operational limitations or acceptance. There is an ongoing challenge with how we manage changing software, it might be that in the early stages an instantiation is tested on a 3 monthly basis until confidence is such that the timeline can be extended. We know the model will be wrong, but we need to understand the uncertainty such that we can make an informed decision on if it is acceptable or not. Autonomy will only be possible with the acceptance of synthetic assurance and therefore its development is as important as the autonomy software itself.

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References

BMT, 2024. Maritime Autonomous Systems (MAS) Services. URL https://www.bmt.org/services/defence-security-customer-friend/maritime-autonomous-systems/ (accessed 3.15.24).

DE&S, n.d. Autonomous Mine-Hunting Systems. URL https://des.mod.uk/what-we-do/navy-procurement-support/autonomous-mine-hunting-systems/ (accessed 3.28.24).

DNV-GL, 2023. Maritime simulator systems- Standard- DNV-ST-0033.

DNV-GL, 2021. Assurance of simulation models- Recommended Practice - DNV-RP-0513.

European Maritime Safety Agency, 2023. ANNUAL OVERVIEW OF MARINE CASUALTIES AND INCIDENTS 2023.

Ford, 2024. FORD BLUECRUISE. URL https://www.ford.co.uk/technology/driving-assistance/ford-bluecruise

International Maritime Organisation, 2018. BWM.2/Circular.33/Rev.1 – Guidance on Scaling of Ballast Water Management Systems - Annex - Guidance on Scaling of Ballast Water Management Systems.

International Maritime Organisation, 1972. International Regulations for preventing Collisions at Sea, 1972.

Kaya, Gulsum, 2018. Good risk assessment practice in hospitals.

Marine Accident Investigation Branch, 2024. Collision between general cargo vessel Scot Explorer and gas carrier Happy Falcon [WWW Document]. URL https://www.gov.uk/maib-reports/collision-between-general-cargo-vessel-scot-explorer-and-gas-carrier-happy-falcon (accessed 4.18.24).

Maritime and Coastguard Agency, 2020. New simulator training experience approved for seafarers. URL https://www.ukshipregister.co.uk/news/new-simulator-training-experience-approved-for-seafarers/ (accessed 3.28.24).

Ministry of Defence, 2024. Safety Risk Matrices. Acquis. Saf. Environ. Manag. Syst.

NASA, 2023. An Introduction to Uncertainty Quantification for Modeling & Simulation.

Oberkampf, W.L., Trucano, T.G., 2002. Verification and Validation in Computational Fluid Dynamics.

Royal Navy, 2024. NavyX. URL https://www.royalnavy.mod.uk/news-and-latest-activity/operations/united-kingdom/navy-x

Royal Navy, 2022. MARITIME OPERATING CONCEPT.

Society of Automotive Engineers, 2021. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles.

The Nippon Foundation, 2024. The Nippon Foundation MEGURI2040 Fully Autonomous Ship Program. URL https://www.nippon-foundation.or.jp/en/what/projects/meguri2040

Warsash Maritime Academy, 2024. Warsash Maritime Academy- Deck courses. URL https://maritime.solent.ac.uk/courses/deck (accessed 4.18.24).

Waymo, 2024. Waymo Driver. URL https://waymo.com/waymo-driver/

Yara, 2024. Yara Birkeland, two years on. URL (accessed 6.30.24).

Naval sector and Decarbonisation using Industry 4.0

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Synopsis

The Paris Agreement forced the International Maritime Organisation (IMO) to create fresh paradigm for the maritime industry to achieve net zero carbon emissions by 2050. In doing so, IMO exempted warships from complying with these emission norms. However, advanced navies promulgated several initiatives to contribute progressively towards net-zero emission. While the 'Climate Change and Sustainability Strategic Approach' of the UK Ministry of Defence (MoD) and the 'Green Fleet Navy' of the US are well known, efforts such as the joint venture of the Indian Navy with the Indian Oil Company to develop a fuel recipe by varying over 22 parameters to reduce GHG emissions from warships is also noteworthy. In recent years, the EU initiative of 'Adaptation of Industry 4.0 Model to the Naval Sector' has aimed to reduce carbon emissions in the naval sector using automated technologies of Industry 4.0 by creating new techniques to monitor, control and manage emissions from the ships, repair yards, shipbuilding yards and mercantile marine. It is expected that by carefully curating and cataloguing the emissions from naval assets, both movable and immovable, positive changes towards emission control from the naval sector can be achieved. The paper thus aims to discuss Industry 4.0 to provide a better trajectory towards net zero carbon emission from the maritime domain in general and the naval sector in particular. In doing so, the Green Initiatives of the Indian Navy using Industry 4.0 are discussed.

Keywords: Industry 4.0; Decarbonisation; Digitalisation; Automation; Emissions; IMO

Author's Biography

Captain (Dr) Nitin Agarwala, a serving naval officer, has experienced various facets of a warship as a user, designer, inspector, maintainer, a policymaker, a teacher and a researcher. He has authored over 80 articles, papers, book chapters and two books. He was a Research Fellow at the National Maritime Foundation from 2017- 2019 and is presently a Senior Fellow at the Centre for Joint Warfare Studies and a Visiting Faculty at the Naval War College, Goa and the Centre for Maritime Studies at the University of Mumbai.

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1. Introduction

In The Kyoto Protocol of 1997 was based on scientific consensus that global warming is due to anthropogenic efforts (Agarwala and Polinov, 2021). It *commits* States to reduce greenhouse gas (GHG) emissions from aviation and shipping through the International Civil Aviation Organisation (ICAO) and International Maritime Organisation (IMO) respectively (IMO, n.d). Since it gave binding targets, the US negotiated the Protocol to ensure that their expeditionary military was exempted from emission reduction (US Senate, 1998). Based on the Protocol, in December 2003, IMO adopted resolution A.963(23) "IMO Policies and Practices related to Reduction of GHG Emissions from Ships" that led to numerous studies by the Marine Environment Protection Committee (MEPC) to identify and develop mechanisms for GHG reduction from shipping. Accordingly, CO_2 emissions were addressed by Phase 1 studies (Buhaug *et al.*, 2008) and other GHG emissions by Phase 2 studies (Buhaug *et al.*, 2009). Since these studies were based on agreements of the Kyoto Protocol, they excluded military and fishing vessels.

Subsequently, the 2015 Paris Agreement (UNFCCC, 2015) allowed nations to decide on sectors to cut emissions which could be the military or some other sector. Since then, many navies have made concerted efforts to move towards net-zero emission. Some efforts include '*Climate Change and Sustainability Strategic Approach*' of the UK that aims to move the military to products, practices and behaviours that are climate aware, environmentally sound and reduces emissions using fuel standards, energy storage and more (UK MoD, 2021). Similarly, the US Navy deployed '*Great Green Fleet*' in 2016 that used nuclear energy, energy efficiency, and alternative fuels such as diesel-biofuel, and hybrid electric-diesel propulsion to demonstrate their ability to perform with new energy-saving measures. These efforts were with 10% blend of biofuel with an intention to reach 50% (Chambers and Yetiv, 2011; EESI, 2016). Other efforts include those of the Italian Navy's Green Fleet Project ('*Flotta Verde*') of 2012 to develop alternative marine fuel such as renewable synthetic fuel, innovative eco-design technologies and energy saving procedures (Ministero Della Difesa, n.d). Closer home, the Indian Navy's '*Green Initiatives Program*' (GIP), aims to achieve reduction, diversification and use of clean technologies (Batra and Prakash, 2018).

While these efforts are path breaking and considered critical to achieve commitments of the Paris Agreement, they are not conclusive due to environmental sustainability of biofuels (Jeswani *et al.*, 2020) and not considered reliable to achieve decarbonisation. To achieve decarbonisation, indirect emissions and environmental costs should be considered for alternate fuels (Agarwala, 2022d) and operational changes when using energy efficiency methods are to be considered (Hodgkins, 2021; Bowcott *et al.*, 2021). However, these changes cannot be adopted due to various considerations.

As ships become sophisticated with digitalisation at its core, the focus for decarbonisation has shifted to use of digitalisation (Agarwala *et al.*, 2021). It is no wonder that the EU initiative of 'Adaptation of Industry 4.0 Model to Naval Sector' aims to reduce carbon emissions in the naval sector using Industry 4.0 (I4.0) by creating techniques to monitor, control and manage emissions from ships, repair yards, shipbuilding and mercantile marine. By carefully curating and cataloguing emissions from naval assets, using I4.0, positive changes towards emission control can be achieved.

With this understanding the paper discusses I4.0 to provide a better trajectory towards decarbonisation from the naval sector. It will first provide a brief background of the military carbon footprints followed by evaluating areas where I4.0 can help reduce carbon emissions for naval vessels. To show these methods can be used, the Green Initiatives of the Indian Navy using Industry 4.0 will be discussed next. The paper will conclude by discussing possible options for naval assets to achieve decarbonisation using I4.0.

2. Curating and Cataloguing Emissions of the Military

Exemption of the military from emission norms by the Kyoto Protocol was to cater for the US interests. However, it exempted a major contributor of government emissions (80% for the US and 50% for the UK and Canada) (Hodgkins, 2021).

Analysis of emissions from military activities shows that emissions from equipment operations are accounted for while equipment procurement is not. Accordingly, for the EU in 2019 while direct emission was 8 million CO_2e, indirect emission was 16.8 million CO_2e. That for the UK in 2018 was 3 and 8 million CO_2e respectively (Conflict and Environment Observatory, 2021b). The military emission evaluation is difficult as the military lacks transparency. Then there are conflicts that add to emissions (Parkinson, 2020; Conflict and Environment Observatory, 2021a). Yet another area of emission by the military is their Bases which account for nearly 1 to 6% of the global land area (Zentelis and Lindenmayer, 2015). The way land is used impacts global GHG emissions. In addition, waste management is responsible for carbon emissions to about 3% of global GHG emissions (Hannah *et al.*, 2020). It is thus important that the military reduces and manages the waste generated (surplus materiel, equipment, ammunitions and ground contamination). Such calculations also disregard emissions from supply chains which require evaluations of 'corporate responsibility' reports of suppliers.

Studies have shown that the total carbon emission by the US military in 2017 was 59 million CO_2e at an average of 66 million CO_2e for 2010 to 2018 of which Bases account for 40% while fuel use accounts for the remaining (Crawford, 2019). However, once again this figure does not include supply chain emissions. A comprehensive estimate of net emissions is possible if data on energy consumption and economic activity is available. Unfortunately, this is published by only a few nations and hence estimation becomes difficult. These notwithstanding, estimates indicate military emissions including those from supply chains are between 3.3 to 7% of the global total (Parkinson and Cottrell, 2022). **Table 1** shows a breakdown of these emissions for various branches of the US military.

Table 1: CO_2 emissions (kt) by branch for the US military for 2017 (Source: Belcher *et al.*, 2019)

Branch	**Kt CO_2e FY-2017**
Air Force	13,202.4
Army	2,204.7
Marines	112.1
Navy	7847.8

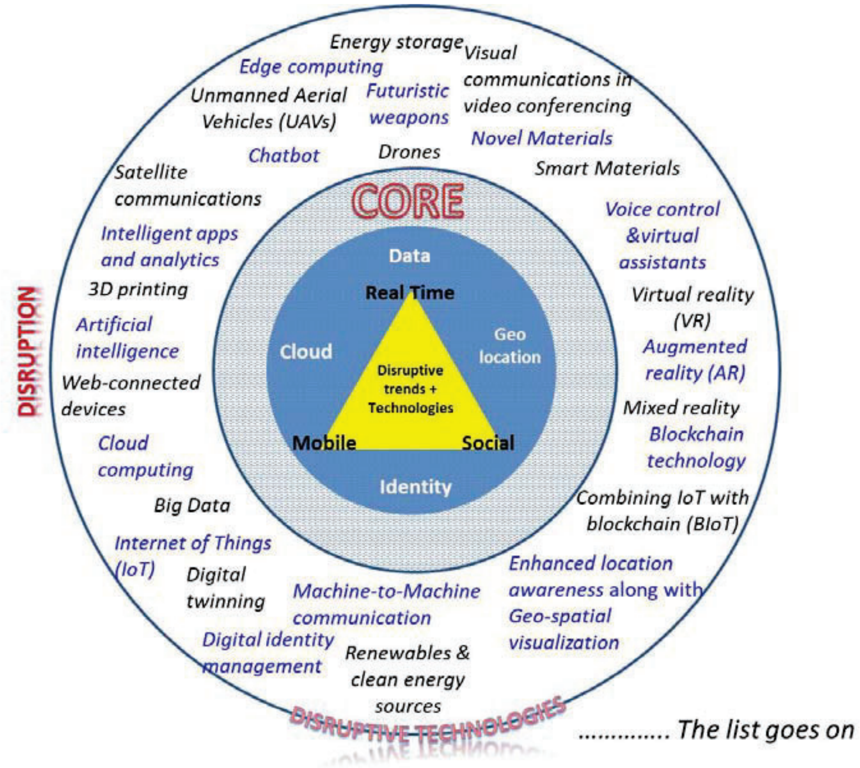


Figure 1: Disruptive technologies in the maritime industry (*Source*: Agarwala, 2022a)

3. Evaluating and Reducing Emissions from Naval Assets using Industry 4.0

Emissions occur from a naval asset during design, production, operation, maintenance and scrapping. With advancements in Industry 4.0 these facets can be monitored more closely to ensure monitoring and minimising of carbon emissions. It is important to mention that the definition of I4.0 is viewed differently by different researchers. With available disruptive technologies increasing daily for the maritime domain, as seen in Figure **1**, the canvas of I4.0 is increasing. Some consider it as increasing automation, some as an umbrella term for new technologies and concepts while others consider it a manufacturing concept to gain competitive advantage.

While these views reflect some part of I4.0, for the authors, I4.0 is about transformation to digital form to achieve digitalisation (Razmjooei et al., 2023).

For naval assets, emission reduction is critical as even though countries are not obliged to cut military emissions under the Paris agreement, they are not exempted either (Neslen, 2015). To achieve this, use of I4.0 is a possible option. Some efforts to reduce emissions of naval assets using I4.0 are summarised in Figure 2 and discussed in some detail in Figures 3 to 6. To appreciate the effectiveness and the factual use of these technologies, the efforts of the Indian Navy in reducing carbon emissions will be discussed in the subsequent section.

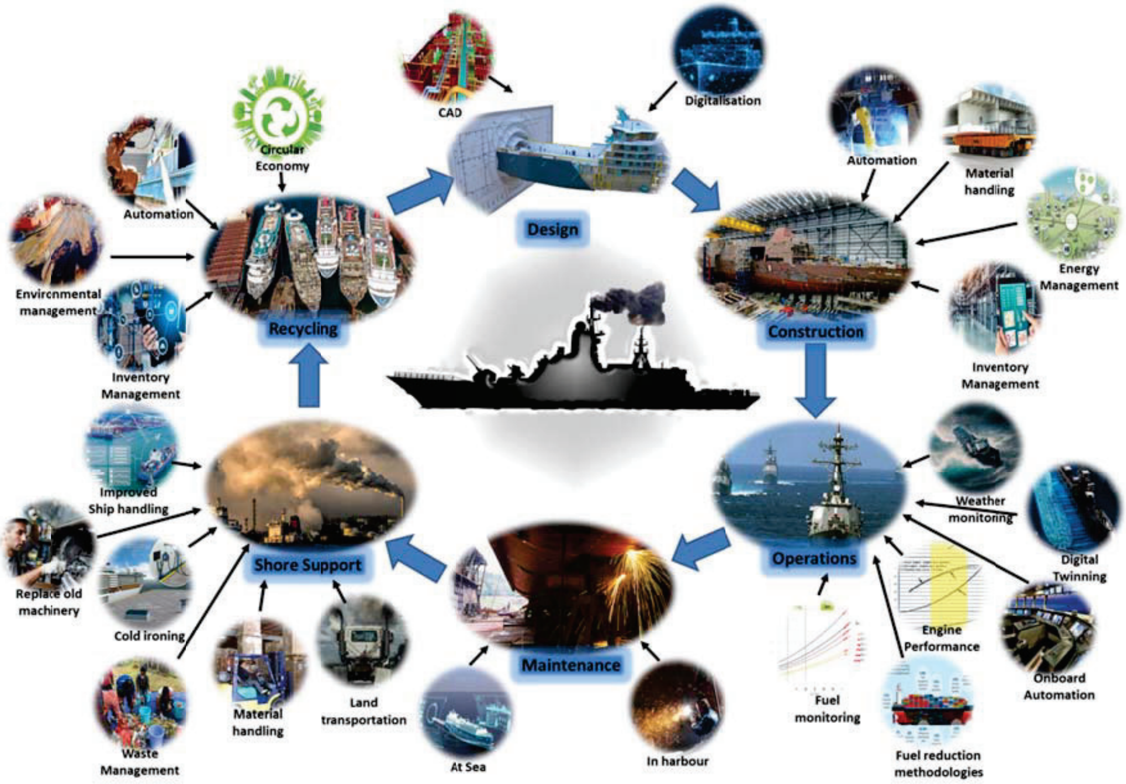
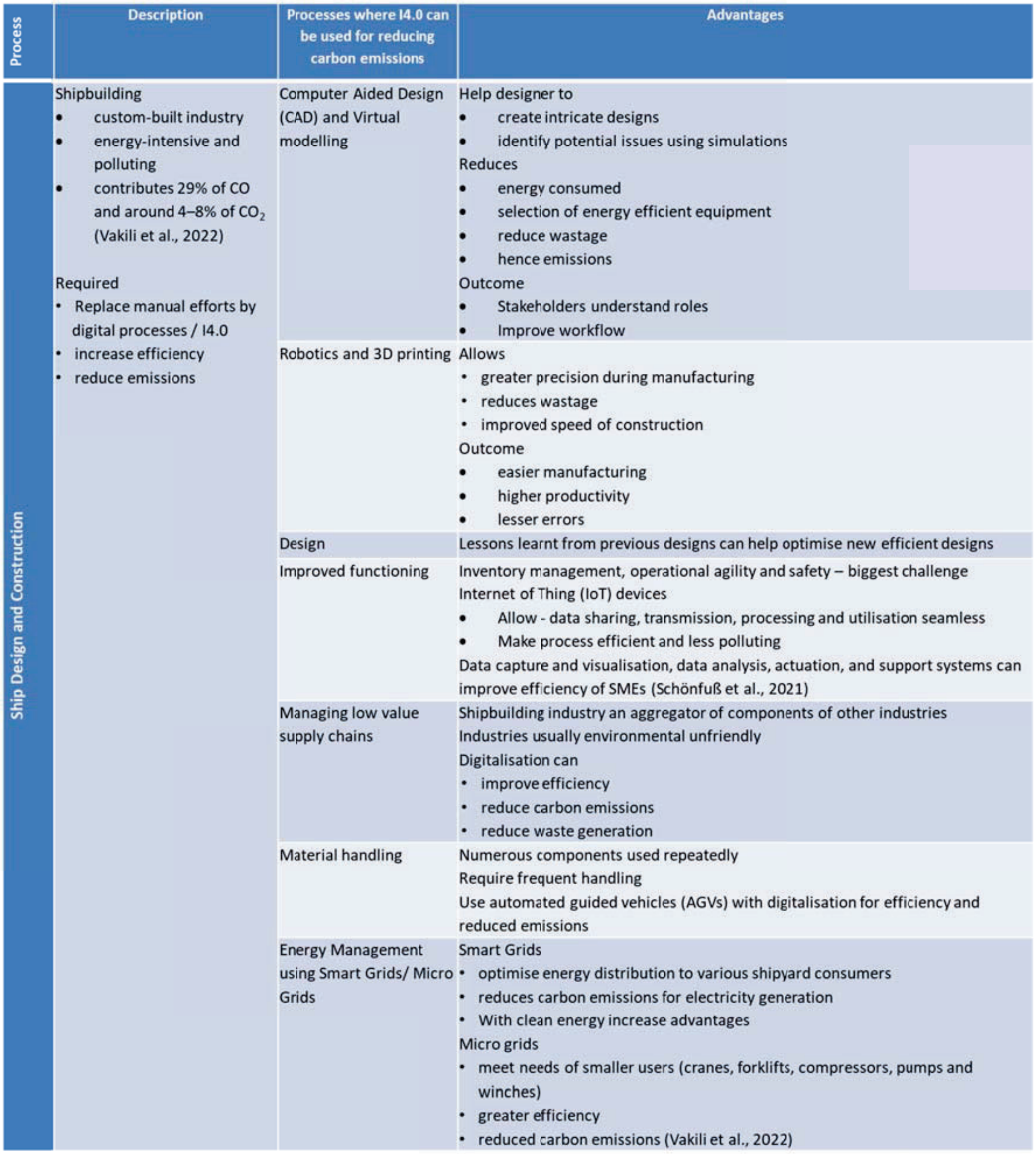
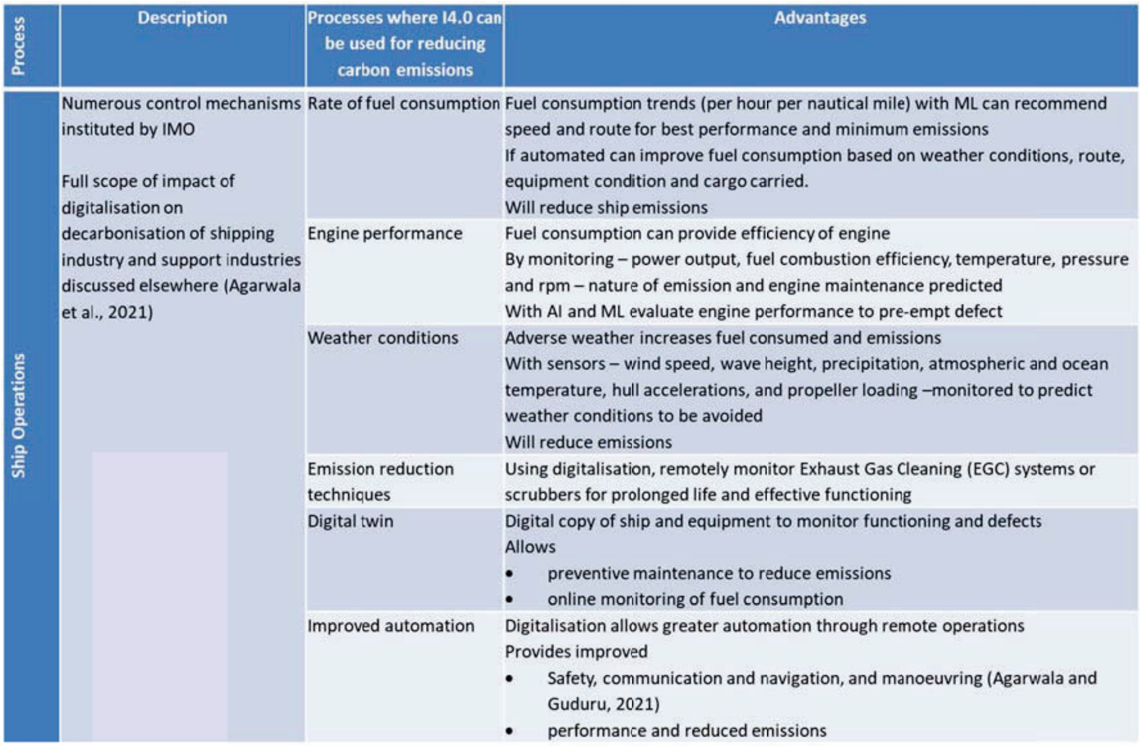


Figure 2: Emission reduction by naval assets using Industry 4.0



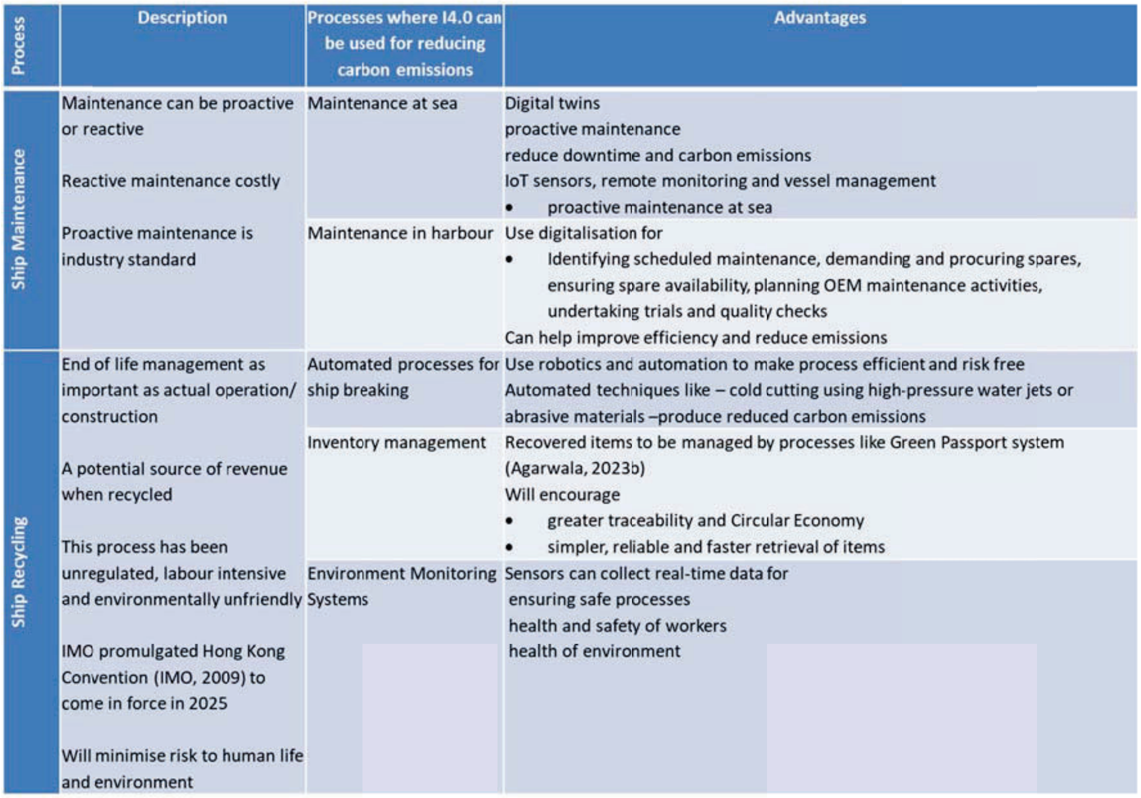
Process	Description	Processes where I4.0 can be used for reducing carbon emissions	Advantages
Ship Design and Construction	Shipbuilding • custom-built industry • energy-intensive and polluting • contributes 29% of CO and around 4–8% of CO_2 (Vakili et al., 2022) Required • Replace manual efforts by digital processes / I4.0 • increase efficiency • reduce emissions	Computer Aided Design (CAD) and Virtual modelling	Help designer to • create intricate designs • identify potential issues using simulations Reduces • energy consumed • selection of energy efficient equipment • reduce wastage • hence emissions Outcome • Stakeholders understand roles • Improve workflow
		Robotics and 3D printing	Allows • greater precision during manufacturing • reduces wastage • improved speed of construction Outcome • easier manufacturing • higher productivity • lesser errors
		Design	Lessons learnt from previous designs can help optimise new efficient designs
		Improved functioning	Inventory management, operational agility and safety – biggest challenge Internet of Thing (IoT) devices • Allow - data sharing, transmission, processing and utilisation seamless • Make process efficient and less polluting Data capture and visualisation, data analysis, actuation, and support systems can improve efficiency of SMEs (Schönfuß et al., 2021)
		Managing low value supply chains	Shipbuilding industry an aggregator of components of other industries Industries usually environmental unfriendly Digitalisation can • improve efficiency • reduce carbon emissions • reduce waste generation
		Material handling	Numerous components used repeatedly Require frequent handling Use automated guided vehicles (AGVs) with digitalisation for efficiency and reduced emissions
		Energy Management using Smart Grids/ Micro Grids	Smart Grids • optimise energy distribution to various shipyard consumers • reduces carbon emissions for electricity generation • With clean energy increase advantages Micro grids • meet needs of smaller users (cranes, forklifts, compressors, pumps and winches) • greater efficiency • reduced carbon emissions (Vakili et al., 2022)

Figure 3: Emission reduction during Ship Design and Construction (*Source*: Authors)



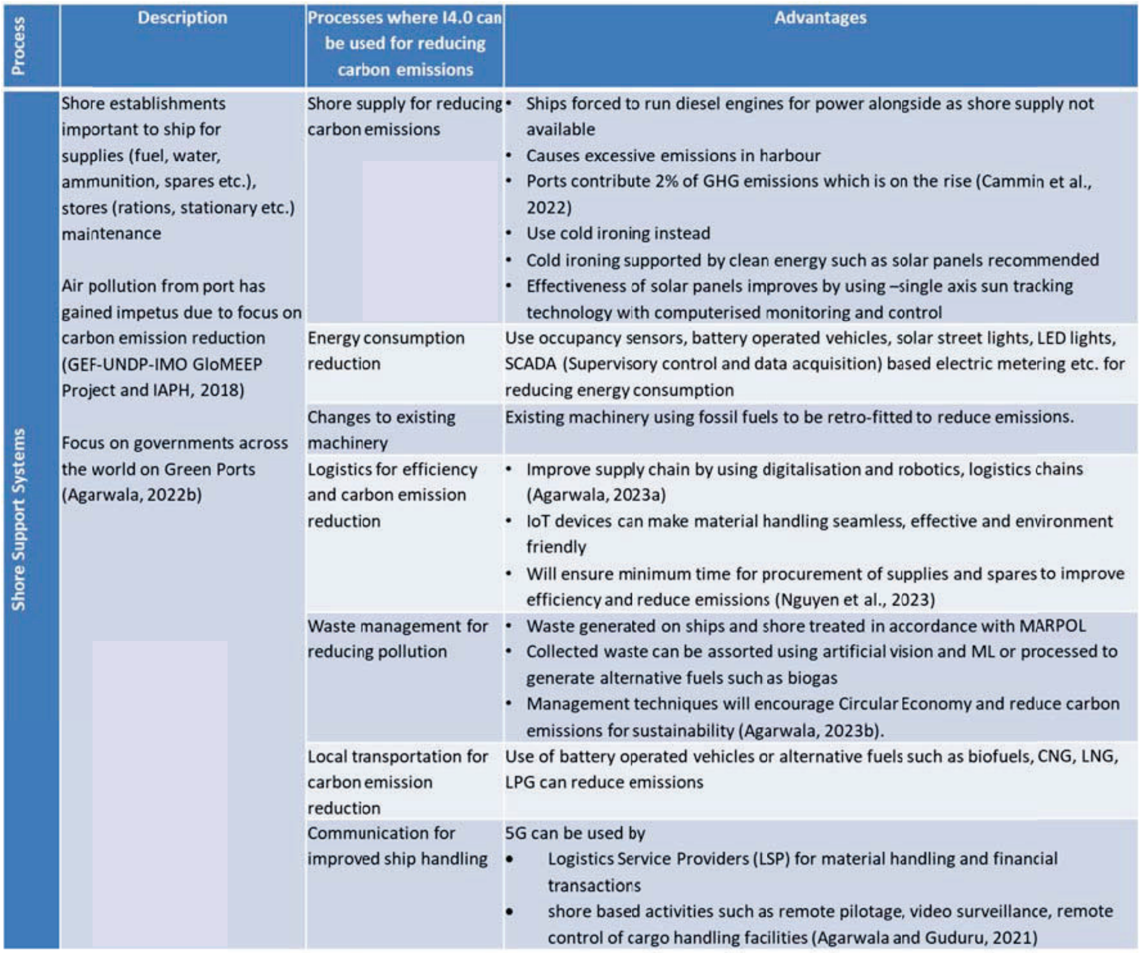
Process	Description	Processes where I4.0 can be used for reducing carbon emissions	Advantages
Ship Operations	Numerous control mechanisms instituted by IMO Full scope of impact of digitalisation on decarbonisation of shipping industry and support industries discussed elsewhere (Agarwala et al., 2021)	Rate of fuel consumption	Fuel consumption trends (per hour per nautical mile) with ML can recommend speed and route for best performance and minimum emissions If automated can improve fuel consumption based on weather conditions, route, equipment condition and cargo carried. Will reduce ship emissions
		Engine performance	Fuel consumption can provide efficiency of engine By monitoring – power output, fuel combustion efficiency, temperature, pressure and rpm – nature of emission and engine maintenance predicted With AI and ML evaluate engine performance to pre-empt defect
		Weather conditions	Adverse weather increases fuel consumed and emissions With sensors – wind speed, wave height, precipitation, atmospheric and ocean temperature, hull accelerations, and propeller loading –monitored to predict weather conditions to be avoided Will reduce emissions
		Emission reduction techniques	Using digitalisation, remotely monitor Exhaust Gas Cleaning (EGC) systems or scrubbers for prolonged life and effective functioning
		Digital twin	Digital copy of ship and equipment to monitor functioning and defects Allows • preventive maintenance to reduce emissions • online monitoring of fuel consumption
		Improved automation	Digitalisation allows greater automation through remote operations Provides improved • Safety, communication and navigation, and manoeuvring (Agarwala and Guduru, 2021) • performance and reduced emissions

Figure 4: Emission reduction during Ship Operations (*Source*: Authors)



Process	Description	Processes where I4.0 can be used for reducing carbon emissions	Advantages
Ship Maintenance	Maintenance can be proactive or reactive Reactive maintenance costly Proactive maintenance is industry standard	Maintenance at sea	Digital twins proactive maintenance reduce downtime and carbon emissions IoT sensors, remote monitoring and vessel management • proactive maintenance at sea
		Maintenance in harbour	Use digitalisation for • Identifying scheduled maintenance, demanding and procuring spares, ensuring spare availability, planning OEM maintenance activities, undertaking trials and quality checks Can help improve efficiency and reduce emissions
Ship Recycling	End of life management as important as actual operation/ construction A potential source of revenue when recycled This process has been unregulated, labour intensive and environmentally unfriendly IMO promulgated Hong Kong Convention (IMO, 2009) to come in force in 2025 Will minimise risk to human life and environment	Automated processes for ship breaking	Use robotics and automation to make process efficient and risk free Automated techniques like – cold cutting using high-pressure water jets or abrasive materials –produce reduced carbon emissions
		Inventory management	Recovered items to be managed by processes like Green Passport system (Agarwala, 2023b) Will encourage • greater traceability and Circular Economy • simpler, reliable and faster retrieval of items
		Environment Monitoring Systems	Sensors can collect real-time data for ensuring safe processes health and safety of workers health of environment

Figure 5: Emission reduction during Ship Maintenance and Recycling (*Source*: Authors)



Process	Description	Processes where I4.0 can be used for reducing carbon emissions	Advantages
Shore Support Systems	Shore establishments important to ship for supplies (fuel, water, ammunition, spares etc.), stores (rations, stationary etc.) maintenance Air pollution from port has gained impetus due to focus on carbon emission reduction (GEF-UNDP-IMO GloMEEP Project and IAPH, 2018) Focus on governments across the world on Green Ports (Agarwala, 2022b)	Shore supply for reducing carbon emissions	• Ships forced to run diesel engines for power alongside as shore supply not available • Causes excessive emissions in harbour • Ports contribute 2% of GHG emissions which is on the rise (Cammin et al., 2022) • Use cold ironing instead • Cold ironing supported by clean energy such as solar panels recommended • Effectiveness of solar panels improves by using –single axis sun tracking technology with computerised monitoring and control
		Energy consumption reduction	Use occupancy sensors, battery operated vehicles, solar street lights, LED lights, SCADA (Supervisory control and data acquisition) based electric metering etc. for reducing energy consumption
		Changes to existing machinery	Existing machinery using fossil fuels to be retro-fitted to reduce emissions.
		Logistics for efficiency and carbon emission reduction	• Improve supply chain by using digitalisation and robotics, logistics chains (Agarwala, 2023a) • IoT devices can make material handling seamless, effective and environment friendly • Will ensure minimum time for procurement of supplies and spares to improve efficiency and reduce emissions (Nguyen et al., 2023)
		Waste management for reducing pollution	• Waste generated on ships and shore treated in accordance with MARPOL • Collected waste can be assorted using artificial vision and ML or processed to generate alternative fuels such as biogas • Management techniques will encourage Circular Economy and reduce carbon emissions for sustainability (Agarwala, 2023b).
		Local transportation for carbon emission reduction	Use of battery operated vehicles or alternative fuels such as biofuels, CNG, LNG, LPG can reduce emissions
		Communication for improved ship handling	5G can be used by • Logistics Service Providers (LSP) for material handling and financial transactions • shore based activities such as remote pilotage, video surveillance, remote control of cargo handling facilities (Agarwala and Guduru, 2021)

Figure 6: Emission reduction during Shore Support (*Source*: Authors)

4. Efforts of the Indian Navy towards decarbonisation

The Indian Navy (IN) adopted the Green Initiative Programme (GIP) in 2014 with an aim to add a Green footprint to its Blue Water capabilities. To monitor implementation of green energy programmes, the IN established an Energy and Environment Cell at Naval Headquarters (PIB, 2016). Since 2014, they have been instrumental in working towards Clean and Green energy from Renewable Energy, formulation of an Environment Conservation Roadmap (INECR) to provide impetus to green operations, maintenance, administration and infrastructure/ community living, and sustained use of biodiesel for all motor transport vehicles (PIB, 2019). The set goals would be achieved through efficient operations, predictive and proactive maintenance, energy efficient infrastructure, informed community living and regulations adhering administration.

While these set goals contribute to a Green Planet, let us look at those efforts that contribute directly to reduce carbon emission from naval assets.

4.1. Generating clean energy and reduction of energy consumption

As discussed, contribution of carbon emissions from the military is both from shore establishments, personnel and military hardware. Accordingly, in an effort to reduce emissions from shore establishments and ships in harbour, alternative energy and power sources that generate clean energy are considered essential. Accordingly, the IN has promulgated numerous policies to ships and establishments for reducing existing energy consumption and to produce clean and green energy.

The IN has pledged 1.5% of its ‘Works’ Budget for generating energy from renewable sources with a focus towards rooftop and land based solar photovoltaic (PV) projects. This helped achieve 11 MW of solar capacity by July 2020 (PIB, 2021) and 15.87 MW by June 2023 (PIB, 2023b) at naval stations as seen in Figure 7. Since these plants are grid connected, they utilise the state of art single axis sun tracking technology with computerised monitoring and control.

Figure 7: Solar Power Plants under Jawaharlal Nehru National Solar Mission

Additionally, 16 MW of projects are at various stages of execution (PIB, 2023b). Pilot projects of wind and a mix of solar and wind (hybrid) are also being progressed. Renewable energy generation has been successfully experimented on INS Sarvekshak in 2017 (Figure 8) wherein a 5kW solar power system was installed onboard (PTI, 2018).

Figure 8: Solar Panels Installed on the Hello Hanger of INS Sarvekshak

To reduce energy consumption and emissions, energy conservation measures such as occupancy sensors, battery operated vehicles, solar street lights, LED lights, audit of yards, SCADA (Supervisory control and data acquisition or Integrated Platform Management Systems) based electric metering etc. are being encouraged. Where applicable, they are used both on ships and shore establishments (PIB, 2023b).

4.2. Green Fuels

Sustained usage of biofuel (B-5 and B-7 blend of High Speed Diesel) has been implemented in motor transport vehicles used in establishments. In addition, used Cooking Oil-based biodiesel has been experimented with to reduce vehicular emissions (PIB, 2023b). Similarly, to reduce emissions from fossil fuel used by ships, a joint venture with the Indian Oil Company to develop the HFHSD – IN 512 (High Flash High-Speed Diesel) fuel by varying over 22 parameters to reduce carbon footprint (PIB, 2020) has been experimented with.

To use Hydrogen as an alternate fuel, successful shore trials in a Hydrogen Aspirated Diesel Engine have been conducted, Figure 9. The engine is now being tried out on a ship for efficacy. To move away from fossil fuels, construction of a ferry craft powered by a hydrogen fuel cell within India as a developmental project is being explored (PIB, 2023b).

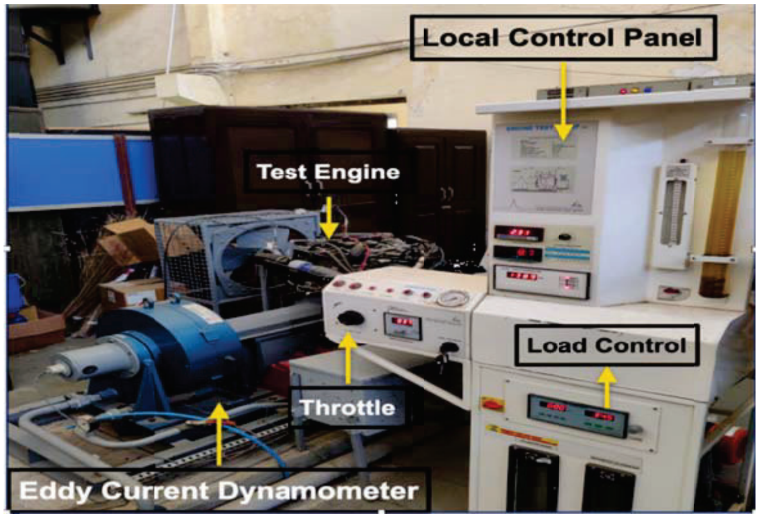


Figure 9: Hydrogen Aspirated Diesel Engine Trials

4.3. Technological Changes

To achieve goals of GIP without altering primary task of the organisation, both behavioural changes and technology are being tried out during design and acquisition, operations, and maintenance. As part of their behavioural change, the Indian Navy has been conducting energy conservation awareness drives, coastal cleaning, lectures, Shramdaan (Volunteer Work), etc. with an aim to contribute to developing better and clean communities and contribute to the "Swachh Bharat Abhiyan (Clean India Campaign)". On ships, some technological changes are.

(a) *Design*. Indian Navy has nurtured and developed its own dedicated Warship Design Bureau for more than six decades and has progressively incorporated advanced design features and State of the Art technologies (Raghavan, 2018). Amongst many other parameters, special attention has always been paid to reduction in energy consumption as well as reduction in emissions. For older platforms, energy efficient modules have been retro-fitted.

(b) *Operations*. With the crew becoming more and more conscious of decarbonization, there is a general tendency to minimise energy consumption, of course without comprising on the either the safety of the ship or its missions. In addition, green energy technology such as renewable energy is being used to reduce emissions. To reduce power consumption during operations, smart LED lighting has been adopted and HVAC and waste heat recovery systems have been optimised (PIB, 2023b).

(c) *Maintenance*. With large amount of data collected over the years by the Indian Naval Ship Maintenance Authority, AI and ML I4.0 technologies are finding their way into predictive maintenance on board IN ships by leveraging the strengths of startups (DIO, 2022: problem statement 29).

4.4. Emission Reduction

To reduce emissions from legacy shore based diesel engines an indigenous patented retrofit device has been developed and successfully tried out by M/s Chakr Innovations, Figure 10. The retrofit reduces Hydrocarbons, Carbon Monoxide, and Particulate Matter in the exhaust by 70% (PIB, 2023a).

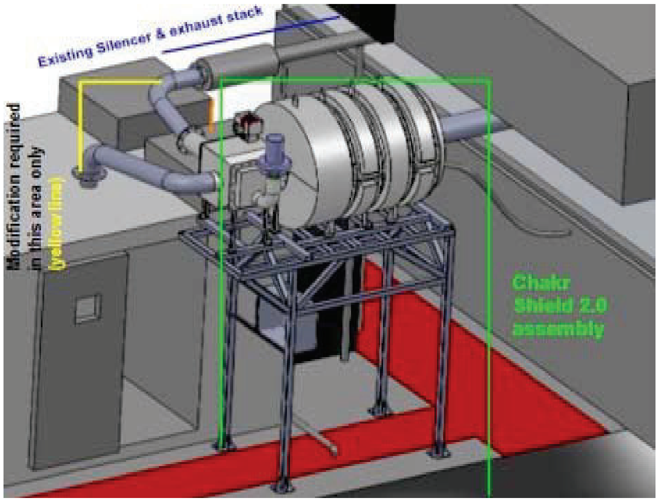


Figure 10: Diesel Engine Emissions Reduction

4.5. Natural Refrigerant AC Plant

To phase out HCFCs, the IN in collaboration with Indian Institute of Science (IISc, Bangalore) has developed a 100kW capacity AC plant that uses Carbon dioxide as a refrigerant. The plant (Figure 11) is currently under trials and has completed 850 hours of successful operations (PIB, 2023a).

#

Figure 11: AC plant with CO_2 as a refrigerant

4.6. Air Pollution

Plantation, arboriculture and horticulture are means of reducing emission impact and need to be encouraged. Accordingly, the Indian Navy has focused on various environmental remediation measures by plantation, arboriculture and horticulture, anti-plastic drive, bio toilets, effluent treatment plants etc. This has led to plantation of more than 18,000 plants in one year and can mitigate an estimated 365 tonnes of CO_2.

4.7. MARPOL Compliance

To control pollution in harbour and seas MARPOL compliance is essential. For this, the IN uses sullage barges for collection of effluent from ships, effluent treatment plants to neutralize toxic waste before discharge, and ensures that newly inducted equipment is MARPOL compliant. To combat oil spills in harbour, eco-friendly marine bio-remedial agents have been indigenously developed by Naval Materials Research Laboratory (NMRL) that clean sea water by consuming oils by using a combination of micro-organisms. In addition, Segregated Waste Collection Centre (SWCC) aims to treat and manage collected waste. By using biogas plants, compost pits and paper recycling, an estimated savings of 140 LPG cylinders per year has been achieved. This reduces the overall emissions by reducing consumption and using alternative and renewable resources as fuel.

4.8. Leveraging Growing Startup Eco-System in India

The Ministry of Defence has created a Defence Innovation Organisation through which they are propagating the problem statements that define technical challenges needing efficient solutions. These are prepared by the Indian Army, the Indian Navy, the Indian Air Force and other entities under them. These statements are issued as series of Defence India Startup Challenges (DISCs), under the umbrella of Innovations for Defence Excellence (iDEX) (https://idex.gov.in/). Response from the start-ups has been encouraging with many products and systems finding their way in use in the Indian Navy, including those utilizing I4.0 technologies for the naval sector decarbonization

5. Discussion

Emerging need to reduce carbon emission from all facets of our lives has becomes an essentiality and is no more a desire. Under the Paris Agreement, while countries are not obliged to cut their military emissions, they are not exempted either. This necessitates curating and cataloguing emissions of these assets to address global emissions. Using data on energy consumption and economic activity (Parkinson, 2020) published by nations of the Organisation for Economic Co-operation and Development (OECD), one can estimate emissions by the military. However, for growing economies that have otherwise heavy military expenditures, lack of this data disallow any estimates.

With advances in disruptive technologies, the required task of measuring carbon emissions from naval assets can be simplified and have been discussed in this paper. One notices that while disruptive technologies exist and are in use in various ways, there is limited impetus towards monitoring carbon emissions. In some cases, these technologies are still to make inroads in naval assets due to legacy equipment.

This requires that environment conscious nations take a lead to showcase advantages such digital technologies can provide in both monitoring of equipment and systems and achieving decarbonisation of the naval sector. In this regard, the paper has discussed efforts of the Indian Navy in moving the Green way. While these efforts are commendable, resulting changes would be better appreciated if the before and after carbon emission calculations are used and made available. By imbibing digitalisation in various aspects of naval assets, these calculations would not be difficult and would require formulation of procedures with a plug and play module that would synthesise data collected from numerous sensors to provide desired carbon emissions.

Since the usage of I4.0 is known to improve energy efficiency between 15-20% (Vakili et al., 2022), use of I4.0 should be encouraged. With advancement in sensors and technology, these benefits will only increase. Since use of this technology is equally applicable to commercial shipping, their use would eventually help achieve the desired decarbonisation goals of IMO.

6. Way Ahead

There is no denial that the need of accounting carbon emission from naval assets and other military assets is becoming important. While so far this computation has been avoided and disregarded, there is a growing need and focus on developing ways and means of accounting and calculating GHG emissions of the military. Since the procedure is complicated as it involves numerous downstream organisations the task has been speculative. Accordingly, some efforts such as those by Crawford (2019) and Parkinson (2022) are noteworthy. However, with digitalisation as discussed here, the efforts can be simplified. The present need is to ensure that these efforts are taken forward to define a logical process and schema that will permit a plug and play module for calculation of carbon emissions.

In addition, present use of digitalisation should encourage fine tuning of existing sensors and development of more sensitive ones to ensure improved data gathering. This should encourage development of new digital technologies that can further improve and simplify data collection and computation. Advances made by AI using ML and DL such as those towards object identification and segregation of pollutants (Agarwala, 2021) are some future areas of development in assessing carbon emissions that need greater scholarship. Similarly, use of ocean energy as a means of producing renewable energy for meeting power requirements (Agarwala, 2022c) of the shipping sector needs greater scholarship.

In terms of monitoring carbon emissions from the shipping sector, they are currently experimental and involve isolated monitoring activities for scientific research (Zhou et al., 2022). However, this is an area of serious scholarship that needs to be perfected and implemented. Such a comprehensive monitoring when linked to the flag of the ship will act as a deterrent and address growing concerns of ‘Flags of convenience’.

Yet another important and critical aspect that needs continuous updating is the need of cyber security for systems that are digitalised and are connected. Inability to provide necessary confidence in cyber related security issues to owners and operators will not allow accruing benefits of digitalisation. Since cyber security is a 'cat and mouse' game, efforts have to be ongoing and continuous to ensure economic and security interests of all stakeholders.

7. Conclusions

The paper has discussed usage of Industry 4.0 in monitoring of carbon emission from the naval sector, a sector that has been under no obligation to address emissions. Since the global environment does not differentiate between the military and the civilian domain, the present concept of 'no obligation to address emissions' needs to be reconsidered. Self-driven efforts to reduce carbon emissions by the Indian Navy have been discussed and considered commendable. The need of the hour is to raise the bar and develop plug and play solutions for calculating overall contribution of carbon emissions from the naval sector with an aim to reduce it to net zero in line with the Nationally Determined Contributions (NDC). After all the Earth is one and there is no Planet B where we can move to if this one face destruction due to lack of our commitment to reduce global warming.

While the paper has discussed available avenues wherein digital technologies can be used to monitor and achieve reduction in carbon emissions these are considered a work-in-progress which are meant to initiate debate and further advancement in terms of use and technology development. Since every good has a flip side, use of digitalisation and connected networks is susceptible to cyber vulnerabilities which will need to be addressed to avoid compromising defence capabilities for the military and financial loss for the commercial sector.

Disclaimer

Views expressed are those of the authors and do not reflect those of the Government of India or the Indian Navy.

References

Agarwala, N., (2021), Managing marine environmental pollution using Artificial Intelligence, *Maritime Technology and Research*, 3(2): 120-136, https://doi.org/10.33175/mtr.2021.248053

Agarwala, N. and Polinov, S., (2021), Curtailing Anthropogenic Carbon Dioxide to Meet the Targets of the Paris Agreement using Technology Support Mechanisms, *Journal of Human-centric Research in Humanities and Social Sciences*, Vol.2, No.1, pp.1-24 http://dx.doi.org/10.21742/jhrhss.2021.2.1.01

Agarwala, N., (2022a), Role of policy framework for disruptive technologies in the maritime domain, *Australian Journal of Maritime & Ocean Affairs*, 14:1, 1-20, DOI:10.1080/18366503.2021.1904602

Agarwala N., (2022b), Project Green Ports: Are Indian ports on the right track?, *Maritime Affairs: Journal of the National Maritime Foundation of India*, 18:2, 15-36, DOI:10.1080/09733159.2022.2143134

Agarwala, N., (2022c), Powering India's Blue Economy through ocean energy, *Australian Journal of Maritime & Ocean Affairs*, 14:4, 270-296, DOI: 10.1080/18366503.2021.1954494

Agarwala, N. (2022d), Is LNG the solution for decarbonised shipping?, *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, , 6:4, 158-166, https://doi.org/10.1080/25725084.2022.2142428

Agarwala, N. (2023a), Robots and Artificial Intelligence in the Military, *Obrana a strategie* 23 (2): 083-100. https://doi.org/10.3849/1802-7199.23.2023.02.083-100

Agarwala, N. (2023b), Promoting Circular Economy in the shipping industry, *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 7:4, 2276984, DOI: 10.1080/25725084.2023.2276984

Agarwala, N., and Guduru, SSK, (2021), The potential of 5G in commercial shipping, *Maritime Technology and Research*, 3(3): 254-267, https://doi.org/10.33175/mtr.2021.248995

Agarwala, P., Chhabra, S. and Agarwala, N., (2021), Using digitalisation to achieve decarbonisation in the shipping industry, *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 5:4, 161-174, DOI: 10.1080/25725084.2021.2009420

Batra, A., Prakash, R. (2018). Energy Efficient Operations of Warships: Perspective of the Indian Navy. In: Ölçer, A., Kitada, M., Dalaklis, D., Ballini, F. (eds) Trends and Challenges in Maritime Energy Management. *WMU Studies in Maritime Affairs*, vol 6. Springer, Cham. https://doi.org/10.1007/978-3-319-74576-3_7

Belcher, O, Bigger, P, Neimark, B, Kennelly, C. Hidden carbon costs of the "everywhere war": Logistics, geopolitical ecology, and the carbon boot-print of the US military. *Trans Inst Br Geogr*. 2020; 45: 65– 80. https://doi.org/10.1111/tran.12319

Bowcott, H., Gatto, G., Hamilton, A., and Sullivan, E., (2021, Jul 01), Decarbonizing defense: Imperative and opportunity, *McKinsey & Company*, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/decarbonizing-defense-imperative-and-opportunity

Buhaug, Ø.; Corbett, J. J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D. S.; Lee, D.; Lindstad, H.; Mjelde, A.; Pålsson, C.; Wanquing, W.; Winebrake, J. J.; Yoshida, K., (2008), *Updated Study on Greenhouse Gas Emissions from Ships: Phase I Report*; International Maritime Organization (IMO) London, UK, 1 September

Buhaug, Ø.; Corbett, J.J. ; Endresen, Ø.; Eyring, V.; Faber, J. ; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; Mjelde, A.; Nelissen, D.; Nilsen, J.; Pålsson, C.; Winebrake, J.J.; Wu, W.–Q.; Yoshida, K., (2009), *Second IMO GHG study 2009*; International Maritime Organization (IMO) London, UK, April, https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/MEPC%2059-INF.10%20-%20Second%20IMO%20GHG%20Study%202009.pdf#

Cammin, P., Brüssau, K., Voß, S., (2022), Classifying maritime port emissions reporting, Maritime Transport Research, Volume 3, https://doi.org/10.1016/j.martra.2022.100066

Chambers, A.M. and Yetiv, S.A., (2011), The Great Green Fleet: The U.S. Navy and Fossil-Fuel Alternatives, *Naval War College Review*, Vol. 64, No. 3, http://large.stanford.edu/courses/2016/ph240/ramadan2/docs/a619258.pdf

Chhabra, S., and R. K. Rana, (2020). Ingress of Industry 4.0 In Indian Naval Ship Design and Building - Prognosis of VR/ AR Technologies, *International Naval Engineering Conference and Exhibition (iNEC 2020)* Virtual Online Conference. doi:10.24868/.2515-818X.2020.040

Conflict and Environment Observatory, (2021a), How does War contribute to Climate Change, June 14, *Conflict and Environment Observatory*, https://ceobs.org/how-does-war-contribute-to-climate-change/

Conflict and Environment Observatory, (2021b), The Military's contribution to climate change, June 16, *Conflict and Environment Observatory*, https://ceobs.org/the-militarys-contribution-to-climate-change/

Crawford, N., (2019), Pentagon Fuel Use, Climate Change, and the Costs of War, https://watson.brown.edu/costsofwar/papers/ClimateChangeandCostofWar

DIO, (2022), Summary of Defence India Startup Challenge – 6 (DISC 6) Problem Statements, https://idex.gov.in/sites/default/files/2022-04/DISC%206%20DETAILED%20CHALLENGE%20%281%29.pdf

EESI, (2016), U.S. Navy Deploys 'Great Green Fleet' in Bid to Reduce Military Energy Use, *Environmental and Energy Studies Institute*, https://www.eesi.org/articles/view/u.s.-navy-deploys-great-green-fleet-in-bid-to-reduce-military-energy-use

Fish, T., (2022), Indian Navy Expanding to Meet China Threat, Better Team With Allies, *USNI News*, https://news.usni.org/2022/07/20/indian-navy-expanding-to-meet-china-threat-better-team-with-allies

GEF-UNDP-IMO GloMEEP Project and IAPH, (2018), Port Emissions Toolkit, Guide No.1, Assessment of port emissions

Hannah, R., Roser, M and Rosado, P., (2020), CO_2 and Greenhouse Gas Emissions, *OurWorldInData.org*, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Hodgkins, L., (2021), The Royal Canadian Navy Fleet: A Pathway to Decarbonisation, Niobe Papers, No. 15, https://www.cfc.forces.gc.ca/259/290/22/305/Hodgkins.pdf

IMO, (n.d), Historic Background, https://www.imo.org/en/OurWork/Environment/Pages/Historic%20Background%20GHG.aspx

IMO, (2009), Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, 2009, *International Conference on the Safe and Environmentally Sound Recycling of Ships*, https://www.basel.int/Portals/4/Basel%20Convention/docs/ships/HongKongConvention.pdf

Jeswani H. K., Chilvers A. and Azapagic A. (2020), Environmental sustainability of biofuels: a review, *Proc. R. Soc. A*.476: 20200351. 20200351, http://doi.org/10.1098/rspa.2020.0351

Ministero Della Difesa, (n.d), Green Fleet, https://www.marina.difesa.it/EN/facts/greenfleet/Pagine/default.aspx

Neslen, A., (2015), Pentagon to lose emissions exemption under Paris climate deal, *The Guardian*, https://www.theguardian.com/environment/2015/dec/14/pentagon-to-lose-emissions-exemption-under-paris-climate-deal

Nguyen, H.P., Nguyen, P.Q.P., Nguyen , D.K.P., *Bui,* V.D., *Nguyen, D.T., (2023),* Application of IoT Technologies in Seaport Management, *Int. J. Inform. Visualization*, 7(1), 228-240, https://dx.doi.org/10.30630/joiv.7.1.1697

PTI, (2018), INS Sarvekshak goes green; Installs solar power system, *The Economic Times*, 15 July, https://economictimes.indiatimes.com/news/defence/ins-sarvekshak-goes-green-instals-solar-power-system/articleshow/57110554.cms?from=mdr

PIB, (2016, June 05), Indian Navy Pledges 1.5 Per Cent of its Works Budget Towards Renewable Energy Generation, *Press Information Bureau, Government of India, Ministry of Defence,* http://pib.nic.in/newsite/PrintRelease.aspx?relid=145978

PIB, (2019, Jun 04), Indian Navy SAILS towards pursuance of the energy and environmental goals of country - World Environment Day 2019, *Press Information Bureau, Government of India, Ministry of Defence*, https://pib.gov.in/Pressreleaseshare.aspx?PRID=1573389

PIB, (2020, January 13), Indian Navy to Get Upgraded Fuel HFHSD – IN 512, *Press Information Bureau, Government of India, Ministry of Defence*, https://pib.gov.in/newsite/PrintRelease.aspx?relid=197399

PIB, (2021, Jun 05), Indian Navy – Blue Water Operations With A Green Footprint - World Environment Day 2021, *Press Information Bureau, Government of India, Ministry of Defence*, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1724637

PIB, (2023a, Jun 04), Indian Navy's Green Initiatives: Imbibing Green Technologies, Press Information Bureau, Government of India, Ministry of Defence, https://pib.gov.in/PressReleasePage.aspx?PRID=1929750

PIB, (2023b, Jun 05), Indian Navy's Green Initiatives, Imbibing Green Technologies - World Environment Day 2023, *Press Information Bureau, Government of India, Ministry of Defence*, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1929750

Parkinson, S., (2020), The carbon boot-print of the military, Responsible Science, No. 2, Winter, https://www.sgr.org.uk/sites/default/files/2020-08/SGR-RS02-Military-carbon-boot-print.pdf

Parkinson, S., and Cottrell, L., (2020), Estimating the Military's Global Greenhouse Gas Emissions, *Scientists for Global Responsibility*, https://www.sgr.org.uk/publications/estimating-military-s-global-greenhouse-gas-emissions

Raghavan, S., (2018), Military technological innovation in India: A tale of three projects. *India Review*, *17:1*, 122-141. DOI: 10.1080/14736489.2018.1415286

Razmjooei, D., Alimohammadlou, M., Ranaei Kordshouli, HA. *et al.*, (2023), Industry 4.0 research in the maritime industry: a bibliometric analysis, *WMU J Marit Affairs* 22, 385–416, https://doi.org/10.1007/s13437-022-00298-8

Schönfuß, B., McFarlane, D., Hawkridge, G., Salter, L., Athanassopoulou, N., de Silva, L., (2021), A catalogue of digital solution areas for prioritising the needs of manufacturing SMEs, *Computers in Industry*, 133, https://doi.org/10.1016/j.compind.2021.103532

Spoehr, J., Jang, R., Manning, K., Rajagopalan, A., Moretti, C., Hordacre, A-L., Howard, S., Yaron, P. and Worrall, L., (2021), The Digital Shipyard, Opportunities and Challenges, *Australian Industrial Transformation Institute*

UK, MoD, (2021), 'Ministry of Defence Climate Change and Sustainability Strategic Approach', 30 March, https://www.gov.uk/government/publications/ministry-of-defence-climate-change-and-sustainability-strategic-approach

US Senate, (1998), 'Hearing, 105-457 - Implications of the Kyoto Protocol on Climate Change', Hearing before the Committee on Foreign Relations, United States Senate, One Hundred Fifth Congress Second Session, February 11, 1998, https://www.govinfo.gov/content/pkg/CHRG-105shrg46812/html/CHRG-105shrg46812.htm

UNFCC, (2015), ‘Paris Agreement’, https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Vakili, S., Schönborn, A. & Ölçer, (2022), A.I. Application of the transdisciplinary shipyard energy management framework by employing a fuzzy multiple attribute group decision making technique toward a sustainable shipyard: case study for a Bangladeshi shipyard. J. shipp. trd. 7, 22, https://doi.org/10.1186/s41072-022-00123-8

Zentelis, R. and Lindenmayer, D. (2015), Bombing for Biodiversity—Enhancing Conservation Values of Military Training Areas, *Conservation Letters*, 8: 299-305. https://doi.org/10.1111/conl.12155

Zhou, F., Fan, Y., Zou, J., An, B., (2022), Ship emission monitoring sensor web for research and application, *Ocean Engineering* 249, https://doi.org/10.1016/j.oceaneng.2022.110980

Margins – their use as Metrics and Key Performance Indicators when Designing and Building Warships

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Synopsis

Warship acquisition projects are technically complex, high value, subject to intense public scrutiny, and typically take a long time to bring to fruition. The technical complexity and inevitable clash of priorities between hull form, platform systems and combat systems design may necessitate compromises between key platform characteristics. Due to both the interconnected aspects and the need to carefully balance platform and combat system requirements and performance, it is not practical to separate them completely.

When designing a warship to keep pace with the perceived threat environment, the long gestation period between project initiation and the First of Class vessel entering service can generate several problems for the delivery agency and the recipient Navy. These are caused by requirements creep due to evolving threat scenarios, technological advancement, obsolescence, and the impact of legislative changes. In addition, the delivered ship will often experience design trade-offs (i.e. combat systems equipment versus speed, range and weight growth) that have been required during the design, build and introduction-into-service phases.

The development and implementation stages for weapon, sensor and communication systems life cycles are often far shorter (system update cycles are planned on approximately 5-year periods) than the service life for a warship platform, which are typically >25 years but often end up being extended. This sets a difficult challenge for warship design and requires provision to be made in design for systems that are at a low Technology Readiness Level (for example, Directed Energy Weapons, or even conceptual systems, considering the increasing use of autonomous and off board systems). Thus, their interface requirements will be immature. Associated estimates for Space, Weight, Power and Cooling will inevitably need to be larger to cater for the increased uncertainty, making it more challenging to assess Margin requirements for future capability upgrades.

To deal with the problems identified above, metrics and key performance indicators are incredibly helpful in assessing a warship's potential to fulfil its design criteria through to end of life. These aid in determining whether the platform can meet its designated Mission System Requirements and if it is flexible enough to receive weapon and sensor upgrades through life to ensure it can deal with contemporary threat environments and deal with obsolescence. Using appropriate Margins ensures sufficient contingency is provided in the design and, their consumption or usage is monitored and controlled through the platform's life cycle, are excellent metrics and key performance indicators to assess the platform's fundamental capabilities.

Margin policies (traditionally stipulated for Space, Weight, Power and Cooling) have proved their worth many times during previous warship design and build projects. The specification and management of Margins that are intended to be consumed during design, build and in-service is therefore tantamount to ensuring a warship can maintain viability in a constantly changing threat environment. The purpose of this paper is to discuss the impacts Margins have on a vessel's capability and identify strategies to manage these proactively to ensure that the warship can meet its Mission System Requirements through to end of life.

Keywords: Warship Design; Shipbuilding; Space, Weight, Power and Cooling Margins; Frigate; Destroyer, Acquisition; Sustainment.

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1. Introduction

> *Margins are defined as the difference between a design parameter's minimum required value to ensure functionality and its actual capability. Margins allow Engineers to mitigate uncertainties of various kinds.*

Warship acquisition projects are technically complex, high value, subject to intense public scrutiny, and typically take a long time to bring to fruition. The technical complexity and inevitable clash of priorities between hull form, platform systems and combat systems design may necessitate compromises between key platform characteristics. Platform impacts include stability, seakeeping, signatures, speed, range and endurance. Combat system capabilities affected include size of Vertical Launch System, Magazines, and Aviation facilities. Vessel range and sensor capability will also be affected by platform characteristics such as available structure to mount systems and the amount of electrical power and cooling available. Due to the need to carefully balance platform and combat system requirements and performance, it is not practical to separate them completely when developing a warship design.

Traditionally ship design can be performed by making use of the well-known Design Spiral[1], which was originally introduced in 1959[2] with an elaborated version published for Naval ship design in 1998.[3] The design spiral effectively illustrates the sequential course of ship design through the various design steps, the repeating, iterative procedure for the determination of ship dimensions and of other properties and, finally, the gradual approach to the final stage of detailed ship design.[4] This is illustrated below in Figure 1:

When designing a warship to keep pace with the perceived threat environment, the long gestation period between project initiation and the First of Class (FoC) vessel entering service can generate several problems for the delivery agency and the recipient Navy. These are caused by requirements creep due to evolving threat scenarios, technological advancement, obsolescence, and the impact of legislative changes. In addition, the delivered ship will have to cope with design trade-offs that have been required during the design, build and introduction-into-service phases.

The development and implementation stages for weapon, sensor and communication systems life cycles are often far shorter (system update cycles are planned on approximately 5-year periods) than the service life for a warship platform, which are typically >25 years but often end up being extended.[5] This sets a difficult challenge for warship design and requires provision to be made in design for systems that are at a low Technology Readiness Level (for example, Directed Energy Weapons, or even conceptual systems, considering the increasing use of autonomous and off board systems). Thus, their interface requirements will be immature. Associated estimates for Space, Weight, Power and Cooling will inevitably need to be larger to cater for the increased uncertainty, making it more challenging to assess Margin requirements for future capability upgrades.

To deal with the problems identified above, metrics and key performance indicators are incredibly helpful in assessing a warship's potential to fulfil its design criteria through to end of life. These aid in determining whether the platform can meet its designated Mission System Requirements and if it is flexible enough to receive weapon and sensor upgrades through life to ensure it can deal with contemporary threat environments and obsolescence. Using appropriate Margins ensures sufficient contingency is provided in hull and platform system design and, their consumption or usage is monitored and controlled through the platform's life cycle, are excellent metrics and key performance indicators to assess the platform's fundamental capabilities.

In Naval warship practice, a Margin is the owner's attempt to manage the risk associated with requirements setting, design, build and subsequent in-service changes.[6] Margin policies (traditionally stipulated for Space, Weight, Power and Cooling) have proved their worth many times during previous warship design and build projects. The specification and management of Margins that are intended to be consumed during design, build and in-service is therefore tantamount to ensuring a warship can maintain viability in a constantly changing threat environment.

The purpose of this paper is to discuss the impacts Margins have on a vessel's capability and identify strategies to manage these proactively to ensure that the warship can meet its Mission System Requirements through to end of life. This will be illustrated using Marine Engineering system, platform-centric examples based on a hypothetical warship design and build project (HMAS LANCLOVELY, a County Class Surface Combatant) developed by Gibbs and Cox Australia based upon the authors' combined shipbuilding experience.

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[1] (Bottero & Gualeni, 2024)

[2] (Evans, 1959)

[3] (Watson, 1998)

[4] (Papanikolaou, 2014)

[5] (Button, et al., 2015)

[6] (UK Ministry of Defence, 2009)

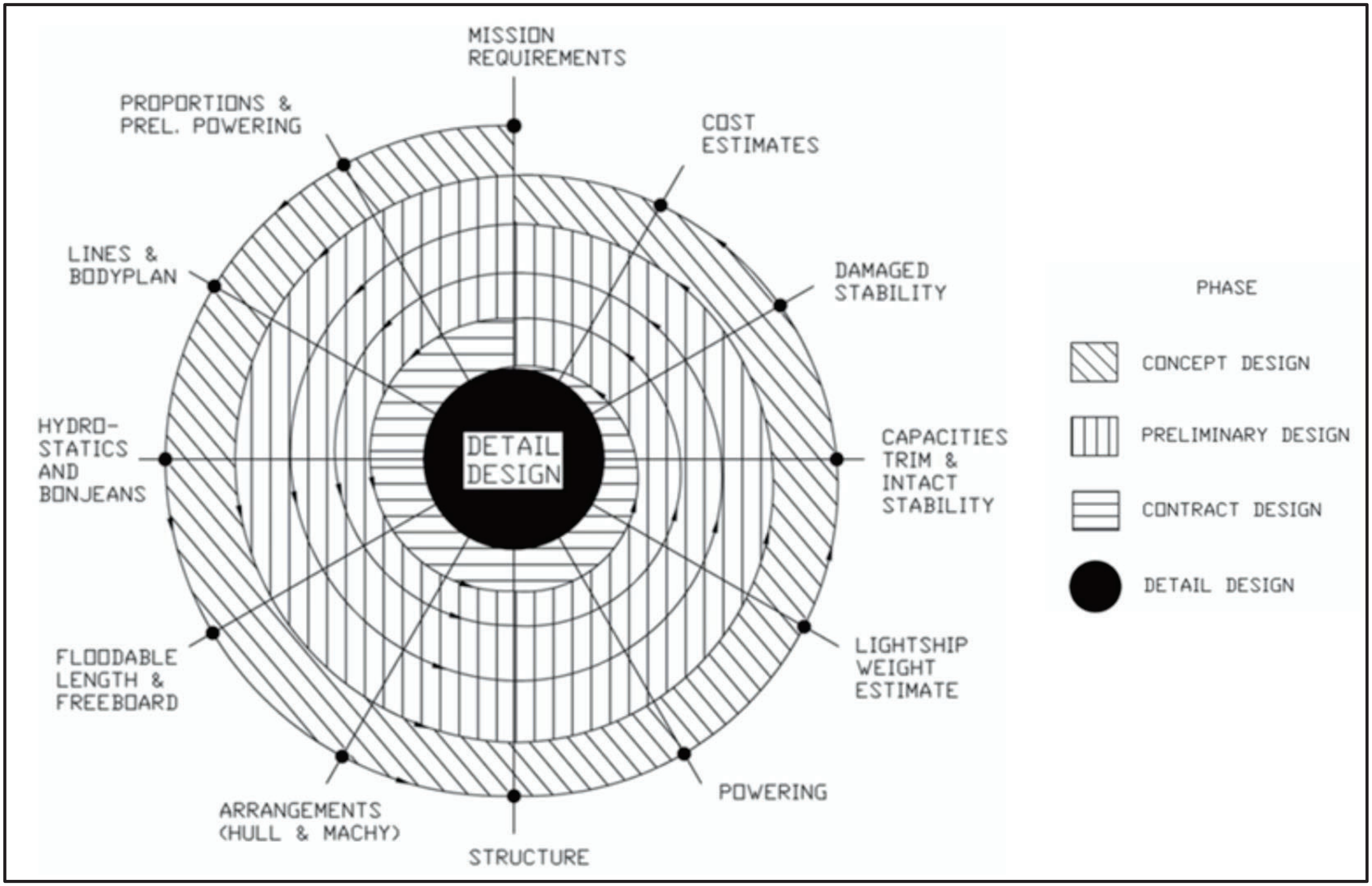

Figure 1: **Design Spiral**

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2. Margin Definitions

There are several different Margin types used commonly throughout warship Acquisition and In-Service phases. Policy and practice vary subtly between countries but, from an Australian perspective, the two standard references include ANP 4801 – Development and Maintenance of Materiel Margins for Naval Capabilities[7] and DEF(AUST) 5000 Volume 02 Part 29 - Margin Requirements,[8] in addition to the UK Maritime Acquisition Publication (MAP) 01-070 - Surface Ship and Submarine Margins Guidance.[9]

The three fundamental reasons for the various Margin types include:[10]

- Mitigating Uncertainty in Acquisition,
- Ensuring Safety Throughout the Service Life, and
- Providing Capacity for Technology Upgrades in an Evolving Threat Environment (utilising the philosophy of Upkeep, Update, and Upgrade).

Further detail on Margin types is outlined in Table 1, and these can be applied to any number of Margin categories. They are traditionally used for Space, Weight, Electrical Power and Cooling (Chilled Water and HVAC systems) as a minimum.

Margin Type	Notes
Design and Build Margin (DBM)	During the design and build phases, the designer faces uncertainty around design characteristics. This uncertainty is gradually reduced and then retired as the design evolves and matures towards a production baseline. The amount of Design and Build Margin should address the development risk and design uncertainty in the program. Following expiry of warranties, unused Design and Build Margin is rolled into the Capability Upgrade Margin (CUM) or the In-Service Growth Margin (ISGM). DBM may need to be split into two separate Margins if the design and build are performed by different organisations.
Contract Modification Margin (CMM)	Due to the complexity of naval ships, and the typically long development time from initial requirements establishment to delivery, there are often changes to requirements or Government Furnished Material (GFM) allocations during the acquisition phase. The customer may include Margins to account for these uncertainties during design and build. Unused Contract Modification Margin at delivery is rolled into CUM or ISGM.
In-Service Growth Margin (ISGM) or Through-Life Growth Margin (TLGM)	Margins are included at the design stage to allow for unplanned, unattributable or uncontrolled changes that typically occur during the service life. These changes can be forecast based on historical data, and various standards offer recommendations on the Margins to apply in early design for different ship types, based on analysis of technical records from current and previous classes. This Margin is also referred to as IGM in ANP 4801, and separately as the Through-Life Growth Margin (TLGM) for mechanical and electrical systems.
Capability Upgrade Margin (CUM)	Margins should be included to address future uncertainty around technology development, and the changing threat environment over the life of the vessel. There is also the inevitable need to add equipment or change configuration to avoid obsolescence and remain effective in an evolving threat environment. Margins applied for capability upgrade depend on the type of missions the ship performs, the expected pace of technology development associated with the threat environment, and the types of systems needed to address the future threat environment (for example, Directed Energy Weapons).

Table 1 – Margin Types

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[7] (Directorate of Naval Engineering, 2023)
[8] (Directorate of Naval Engineering, 2008)
[9] (UK Ministry of Defence, 2009)
[10] (Catton, 2022)

The Margin types described in Table 1 should be applied to Platform systems (eg, Chilled Water and Electrical Distribution systems) and attributes (eg, Weight, Centre of Gravity) as required to ensure that operability, safety, environmental, service life and legislative requirements are not compromised. Achieving the correct Margin size is a compromise between allowing sufficient contingency to deal with uncertainty, requirements creep, growth in-service and design change, and the increased cost that arises from this provision.[11] Margin categories that are typically tracked and analysed throughout the vessel life are described in Table 2 below. These are based upon Platform design, but the concept applies equally well to Combat systems.

Margin Category	**Notes**
Weight	Weight distribution and aggregation has a significant influence on stability, loading, speed, range, and seakeeping. These are all critical to the vessel's ability to meet its Mission System Requirements. Tracking, control and assessment of weight growth throughout the life of the ship is critical to assuring adequate Service Life Margin.[12]
Centre of Gravity (CoG)	The position and magnitude of the Vertical and Longitudinal Centres of Gravity (VCG and LCG) fundamentally influence the ship's stability and seakeeping characteristics. Accurate and effective control over these throughout the entire ship life cycle is critical in meeting many of the ship's core performance requirements.
Structural Strength	Allowances for Corrosion Margins are stipulated as part of broader global structural strength considerations to ensure that hull strength has not been eroded below an acceptable level, and thickness measurements should be routinely undertaken in service to support this. Guidelines issued by Classification Societies focus upon allowable diminution, noting that any nominal thicknesses should always be considered as the minimum as these form the basis for global strength calculations.[13]
Space	Bidding for space allocation is always undertaken early in the design cycle, and once it is exhausted, retrospective changes to the General Arrangement are time consuming, difficult and expensive. The most common types of Space tracked via the Margins process include compartment volume or deck area for capability upgrades, stores volumes and accommodation. Care is to be taken that if volumes are aggregated, the space is usable and not compromised by compartment geometry or protruding fittings.
Chilled Water	The Chilled Water system cooling capacity and associated Margins is critical to the platform's ability to support cooling for combat systems and habitability via the Heating, Ventilation and Air Conditioning (HVAC) system) throughout the life of the vessel. Monitoring of the overall magnitude and distribution of cooling load is key, along with the ability to meet required coolant flow rates through to end-of-life.
HVAC	Similar to the Chilled Water system, monitoring of cooling load (including wild heat[14] and heat transmission through ship structure[15]) by sub-system (typically broken down into Damage Control zones) and maximum air flow rates is key. Use of Margins to monitor required cooling air flow rates versus maximum capacity is also important.
Electrical Power	Electrical distribution system generation capacity, redundancy and functionality in normal and reversionary operating modes is critical to the platform's ability to fulfil its Mission System Requirements and support in-service growth and capability upgrades.
Environmental Management Systems	Environmental System capacity is vitally important to patrol endurance, particularly when operating in Special Areas as defined in MARPOL 73/78.[16] Attributes to be tracked include Black Water, Grey Water and Sullage storage capacities.

Table 2 – Platform Margin Categories

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[11] (Catton, 2022)
[12] (Pedatzur, 2016)
[13] (Lloyd's Register, January 2001)
[14] (UK Ministry of Defence, 2007)
[15] (International Standards Organisation, 2002)
[16] (International Maritime Organisation, 2019)

Warship designers and Navies are under increasing pressure to provide enhanced levels of automation and control that brings with it the associated benefits of enhanced remote and/or automatic modes of operation plus the potential to reduce personnel numbers. Hence, consideration should also be given to assigning Margins to systems such as the Platform Management System, including numbers of spare channels and server capacity.

From a Combat System perspective, the challenge is more acute, as weapon, sensor and communication systems life cycles are often shorter, and the corresponding rate of growth in infrastructure requirements can be significant. Assigning Margins to key systems (including attributes such as Combat System hardware and data handling capacity, or Communications system bandwidth) is also recommended.

3. Specific Considerations for Cooling and Power Margins

The main ethos behind Margins management during Acquisition and In-Service phases is to ensure that the platform remains fit-for-purpose, safe to operate, and can meet its Mission System Requirements. This needs to apply across the whole ship life cycle. Figure 2 illustrates many of the parameters to be considered.

Technology upgrade cycles for weapons, sensors, and communications are often shorter in duration than the equivalent for platform systems, so it is important that sufficient provision is made to cater for this, which can be challenging as it can be hard to quantify requirements for systems that haven’t yet been invented.

Margin monitoring can provide excellent metrics and key performance indicators to assess the platform’s overall ability to support warship capability through life. Accordingly, in addition to the guidance notes provided in Table 2 for Margin categories, the following considerations are offered for the engineering management of Cooling and Power Margins. Space and Weight will be covered in a later technical paper

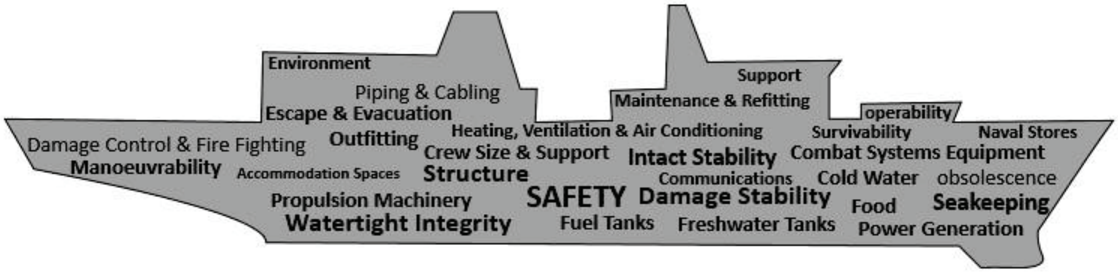

Figure 2: Gibbs and Cox Australia Warship Design Parameters and Requirements[17]

3.1 *Cooling Margins*

Cooling Margins are typically specified for the Chilled Water and HVAC systems, but can also be used for other key cooling systems as required. Examples include a Low-Pressure Sea Water (LPSW) system used to cool propulsion and/or auxiliary systems, or dedicated fresh water cooling systems utilised for the Phased Array Radar or Combat System consoles. For the purposes of this paper, Chilled Water system Margins will be used to illustrate the generic engineering management principles for Cooling systems.

3.1.1 *What Key Design Parameters should be Applied – Chilled Water System*

Chilled Water system cooling supports equipment serviceability (directly and indirectly) and personnel habitability (via the HVAC system). In a typical Surface Combatant, it would be commonplace to have a Chilled Water system design supplying reticulated coolant around the ship via a ring main, that can be reconfigured into smaller sub-systems for survivability and redundancy purposes in high threat states. The system would feature multiple Chilled Water Plants (CWP) and it is a generally accepted operating principal that the Chilled Water system must be capable of supplying the required maximum cooling load[18] with (N-1) CWPs with the Chilled Water system configured in a ring main whilst in cruising watches (N = No. of CWPs). A generic example of a typical Surface Combatant Chilled Water system schematic is illustrated in Figure 3:[19]

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[17] (Blackwood, 2021)

[18] (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2019)

[19] (UK Ministry of Defence, 2007)

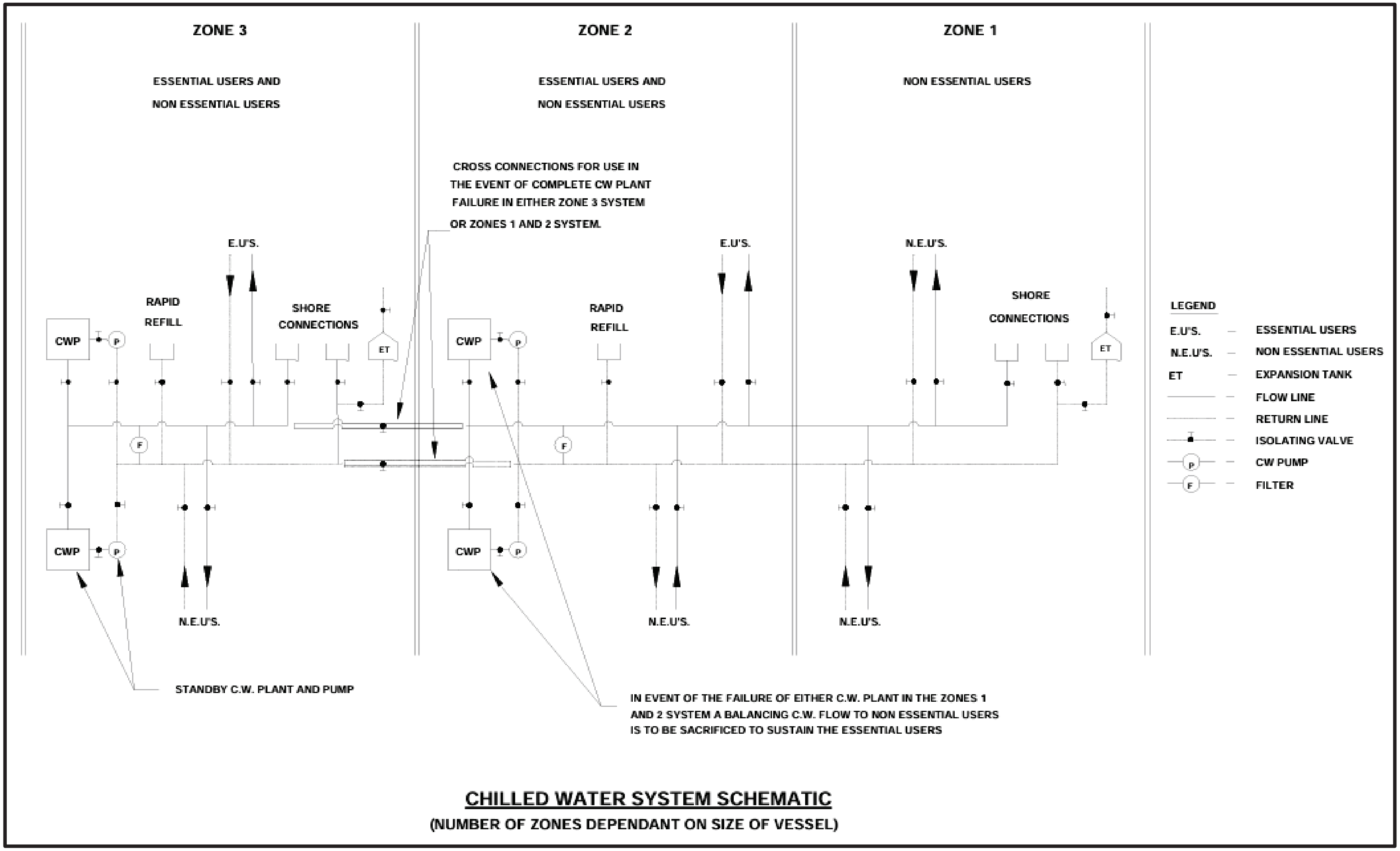

Figure 3: HMAS LANCLOVELY Chilled Water System Schematic

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Example 1 – Chilled Water System (N-1) Cooling Capacity

HMAS LANCLOVELY is the FoC vessel for the new County Class of Surface Combatants that have just been ordered for the Royal Australian Navy.

The Chilled Water system is configured in a ring main that supplies essential and non-essential users utilising a design methodology similar to that illustrated in Figure 3. It is supplied by 4 CWPs, each rated at 1,250 kW Cooling capacity at the maximum specified sea water temperature of 40˚C.

Whilst the ship is operating at Action Stations, for survivability purposes, the ring main is reconfigured into 4 quadrants, with each CWP supplying a quadrant each.

Total Cooling capacity = 4 x 1,250 = 5,000 kW

(N-1) Cooling capacity = 3 x 1,250 = 3,750 kW

3.1.2 Cooling Margin Determination – Chilled Water System

To assess and monitor the Chilled Water system Margins, the Gibbs and Cox Australia (GCA) Mechanical Auxiliaries team collated all the estimated direct-cooled equipment and HVAC cooling loads (these correspond to variables a1 and a2 in Example 2). A 15% Through-Life Growth Margin was then added to account for the physical inequities of in-service growth plus degradation in mechanical performance over time (this figure has been validated empirically over a number of warship design and build programs).[20]

For each of the individual equipment cooling loads, which is generally based upon data supplied from the original equipment manufacturer (OEM), a Design and Build Margin is applied. This is specified as a percentage of the equipment estimated cooling load (typically 15-20% initially) and this figure is gradually reduced over time to 0% as design maturity improves. The methodology for gradually reducing DBM over time is documented succinctly in the UK MAP 01-070.[21] Margin reductions can occur upon receipt of accurate equipment wild heat and/or load data from suppliers, and derivation of utilisation and diversification factors. A worked example of DBM percentages based upon design maturity used by GCA is presented below in Table 3:

DBM Code	DBM Percentage	Notes
00	20%	Equipment specification is preliminary, Wild Heat or Electrical load figures are rough estimates based upon similar installations.
01	16%	Equipment specification is immature, preliminary Wild Heat or Electrical load figures have been discussed with potential suppliers.
02	12%	Equipment specification is partially mature and broad equipment parameters have been agreed with suppliers. This should permit a greater degree of confidence in Wild Heat or Electrical load figures.*
03	8%	Equipment specification is mainly mature, Wild Heat or Electrical load figures are based upon OEM figures and procurement contracts have been placed, allowing these figures to be verified.
04	4%	Equipment specification is mature, Wild Heat or Electrical load figures are based upon OEM figures and the equipment has been integrated fully into the design.
05	0%	Equipment specification is fully mature, Wild Heat or Electrical load figures have been verified and documented within the Load Chart.

Table 3 – DBM Codes and Categories for Chilled Water and Electrical Systems

* DBM Code 02 (Margin = 12%, in Green) has been used in Example 2 (CW) and Example 4 (Electrical).

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[20] (DE&S SE Sea - Surface Ship Division, December 2007)

[21] (UK Ministry of Defence, 2009)

For future Capability upgrades throughout the nominal 25-year service life of the County Class, a nominal Capability Upgrade Margin of 150 kW is also applied as a contingency figure for potential future equipment installations of Directed Energy Weapons (based upon a nominal 500 kW Optical power rating).[22]

Deductions from the overall cooling load can also be made for direct solar gains (applicable to the upper deck and superstructure exposed to solar radiation that cover the entire width of the ship) whilst the sun is not directly overhead.[23] Research indicates that there is a degree of variance in the way these are applied and, consequently, these are not included in the example below.

Chilled Water flow rates are also important, and provision of sufficient spare capacity (typically 15-20%) is important to (a) ensure continued cooling performance through life and (b) accommodate future capability upgrades without having to remove other equipment to ensure sufficient coolant flow.[24]

It is also instructive to assess the Chilled Water system load on each of the 4 CWPs with the system configured into quadrants whilst the ship is in a high threat state, noting that the forward CW load is often greater due to the cumulative effect of direct-supplied cooling loads for the Operations Room complex.

An example of the overall Chilled Water system Margin calculated relatively early in the design phase is presented below, illustrating the practical quantification of the various Margin types.

Example 2 – Chilled Water System Margin

1)	Estimated Chilled Water system HVAC Cooling Load =	2,000 kW	(a1)
	Estimated Chilled Water system Direct-Cooled Load =	600 kW	(a2)
	Through-Life Growth Margin = 0.15 x (a1 + a2) =	390 kW	(b)
2)	Design and Build Margin (DBM Code 02) = 0.12 x (a1 + a2) =	310 kW	(c)
3)	Capability Upgrade Margin =	150 kW	(d)
4)	Total Cooling Load (inc. Margins) = (a1) + (a2) +(b) + (c) + (d) =	3,450 kW	(e)
5)	(N-1) cooling capacity = 3 x 1,250 =	3,750 kW	(f)
6)	Available Cooling Margin = (f) – (e) = 3,750 – 3,450 =	**+ 300 kW**	

3.1.3 *Cooling Margin Assessment – Chilled Water System*

In the example above, the GCA Mechanical Auxiliaries team have done a good job and have managed to maintain a small, positive Chilled Water system cooling Margin of +300 kW (+8.0% of the (N-1) Cooling capacity). This also includes a 12% Design and Build Margin of 310 kW (based upon DBM Code 02, Table 3), which will reduce further over time as design and equipment maturity improves, with the aim that the Cooling Margin remains in positive territory. This means that the Marine Engineers of HMAS LANCLOVELY are able to use the Chilled Water system whilst operating no more than 3 of the 4 CWPs in cruising watches. This helps to promote long-term equipment serviceability and enhance habitability.

This is important as it is often difficult and challenging from a technical and logistical perspective to keep all the CWPs serviceable whilst deployed away from base port for extended periods. If significant maintenance on the CWP refrigeration circuit or compressor is required, this often involves vacuum dehydration which is time consuming and protracted due to the large amount of refrigerant gas contained within CWPs.[25]

3.1.4 *Cooling Margin Management Strategy – Chilled Water System*

In this instance, the Chilled Water Margin appears relatively healthy, noting that the available Margin is positive and that further reductions in the Design and Build Margin (DBM) can be expected as the design matures. As a result, no significant increases in CWP capacity or Chilled Water flow rates are required.

Recommended strategy for Chilled Water loads and flow rates – Monitor noting that the overall Margin should improve incrementally as the DBM decreases over time (no active intervention required at this stage)

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[22] (Sayler, et al., 22 August 2023)

[23] (UK Ministry of Defence, 2007) and (Naval Sea Systems Command, n.d.)

[24] (UK Ministry of Defence, 2009)

[25] (Thomas, 2010), (TRANE, February 2021) and (NSC Ships Support Agency, July 1998)

3.2 Power Margins

For the purposes of this technical paper, coverage of Power Margins is applicable to the Electrical Generation and Distribution system. This article does not cover the determination of Propulsion Power Margins that would be undertaken early in the ship design process to determine Prime Mover installed power ratings.[26]

During the design phase, the initial focus is to select the balance of generating plant that produces and distributes the main generation voltage (if this is higher than 440V) plus the 440V AC Ship Services system. The analysis can also be extended to other sub-systems, including specialist supplies such as 440V, 400 Hz that may be required for weapon and/or sensor systems. Use of Margins to monitor and validate design assumptions is extremely useful and instructive to ensure there is adequate supply provision.

3.2.1 What Key Design Parameters should be Applied – Electrical Generation and Distribution System

In a typical Surface Combatant, the Electrical Distribution system would comprise four Diesel Generators (DG) located in a number of different compartments to enhance Combat Survivability. The system would be configured to supply two main switchboards, directly connected consumers (for example, Chilled Water Plants and the main Phased Array Radar), and Normal and Alternative supplies to the Electrical Distribution Centres located around the ship.

It is considered good practice that the Electrical Distribution system must be capable of supplying the maximum required electrical load with (N-1) DGs operational (N = No. of DGs), thereby enabling one DG to be under maintenance.[27] Whilst this may appear somewhat conservative, the continued growth in demand for installed electrical power attributable to the increased use of high power weapons and sensors shows no sign of abating, and justifies this approach.[28]

If the Propulsion design includes Electric Drive, which requires the DGs to supply electricity for Propulsion purposes as well (as per the indicative example illustrated in Figure 4), the (N-1) requirement is still valid but needs to factor in the maximum Propulsion and Ship Services electrical load. In addition, these loads may vary significantly between Tropical, Temperate and Cold environmental conditions.

As well as comparing the generating capacity and the load, it is also important to assess the distribution system's ability to cope with the sudden loss of one of the Switchboards (Partial Electrical Failure scenario), causing all of the load to be carried by one switchboard.[29] In the example system illustrated in Figure 4, a key metric in this scenario would be the capacity and available Margin for the Ship Services Transformer.[30]

Example 3 – Electrical Generation and Distribution System (N-1) Generation Capacity

HMAS LANCLOVELY's Electrical Distribution system is illustrated in Figure 4, and features 4 x DGs, used to supply Propulsion and Ship Services, each rated at 2.5 MW generating capacity.

Total Generating capacity = 4 x 2.5 MW = 10.0 MW

(N-1) Generating capacity = 3 x 2.5 MW = 7.5 MW

Rating of AC Electric Drive Propulsion Motors (x 2) = 2.2 MW

Maximum estimated 440V Ship Services load = 1.8 MW

Rating of Ship Services Transformers (x 2) = 1.5 MVA

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[26] (Lui, et al., 2022)
[27] (Directorate of Naval Engineering, 2015)
[28] (Defence Science and Technology Laboratory, October 2020) and (Hart, 12 Jan 2022).
[29] (Lloyd's Register, January 2024)
[30] (MOD(PE) Sea Systems, 1995)

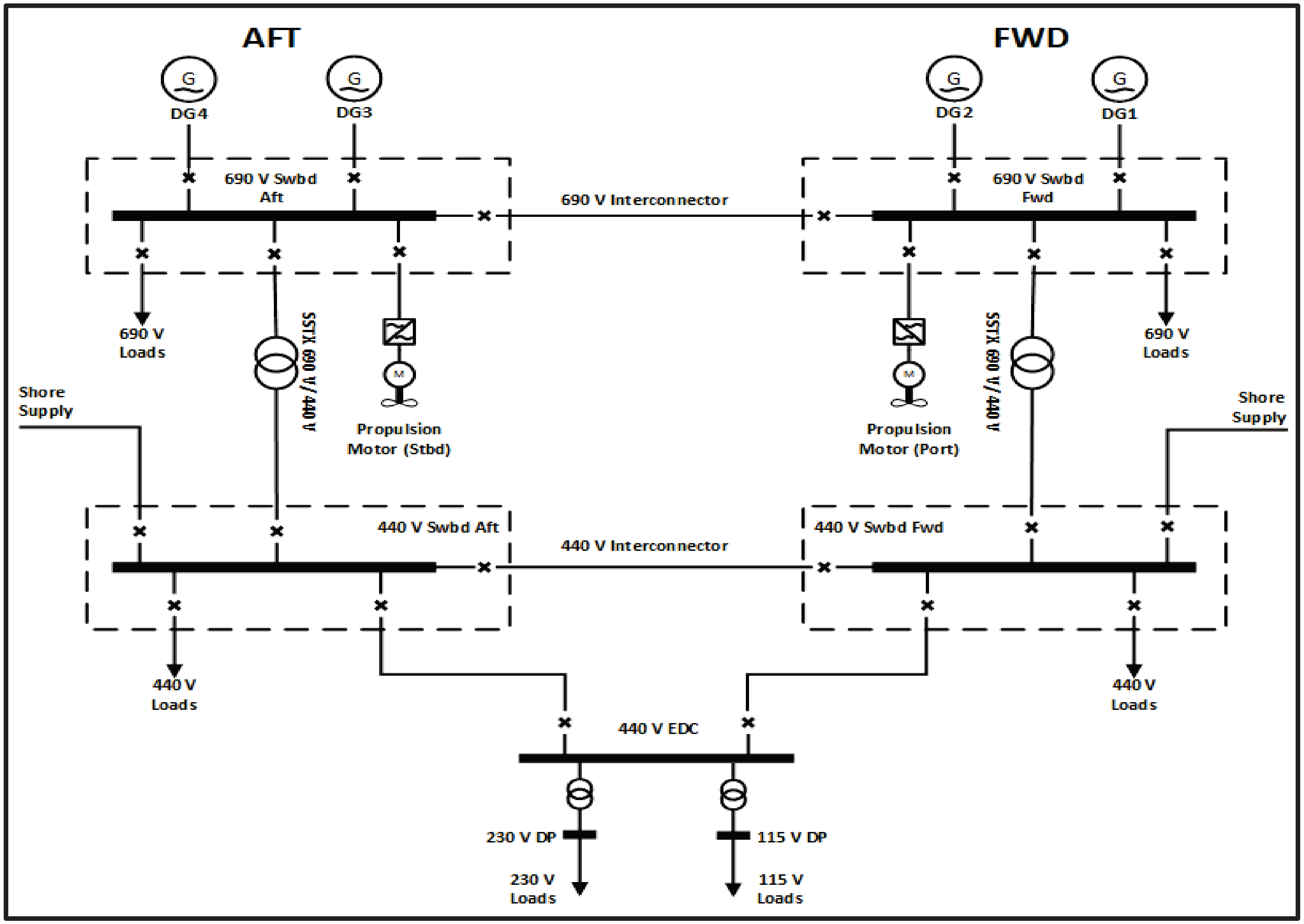

Figure 4: **HMAS LANCLOVELY Electrical Generation and Distribution System**[31]

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[31] (Fleisher, et al., 2022)

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3.2.2 Electrical Power Margin Determination

Following similar principals utilised for the Cooling Margins, the GCA Electrical team collated all the estimated Propulsion system and Ship Services loads (a1 and a2 in Example 4), and 15% Through-Life Growth Margin was then added to this total (this 15% figure is, again, based upon guidance in MAP 01-070.

For each of the individual system or equipment electrical loads (based upon OEM-supplied data), a Design and Build Margin is then applied. This is specified as a percentage of the estimated load (typically 15-20% initially) and this figure is gradually reduced over time to 0% as design maturity improves, updated equipment load data is obtained from suppliers, and accurate utilisation factors are derived. For Example 4 documented below, a DBM Margin of 12% has been used (Table 3 refers).

For future Capability upgrades throughout the estimated 25-year service life of the County Class, a nominal Capability Upgrade Margin of 0.4 MW is also applied as a contingency figure for potential future equipment installations, including systems such as Directed Energy Weapons (based upon a nominal 500 kW Optical power rating) and Combat System upgrades.[32]

As mentioned previously, the ability of a single SSTX to handle the maximum Ship Services load in the event of a Partial Electrical Failure scenario is key. For ships that have provision of electrical ride-through for seamless transition from Normal to Alternative supplies, and/or the capability to provide maintained supplies (to key systems such as the Combat system), allocating TLGM to the SSTX is advantageous.

In addition, monitoring the number of spare breakers in the Electrical Distribution Centres (EDCs), broken down into Essential, Non-Essential and Sheddable[33] sections is highly recommended. If required, this philosophy can also be applied to the capacity of cable glands and cable trays in key compartments such as Switchboards and EDCs.

Example 4 – Electrical Generation and Distribution System Margin

1) Estimated Propulsion Electrical Load = 4.4 MW (a1)
Estimated Ship Services Electrical Load = 1.8 MW (a2)

Through-Life Growth Margin = 0.15 x (a1 + a2) = 0.9 MW (b)

2) Design and Build Margin (DBM Code 02) = 0.12 x (a1 + a2) = 0.7 MW (c)

3) Capability Upgrade Margin = 0.4 MW (d)

4) Total Electrical Load (inc. Margins) = (a1) + (a2) +(b) + (c) + (d) = 8.2 MW (e)

5) (N-1) Generating capacity = 3 x 2.5 MW = 7.5 MW (f)

6) Available Electrical Margin = (f) – (e) = 7.5 – 8.2 = **- 0.7 MW**

3.2.3 Electrical Power Margin Assessment

This scenario is more complex than the previous Cooling Margin example due to the inclusion of Propulsion load as well as Ship Services load. The installed Generating capacity is 10.0 MW, the maximum estimated load is 8.2 MW, and this includes a DBM of 0.7 MW (which should reduce over time as design maturity improves). Historical precedent indicates that consideration should be given to the inherent maintenance burden of Diesel engines which puts a strong onus on adhering to (N-1) Generating capacity.

Warships featuring hybrid Electric Drive propulsion configurations are commonly designed such that the Electrical Distribution system default setting is to bias load priority to Ship Services in preference to Propulsion. The corollary of this is that for a constant Generating capacity, if the Ship Services load increases, the available power for Propulsion (and hence maximum ship speed in Electric Drive) decreases. This does not generally apply to warships with Integrated Full Electric Propulsion (IFEP) due to the typical mix of Generation plant including large Main Turbine Generators (MTG) combined with much smaller Auxiliary Turbine Generators (ATG).[34]

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[32] (Sayler, et al., 22 August 2023)

[33] (Butterfield & Szymanski, 2018)

[34] (Partridge, 2022)

The other Propulsion design factors that influence the tension between Electrical supply and demand are the maximum cruise speed and corresponding range. The cruise speed needs to be sufficient such that the ship can economically perform its roles in this Propulsion mode, but also ensure that the prime movers and fuel tanks required to achieve this can be spatially accommodated within the platform. When designing sprint Propulsion configurations, because speed is directly proportional to the cube of the power installed, there is a significant increase in fuel consumption for each extra knot of top speed (and a corresponding drop in range).[35]

The other major concern in this illustrative example is the capacity of each SSTX (rated at 1.5 MVA) compared to the maximum estimated Ship Services load of 1.8 MW. Irrespective of how much Margin may have been included in system design, in a fault situation where one Switchboard is lost, the SSTX fed from the unaffected Switchboard cannot handle the full load required by the 440V system as affected EDCs switch over to their alternative supplies. This could cause anything from unanticipated load shedding through to a Total Electrical Failure, and this is not a great outcome for a warship featuring Electric Drive. The obvious solution would be to increase the size of the SSTX, and this should have been picked up during the initial Design phase.

3.2.4 Electrical Power Margin Management Strategy

The Electrical system Margin is under duress (the Margin is - 0.7 MW which is -9% of the (N-1) Generating capacity). The size of the negative Margin compared to (N-1) Generating capacity is a key performance indicator and illustrates the scale of the issue. There are also issues with SSTX capacity, noting that they cannot handle the whole Ship Services load in the event of the loss of one of the Switchboards.

This is an artificial scenario but one that illustrates the potential severity of the issues if not dealt with early on during the design phase when fundamental choices are made regarding allocation of space, size of Main Machinery Spaces, and type and size of prime movers.

Recommended strategy for the Electrical Generation and Distribution System – fundamental redesign is required (including potentially increasing the capacity of the DGs and SSTXs, or reducing system load).

Figure 5: HMAS LANCLOVELY in Build

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[35] (Steele, 18-19 June 2024)

4. Summary

The paper describes the role of Margins within warship Acquisition and In-Service phases and documents an approach that can be taken to manage the risks associated with warship requirements setting, design, build and subsequent in-service changes. Margins assist in mitigating uncertainty in Acquisition, ensuring safety throughout the Service Life, and providing capacity for technology upgrades in an evolving threat environment.

Margin types (including DBM, CMM, ISGM/TLGM and CUM) are described, along with practical engineering management guidance as to how to interpret and apply these to technical categories (including Space, Weight, Power , Cooling, Environmental Management Systems and other attributes as required).

Specific worked examples based upon a hypothetical design for a County Class Surface Combatant (HMAS LANCLOVELY) were presented, to assist in demonstrating the utility of Margins as Metrics and Key Performance Indicators. For Cooling and Power, these were developed further based upon indicative system designs for Chilled Water, and Electrical Generation and Distribution.

The paper notes the type of Margins that are typically utilised during warship Acquisition and In-Service phases, as well as the Margin categories used. All of these can provide numerically based metrics that can be used to assess the enduring ability of the warships to meet its Mission System Requirements during the whole warship life cycle, including Design, transition to Production, and through to end-of-life.

5. Conclusions

It is concluded that continuous monitoring of key Margins provides a powerful management tool for enduring quality assurance of a warship's capabilities as it transitions from Design and Production into service.

For specific platform characteristics (including Cooling, Power, Weight and Space), some of the metrics lend themselves readily for use as Key Performance Indicators. Examples of these include adherence to (N-1) operating philosophy for Cooling and Power Margins.

The following specific observations and conclusions are presented for Cooling and Power Margins:

Cooling	Chilled Water Margins were analysed using a representative Chilled Water system design. HMAS LANCLOVELY's metrics highlighted the importance of adhering to an (N-1) operating philosophy, as well as ensuring sufficient provision is made for coolant flow rates for future weapon, sensor, and platform capability upgrades. Chilled Water Margins are critical to ensuring adequate Cooling for (a) weapons, sensors and communications, and (b) habitability. In the example presented, the design offered a positive Margin indicating that the design was fit for purpose and suitable to cope with the challenges of the warship's in-service phase.
Power	Electrical Power Margins were illustrated based upon the Electrical Generation and Distribution system for a CODLOG system design. For warships that keep Propulsion power separate from Ship Services, the importance of achieving (N-1) Generation capacity is evident. This also applies to hybrid systems such as the HMAS LANCLOVELY design that supplies Propulsion and Ship Services, noting this can be more challenging to achieve. This philosophy does not apply to IFEP warships due to the significant difference in installed power between large MTGs and smaller ATGs. The worked example and the negative Margin evident indicated the issues caused by a lack of adherence to the (N-1) philosophy, as well as the inadequate size of the SSTX which is challenging when dealing with system operation in reversionary modes. This example illustrates the benefits of using Margins to assist with analysing system capacity and any consequential operational shortfalls that may arise, particularly under fault conditions.

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References

American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2019. Chapter 14 Ships. In: *2019 ASHRAE Handbook - HVAC Applications.* Atlanta, GA: IHS Markit.

Blackwood, P., 2021. *Warship Survivability Knowledge Transfer Seminar.* Canberra: Gibbs and Cox Australia.

Bottero, M. & Gualeni, P., 2024. Systems Engineering for Naval Ship Design Evolution. *Journal of Marine Science and Engineering,* 12(210).

Butterfield, A. & Szymanski, J., 2018. *A Dictionary of Electronics and Electrical Engineering.* 5 ed. Oxford: Oxford University Press.

Button, R. W., Martin, B., Sollinger, J. M. & Tidwell, A., 2015. *Assessment of Surface Ship Maintenance Requirements,* Santa Monica, CA.: RAND Corporation.

Catton, L., 2022. *Nav Archs (You Gotta) Fight For Your Right (To Margins)!.* Canberra, Gibbs and Cox Australia.

DE&S SE Sea - Surface Ship Division, December 2007. *MAP 01-020 Warship Engineering Management Guide.* Bristol: Defence Equipment & Support.

Defence Science and Technology Laboratory, October 2020. *MOD Science and Technology Strategy 2020,* London: UK Ministry of Defence.

Directorate of Naval Engineering, 2008. *DEF(AUST) 5000 Volume 02 Part 29 (Margin Requirements).* Canberra: Royal Australian Navy.

Directorate of Naval Engineering, 2015. *Electrical Systems for RAN Combatant Ships and Submarines DEF(AUST)5000-Vol 05 Pt 08.* Canberra: Royal Australian Navy.

Directorate of Naval Engineering, 2023. *ANP 4801 - Development and Maintenance of Materiel Margins for Naval Capabilities,* Canberra: Royal Australian Navy.

Evans, J., 1959. Basic Design Concepts. *Journal of the Amercian Society of Naval Engineering,* Issue 71, pp. 671-678.

Fleisher, S., Crane, D., Mahmoud, T. & McKenzie, J., 2022. *Hunter Class Frigate Project – the Path to Designing and Building an Australian ASW Frigate.* Canberra, Gibbs and Cox Australia.

Hart, D., 12 Jan 2022. *DDG(X) Program,* Washington DC: Naval Sea Systems Command.

International Maritime Organisation, 2019. *International Convention for the Prevention of Pollution from Ships (MARPOL).* [Online]
Available at: https://www.imo.org/en/about/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx
[Accessed 07 May 2024].

International Standards Organisation, 2002. *ISO 7547:2002 (Ships and marine technology - Air-conditioning and ventilation of accommodation spaces - Design conditions and basis of calculations.* s.l.:s.n.

Lloyd's Register, January 2001. *Lloyd's Register Guidance Information - Naval Survey Guidance for Steel Ships - Chapter 11 Thickness Measurement - Section 2 Corrosion margins.* London: Lloyd's Register.

Lloyd's Register, January 2024. *Rules and Regulations for the Classification of Naval Ships - Volume 2 Machinery and Engineering Systems - Part 4 Propulsion Devices - Chapter 5 Electric Propulsion - Section 4 Electric propulsion systems.* London: Lloyd's Register.

Lui, S., Shang, B., Chen, H. & Papanikolaou, A., 2022. *A Fast and Transparent Method for Setting Powering Margins in Ship Design.* Hamburg, Germany, Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering OMAE 2022.

MOD(PE) Sea Systems, 1995. *Requirements for the Design of Electrical Supply and Distribution Systems in Surface Ships and Nuclear Submarines,* Bath: UK Ministry of Defence.

Naval Sea Systems Command, n.d. *Design Data Sheet DDS511-2, General Specifications for Building Naval Ships,* Carderock, MD: United States Navy.

NSC Ships Support Agency, July 1998. *BR 3007 Refrigeration Manual.* Bath: Ministry of Defence Naval Technical Publications Authority.

Papanikolaou, A., 2014. *Ship Design Methodologies of Preliminary Design.* New York: Springer Dordrecht Heidelberg.

Partridge, R., 2022. *Don't look back in anger: Lessons and enablers for 2nd generation Integrated Power Systems for warships.* Bristol, Rolls-Royce.

Pedatzur, O., 2016. Weight Design Margins in Naval Ships Design – A Rational Approach. *Naval Engineers Journal,* 128(2), pp. 57-64.

Sayler, K. M., O'Rourke, R. & Feickert, A., 22 August 2023. *Department of Defense Directed Energy Weapons: Background and Issues for Congress,* Washington, DC: Congressional Research Service.

Steele, B. A., 18-19 June 2024. *A Study into the Energy and Propulsion Systems of Modern Warships.* Adelaide, The Royal Institution of Naval Architects.

Thomas, V. C., 2010. *Chiller Plant Design.* [Online]
Available at: https://energy-models.com/chiller-plant-design
[Accessed 07 June 2024].
TRANE, February 2021. *Comprehensive Chilled-Water System Design,* Davidson, NC: TRANE Technologies.
UK Ministry of Defence, 2007. *Defence Standard 02-102 Part 1 Issue 3.* Glasgow: Defence Procurement Agency.
UK Ministry of Defence, 2009. *MAP 01-070 (Surface Ship and Submarine Margins Guidance Part 1).* Bristol: Sea Systems Group, Defence Equipment & Support.
Watson, D., 1998. *Practical Ship Design.* Volume 1 ed. Amsterdam, The Netherlands: Elsevier.

Glossary

Term	Description
AC	Alternating Current
ATG	Auxiliary Turbine Generator
CMM	Contract Modification Margin
CoA	Commonwealth of Australia
CODLOG	Combined Diesel Electric or Gas Turbine
CoG	Centre of Gravity
CUM	Capability Upgrade Margin
CW	Chilled Water
CWP	Chilled Water Plant
DBM	Design and Build Margin
DC&FF	Damage Control and Fire-Fighting
DEF(AUST)	Royal Australian Navy Defence Standard
Def Stan	UK Defence Standard
DEW	Directed Energy Weapon
DG	Diesel Generator
EDC	Electrical Distribution Centre
EM	Propulsion Electric Motor
EU	Chilled Water Essential Users
FoC	First of Class
HVAC	Heating Ventilation and Air Conditioning
IFEP	Integrated Full Electric Propulsion
IMO	International Maritime Organisation
IPMD	Initial Provision Made in Design
ISGM	In Service Growth Margin
Hz	Hertz
kW	Kilo Watt
LCG	Longitudinal Centre of Gravity
LPSW	Low Pressure Sea Water
MAP	UK MOD Maritime Acquisition Publication
MARPOL	Maritime Pollution Convention
MTG	Main Turbine Generator
MVA	Mega Volt Amps
MW	Mega Watt
NEU	Chilled Water Non-Essential Users
NSSG	Australian Department of Defence - Naval Shipbuilding and Sustainment Group
OEM	Original Equipment Manufacturer
PAR	Phased Array Radar
PMS	Platform Management System
RAN	Royal Australian Navy
SSTX	Ship Services Transformer
TLGM	Through Life Growth Margin
VCG	Vertical Centre of Gravity

A revised Operating Model for the Marine Engineering General Service to improve the lived experience of Surface Fleet Marine Engineers.

J F A Ellis, BEng

Synopsis

It has been seen in recent years that there is a chronic inability to retain Marine Engineers which in turn has led to critical gapping in surface units and the potential for the inability to deliver the operational imperative and safely operate warships at sea. The cause of this catastrophic failure is a melting pot of various shortcomings including regular programme instability coupled with the pressure to deliver power to command, battling with inadequate stores and overbearing administration all whilst covering for existing gapping within their unit. The result of this is that Marine Engineers are suffering "burnout" and seeing that the "grass is greener on the other side" leading to highly skilled personnel leaving the service which leads to a spiral and the future of the Marine Engineering General Service branch being uncertain.

There have been multiple attempts to improve the lived experience of Marine Engineers, but these solutions have been concentrated on treating the symptoms rather than the root cause of why Marine Engineers leave the service. The backbone of the revised operating model is to improve Support Solutions by enhancing the access to stores, tools and instructions; to better utilise the Time accessible to Marine Engineers to achieve preventive maintenance and effective training, and finally to bring more choice into the Career pipeline of RN Marine Engineers rather than forcing everyone into a "one size fits nobody" career that holds poor recognition and reward for being the highly skilled workforce that is required to facilitate the operational requirements of modern naval warfare.

This lack of recognition is a prime example of why many personnel make the decision to leave the RN at the LET and PO ranks where upon they can utilise the engineering skills and knowledge gifted to them by the RN to work in a civilian company for an increased salary doing much of the same work whilst not having the pressures of deployment or lack of stores support.

This paper will discuss the changes to the employment of Marine Engineers; the rationalisation of maintenance and the delegation to charge engineers in order to move away from a Navy that does not trust the monitoring systems available and loading unsustainable routines on watchkeepers, to a more efficient engineering workforce that is able to conduct greater preventative maintenance and deliver power to command within a sustainable timeframe.

Keywords: Optimisation, Sustainability, Maintenance Management, Lived Experience, Standards and Certification

1. Introduction

It is the Leading Engineering Technician (Marine Engineering) (LET(ME)) and Petty Officer Engineering Technician (Marine Engineering) (POET(ME)) that are the key focal points of the Marine Engineering General Service (MEGS) branch delivering the maintenance that underpins the seaworthiness and safety case of Royal Navy (RN) warships. With growing tensions across the globe and pressures to increase the availability of units, retention is vital to ensure the safe and efficient operation of platforms to deliver the operational outputs required. To successfully meet Defence Outputs there is a necessity for regular movement of personnel across platforms often leaving departments with critical gapping and an unsustainable workload. Tasks must be completed by other personnel within the unit in addition to their own terms of reference, leading to "Burnout" of our engineers. Burnout is further exacerbated by programme instability, overbearing maintenance administration and stores availability, therefore pressurising engineers to deliver maintenance with insufficient time. Lack of capacity reduces the ability to grow resilience across the department through effective onboard training, developing on the foundation qualifying courses, as such marine engineers are subject to a "one size fits nobody" ethos to training.

Planned maintenance is often of a lower priority to internal operational requirements or emergent defects. Time taken to complete other serials reduces the capacity for skilled engineers to proceed with preventative maintenance which should support a decrease in the likelihood of defects occurring. There is often seen to be an increased use of unsociable working hours to ensure the completion of maintenance and training required to safely operate the propulsion plant, leading to frustration and disparity between personnel onboard. With a necessity to maintain seagoing units at high readiness the majority of a unit's time alongside is conducting Fleet Time Support

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Periods (FTSP) or the rectification of Operational Defects (OPDEFs), therefore marine engineers are routinely remaining onboard to rectify defects and FTSP maintenance prior to immediately returning to sea.

Previous attempts to revitalise, rejuvenate and treat the MEGS retention crisis have been unable to fully deliver as they have not treated the systemic delivery and career problems, instead focussing on short term solutions to battle the workforce structures. To improve the lived experience of marine engineers a solution with two key themes has been envisioned: Career and Time. By improving the efficient usage of engineering time there is a reduction in the volume of daily work to better align the working hours of marine engineers to those of other departments leading to reduced fatigue. Coupled with this is the removal of overbearing Unit Maintenance Management System (UMMS) administration, to ensure consistent time for excellence in maintenance and operation. Furthermore, the ability to control the concession process for a greater number of maintenance tasks has been delegated to charge qualified engineering heads of department (HoDs), empowering seagoing engineers to make decisions as to these tasks with the ability to request guidance and direction from the Platform Chief Engineer and Platform Authority. In addition to improving the utilisation of engineering time, a revised career pipeline allows marine engineers the freedom to choose how far and how fast they progress their career, offering the ability to choose the amount of academic training they wish to conduct resulting in the opportunity to have a reduced amount of time at HMS SULTAN, instead delivering on operations.

2. Employment

The naval watch system has been utilised since the days of sail and yet it is found that engineers are being tasked to complete excessive work on top of this, which in turn leads to dissatisfaction. Currently personnel are to conduct watchkeeping duties of up to eight hours per day as well as section maintenance, divisional responsibilities, and career progression task books. Regular occurrences of marine engineers working excessive hours are noted on units. To this end the sea watch routines have been altered to a “West Country” routine leading to two “all nights in” per four-day watch cycle, as well as utilisation of the long first and long morning (6-hour watches vice 4 hours), allowing for the proper rest and recuperation that personnel require. The implementation team have had the opportunity to evaluate, alter and remove existing policy that has felt to be out of date or non-conducive to the lived experience of engineers onboard. All of this change is supported by a Command Charter that changes the thought process on a large number of traditional ideologies that have been conducted with the reasoning that “this is the way we’ve always done it”. Utilisation of the Command Charter where periods such as maintenance days are to be properly adhered to, as well as not always requiring equipment back online immediately but rather in accordance with the Command Aim. Additional timing for defect rectification enables the most experienced maintainer to conduct rectification and maintenance whilst not being taken away from guaranteed rest periods whilst also being able to take the time to instruct junior engineers how to operate, diagnose, repair, and maintain the equipment that they work with. This is essential in the development of junior engineers and the building of resilience across the department. By protecting forenoons through the reallocation of whole ship evolutions to later in the day, it has enabled engineers to conduct more extensive maintenance during the forenoon watch as they are no longer required to be drawn away from core maintenance tasks to complete whole ship evolutions. Thus, it is as if every day is a half maintenance day which exceeds the number of recommended days by one half day per week in accordance with Fleet Operating Orders (BRd 9424(1)). Feedback from Fleet Operational Standards and Training (FOST) noted that engineering standards on ships have vastly improved in a matter of short months as engineers now have greater time to conduct preventative maintenance, ships husbandry assigned to them and provide specialist advice to other departments conducting their own husbandry. This kind of maintenance and discussion with the unit’s command team enables engineers to Lock Off and Tag Out (LOTO) equipment, conduct the necessary diagnosis or repair to hopefully ensure that equipment remains in working order. Ultimately leading to a reduced number of Operational Defects (OPDEFs) and greater reliability in systems, lessening the risk of failure at key operational moments. Furthermore, all members of the marine engineering department now have increased capacity during the working day that can be utilised for structural preservation and husbandry of MMS, which previously would be subcontracted during a maintenance period or deprioritised to be conducted outside of the working day. Historically, due to the poor standards of ship’s husbandry across all departments, the care and protection of a platform was handed to external agencies for refit and upkeep periods in a poor state. This led to platforms taking longer to return to the fleet than originally expected or scheduled for and in some cases, it has not been financially viable to repair.

3. Training

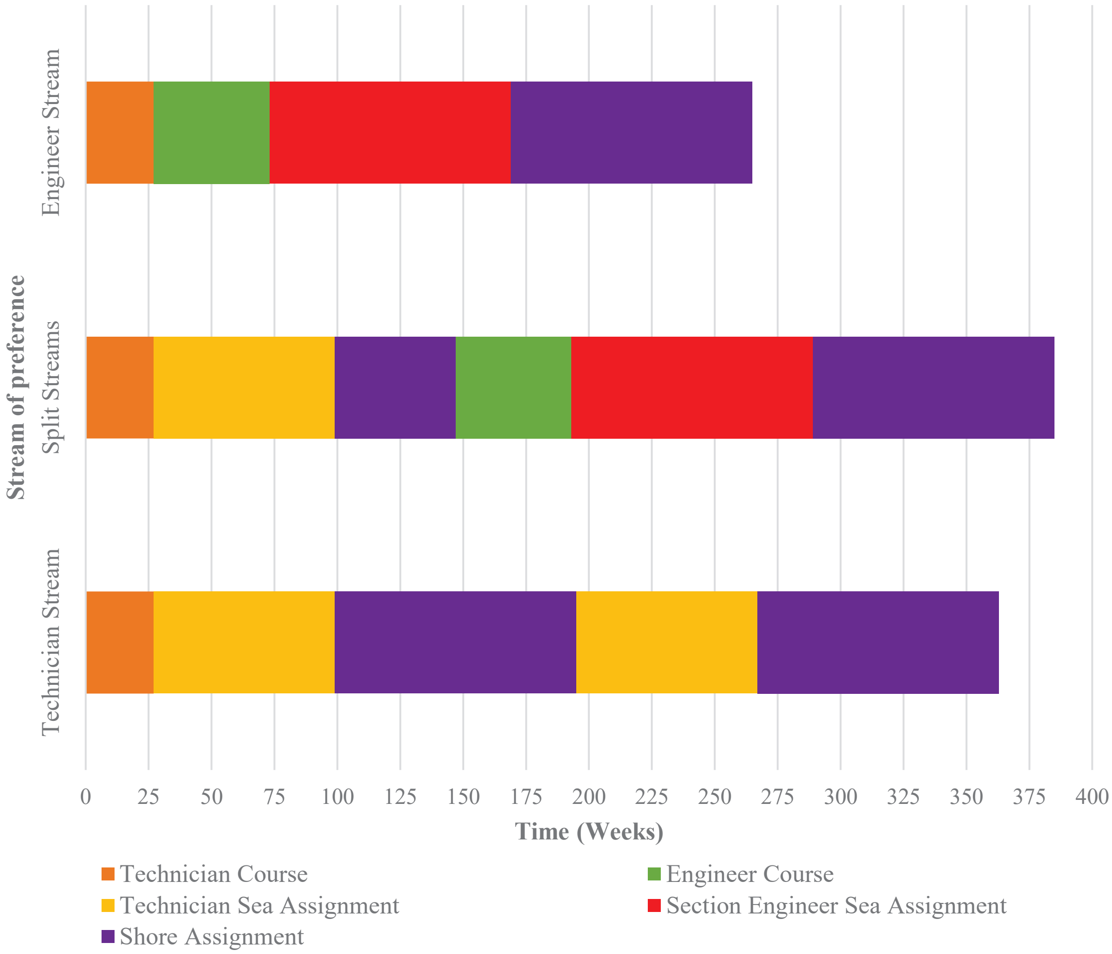

Figure 1: Indicative Career Progression of LET(ME) to POET(ME)

Under the revised Operating Model there is greater opportunity for marine engineers to choose how fast to progress in their career, enabling those who do not wish to progress through the rank hierarchy to remain in gainful engineering employment. Those who do not want to complete all technical and foundation degree modules still have the ability to promote to Warrant Officer. Marine engineers are no longer forced into extensive academic courses at HMS SULTAN, instead there is now an opportunity to offer personnel the choice to conduct higher rank qualifying courses (QC) by three different streams, as seen in Figure 1. The Engineer stream allows for personnel to conduct both Technician and Engineer streams of LET(ME) or POET(ME) QC in one endeavour before returning to operational units as a section engineer having fully completed specialisation training. The split stream allows for marine engineers to have a ‘journey person’s time’ developing experience through section support and conducting routine maintenance whilst on watch prior to returning to HMS SULTAN for the Engineer stream QC. Finally, the Technician stream is for those that do not wish to complete their foundation degree as part of POET(ME) QC or to stovepipe into one ME specialisation, instead supporting all sections during their shortened sea assignments yet still having the opportunity for promotion and gainful engineering shore employment. Technicians will be the key personnel who are trained as Marine Engineering Officers of the Watch (MEOOW) as the operators and supervisors of the propulsion plant; also conducting routine maintenance on watch, whereas section engineers will be conducting in-depth maintenance on equipment requiring greater technical knowledge delivered to them on the Engineer stream QCs. However, marine engineers are not restricted to follow one career path of either Technician or Engineer, instead having the ability to move between the streams so that there is an opportunity to choose as and when they conduct qualifying courses to support their personnel preferences.

4. Maintenance Management

As part of the revised operating model the intention was to reduce the amount of administration relating to maintenance by the removal of thousands of UMMS tasks. The criteria for removal being ME activity driven tasks, duplicate tasks, or those that fall under the remit of good engineering standards, such as “check for leaks” or “check earthing straps”, which are drilled into every marine engineer as soon as they start their first career course at HMS SULTAN. This removal of tasks has culminated in a reduction of up to 2633.45 hours of maintenance loading per month (dependant on class of ship), as seen in Figure 2, enabling marine engineers to conduct preventative maintenance as they are not burdened by the overwhelming number of UMMS tasks. Feedback from units that have implemented the new operating model have announced that engineers are feeling refreshed as they are now either required to conduct in depth technical maintenance and OPDEF rectification or, if they are fulfilling a technician position, they are watchkeeping and conducting routine maintenance, not both. Furthermore, by reducing the UMMS tasks that are required to be completed whether that be by the removal, reallocation or grouping of tasks has heavily reduced the number of hours that personnel must be at a computer terminal undertaking the administration of task completion, reduction in total administration clicks is in excess of 5,000 leading to a minimum of 48.83 maintenance hours saved monthly as seen in Figure 3. These hours can then be utilised by personnel for preventative maintenance, divisional responsibilities, personal and career development or rest and recuperation.

Class of Ship	Number of Tasks Removed	Monthly Loading Reduction (Hours)
QEC	198	2146.67
T45	278	1753.45
T23	196	1346.84
Hunt	188	2633.45

Figure 2: UMMS Tasks removed.

Class of Ship	Total Admin Clicks Saved	Total UMMS Access Hours Saved
QEC	10,312	71.00
T45	5,528	48.83
T23	15,048	98.17
Hunt	6,568	56.58

Figure 3: UMMS Admin Burden Reductions per month.

With operational requirements increasing in tempo, and despite OPDEFs being categorised with a respective repair timeline, engineers often strive to repair these systems as soon as possible at the detriment of their own well-being. Furthermore, due to the demand for equipment to be brought to full operational capability at its earliest opportunity there is often seen to be little to no time allocated for the onboard development and training in the equipment. Reluctancy to conduct diagnosis or repair on equipment that does not fall within personnels specific remit instead relying on part of ship or the Original Equipment Manufacturer (OEM). This management of OPDEF rectification expectations has been addressed in the implementation of the Command Charter, encouraging Operational Commanders of Warships and their schedulers to have a better understanding of defect ramifications, the time required for the diagnosis and repair and the importance of engineering training to provide excellence in OMDR and sustainable organic resilience. Through the changing of mindsets and ideologies about maintenance management and OPDEF rectification, coupled with the sharing of knowledge across the department there will be an increased likelihood for marine engineers to be less inclined to label themselves exclusively through their training. Instead focussing on a whole department approach so that defects are able to be diagnosed and repaired by anyone from the department no matter which trade they have specialised. Direction and guidance from SURFLOT Engineering is that no equipment is ‘untouchable’ and only to be maintained by the OEM, in turn encouraging engineers to conduct intrusive diagnosis and repair during the uninterrupted forenoon watch. If equipment is already Locked Off Tagged Out and out of action then the outcome of repair attempts by an RN engineer will not be detrimental to the operational capability of the unit, no matter the outcome. However, by this same engineer having greater time to conduct an initial attempt at reparation may bring equipment to a usable state or conduct detailed diagnostics that can be supplied to the OEM reduces the length of time whilst alongside for this equipment to remain out of action. If personnel are less reluctant to 'type cast' themselves to one specialisation but rather encouraging a wider engineering knowledge and prowess, it improves the likelihood of personnel having the freedom and capability to transfer between platforms and classes of ship throughout their career. This choice can improve satisfaction of Marine Engineers as they are now able to choose their career progression rather than having it chosen for them.

5. Maintenance Delegation

In the existing operating model, tasks must be completed by their due date else ship's staff would have to raise a formal concession as to the reasons why this maintenance was not conducted. Under the new operating model, tasks are not required to be concessed if ship's staff are unable to complete tasks by the 'Due' date, but rather there is now an 'Overdue' approval limit in accordance with Figure 4 (BRd 1313). Engineers now have greater capability to plan maintenance around ships' operations and programmes to ensure deconfliction from activities such as FOST Directed Readiness Training where all personnel will be required for training evolutions. The 'Overdue' approval limit grants seagoing engineers the capacity to move maintenance later in their programme to account for unforeseen events such as priority OPDEFs, lack of or incorrect stores and immediate programme changes that are frequent in the schedule of an operational warship, so long as the risk has been mitigated. Flexibility in maintenance management enables Operational Commanders the opportunity to retain their units at sea thus increasing availability of ships. To prevent complacency and poor engineering management UMMS databases are regulated and monitored by assurance agencies, such as FOST, ensuring that maintenance tasks are not being left for completion at the 'Overdue' date on regular occurrences without sound justification.

Defined Periodicity	Delegated 'Overdue' approval limit
1 Month or Less	Date of next scheduled occurrence
Up to 6 Months	1 calendar month past Due
Up to 12 Months	2 calendar months past Due
Up to 24 Months	3 calendar months past Due
24 Months or More	4 calendar months past Due
Non-Calendar based triggers (elapsed time, rounds fired, etc.)	10% past Due (rounded up to the nearest full unit of measurement)

Figure 4: 'Due/Overdue' Approval Limit

As part of the revised MEGS OP Model, Engineering HoDs that have passed their necessary charge qualifications, whether that be marine or weapons, are being formally delegated the authority to concess Category A (ship staff conducted and overseen) maintenance of both Safety and Environmental as well as Operational tasks in accordance with Figure 5 (BR1313). Authority has been formally delegated to unit Marine Engineer Officers (MEOs) and Weapon Engineer Officers (WEOs) by the Platform Authority working from Defence Engineering & Support (DE&S) Abbey Wood. By offering the Engineering HoDs the ability to concess Category A maintenance, ships have a far greater ability to react to ever changing command aims and taskings they are directed to. Under the old model a concession would take anything up to thirty-five working days to be processed by the team of personnel in DE&S. Through the delegation from the Platform Authority, it enables charge qualified engineering HoDs to decide whether equipment remains safe to operate whereas their civilian counterparts may never have been onboard an RN warship and have minimal operational experience or knowledge as to the implications of the equipment. Furthermore, as the engineering HoD is onboard they are able to witness the operation and estimate the risk of failure as well as the implications that it will have on operational capability if this equipment is removed from command whether by failure or by LOTO.

Task Category	SE	OP	Non-OP
FHA and PVR Product concessions	PA*	-	-

Cat A	PA*	Platform Charge Engineer	UMMS Manager
Cat A1	Platform Charge Engineer	Platform Charge Engineer	UMMS Manager
Cat A2	PA*	Platform Charge Engineer	UMMS Manager
Cat A3	PA*	Platform Charge Engineer	UMMS Manager
Cat A4	PA*	Platform Charge Engineer	UMMS Manager
Cat B	PA	PA**	PA**
Cat B1	PA	PA**	PA**
Cat B2	PA	PA**	PA**
Cat B3	PA*	Platform Charge Engineer	UMMS Manager
Cat C	PA	PA**	PA**

Notes

* The PA may, in writing, formally delegate these approvals to the Platform Charge Engineer.

** The PA may, in writing, formally delegate these approvals to a duly authorised, individual within the waterfront support organisation. The individual may then be added to the PA's UMMS Approver Group allowing them to approve concessions within the UMMS application.

Figure 5: UMMS Maintenance Concession Approvals

Also, the MEO has the power to concess Flexible Hose Assembly (FHA) and Pressure Vessel Register (PVR) product concessions, once again reducing the administration from collection of eleven signatures to only one, being the MEO. This removes the necessity to contact the Equipment Authority (EA) who may not be of immediate assistance due to different working hours especially when a unit is deployed and in a different time zone or operating outside of office working hours. This opportunity allows for MEOs to conduct diagnosis and a risk assessment of the likelihood of failure and risk to life and operations.

6. Conclusions

The revised MEGS Operating Model has aimed to improve the lived experience of marine engineers through two key themes: Time and Career. Improved utilisation of time has been conducted by the normalisation of the volume of work required by personnel to conduct and the removal of the requirement for personnel to conduct watchkeeping and section maintenance. Career opportunity and freedom has been at the forefront in the development of revised career streaming, offering marine engineers' choice as to the quantity and duration of the academic training they conduct.

These two pillars are supported by the Command Charter and the repackaging of UMMS tasks, which will ensure that there is sufficient timing for engineering personnel to conduct intrusive diagnosis and repair whilst imparting knowledge and guidance to junior engineers. In turn this will increase the organic resilience of the department as more personnel are utilising their experience and knowledge across all engineering problems. Consistent time for preventative maintenance, repair and diagnosis will aid in the early identification and rectification of defects thus increasing the availability and operational capacity of units.

The delegation of the ability to concess category A maintenance and FHA and PVR product concessions empowers the platform charge engineers to carry out their duties as professionally charged qualified engineers whilst also reducing the UMMS administration. The ability for engineers to plan maintenance around ships programme remains in force, however through the use of the due/overdue function there is now greater ability to dynamically react to immediate programme changes, supply chain issues or emergent priority defects.

Through the implementation of these initiatives, it is assessed that the MEGS branch will start to recover as personnel should encounter burnout less frequently with an improved lived experience. This in turn delivers the ultimate aim of retaining professionally competent Marine Engineers that are capable of the delivery and operation of a safe, efficient, and deadly navy.

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References

Fleet Operating Orders BRd 9424 Volume 1. pp 124. Edition: January 2022.
Maintenance Management in Surface Warships BR 1313 Chap 1 pp 5, Chap 9 pp 9. Edition: February 2024

Should Royal Navy Ships Designed for Optional Crewing Only Enable Humans to Survive, or Also Enable Them to Thrive?

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Synopsis

Humans have crewed ships for thousands of years. Over that time, ship design has evolved to incorporate the requirements that humans need to survive. Whilst many see uncrewed systems as the future, it is likely there will be a period of transition utilising optionally crewed vessels. This provides time for quantitative reliability assessments of autonomous systems to be conducted using real world operating statistics. There is also then the option to alternate between crewed and uncrewed operations - in military applications, optionally crewed vessels pose a significant advantage over crewed vessels: continued operation whilst removing the crew from harm's way may mean the difference between life and death.

One benefit of a fully autonomous vessel is the minimal requirement for the vessel to support human habitability, enabling savings on space and cost throughout the design and build phases of the vessel's life, with less systems to maintain in service. However, optionally crewed vessels by definition are required to support human habitability. This presents a critical decision point: does the design of an optionally crewed vessel include basic habitability functions only, or does it incorporate all the functions required for humans to both survive and thrive onboard? For civilian vessels, the intended use case will be specific and therefore go some way to defining this, but for a Royal Navy ship it is likely that the use case will be wide-ranging and varied, and may change during the life of the vessel.

This paper will address the question "should Royal Navy ships designed for optional crewing only enable humans to survive, or also enable them to thrive". It will take the commonly recognised requirements for humans to survive and thrive; consider the form their enablers may take when incorporated into a Naval vessel, and reflect on the human advantages and disadvantages of their inclusion or omission, in scenarios where the Royal Navy may utilise optionally crewed vessels.

Although the Royal Navy's decision on when optionally crewed vessels are to be crewed or uncrewed cannot be pre-determined, it is expected that any vessel required to support human habitability for more than a short period of time will enable humans to thrive, as well as survive.

Keywords: Optional Crewing; Human Requirements; Survive or Thrive; Naval Ship Design

1. Introduction

In the 5000 years since the Ancient World first purpose-built ships for battle (Reilly, Guilmartin, Friedman, Scheina, & Eller, 2024) there have been numerous advances in technology that have dramatically altered the conduct of naval operations: steam powered and iron clad ships; the advent of aircraft carriers; and the use of nuclear technology for power and deterrence are notable, recent examples. In the 21st Century, that shift centres on the use of autonomous vessels to facilitate and conduct naval operations. The IMO (International Maritime Organization) defines four degrees of autonomy (International Maritime Organisation: Maritime Safety Committee, 2021):

- Degree 1 – Ship with automated processes and decision support.
- Degree 2 – Remotely controlled ship with seafarers on board.
- Degree 3 – Remotely controlled ship without seafarers on board.
- Degree 4 – Fully autonomous ships.

For a ship designed for or with autonomous capabilities, no material or technical changes may be required to go from Degree 2 to Degree 3 or 4, it would be a case of whether there is a crew on board. Where the switch between crewed and autonomous can be so easily achieved, it may be tempting for those designing and procuring naval ships to opt for a ship that supports only the basic habitability functions of a crew who will not be there the whole time, lowering the initial and through life costs. However, humans are designed to do more than survive – they are designed to thrive, and yearn to do so once their basic needs are met. Navies globally are looking towards optionally crewed assets (Eckstein, 2018) (Garman, 2024). This paper aims to explore whether Royal Navy ships designed for optional crewing should enable humans to survive, or to survive and thrive, and for the latter why they should do so when there are measurable benefits to designing for survive only.

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Despite much debate on the quantifiable aspect of the theory, the most widely recognised analysis of human requirements remains that developed by Maslow, and commonly dubbed Maslow's Hierarchy of Needs. This has been the topic of thousands of scientific papers, and provide the basis for a substantial number of other psychological theories. As such, this paper will use Maslow's Needs as the definition of what humans need to survive or thrive.

2. Method Definitions

2.1 Maslow's Basic Needs

In his original 1943 paper, Abraham Maslow sought to establish a framework from which the factors that motivate humans could be defined and explored. Maslow identified five 'basic needs' that humans work to satisfy (Maslow, 2017). These have been expanded and modified (particularly the esteem and self-actualisation needs) by many psychologists in the years since original publication (Guy-Evans & Mcleod, 2024), but for brevity the original five areas will be considered here. These were split into two distinct sections: deficiency needs (survive) and growth needs (thrive) (Guy-Evans & Mcleod, 2024).

2.1.1 Survive

Physiological needs form the most basic requirement to sustain human life, and include air, food, water, warmth, and rest – without providing these, a ship would be unable to support human habitation. As such, the physiological needs will not be considered further.

Safety is defined as 'not in danger or at risk', and also as 'protected from danger or harm' (Cambridge University Press and Assessment, 2024). Whilst this is most obviously apparent in physical safety and security, it can also encompass the psychological aspects such as job security and workplace culture. Although safety is a deficiency need, psychological safety is an area often forgotten. Consequently, it will be considered alongside the growth needs here – its ease of being overlooked means that it may not be considered as a key requirement when designing a vessel.

2.1.2 Thrive

The growth need is belongingness and love, which includes relationships, friendships, and human interaction, with belonging defined as 'a feeling of being happy or comfortable as part of a particular group' (Cambridge University Press and Assessment, 2024). Key to this is the link to safety - humans are naturally group creatures, one person alone will struggle to feel like they belong to a group.

Esteem is one's pride in themselves, their team, and their organisation, as well as how they are viewed by others – 'respect for or good opinion of someone' (Cambridge University Press and Assessment, 2024). For someone to feel esteemed there needs to be a sense of purpose and accomplishment to the job or activities being conducted, such as contributing to a greater cause. A secondary consideration of esteem is self-confidence, how an individual feels about themselves directly impacts their pride.

The final tier to be considered is self-actualisation – 'to achieve and be everything they possibly can' (Cambridge University Press and Assessment, 2024). This includes learning, knowing, religious beliefs, and creative activities, and incorporates what many would consider to be pursuits outside of the workplace, but are also things recognised as being vital for our mental health, often incorporating interaction with other people.

2.2 Concepts of Use (CONUSE)

The intended use of a vessel will dictate the percentage of time a crew are likely to be embarked for, which will in turn drive whether the vessel is designed for 'survive' or 'survive and thrive'. There are numerous combinations of local actors, environmental nuances and operational sensitivities that will dictate how and if optionally crewed vessels are utilised in a theatre. For the purposes of this paper, the below concepts of use will be used. The periodicity of the embarkation is based on a monthly aggregate of the weekly night limit for Service personnel to be entitled to Substitute Single Service Accommodation (SSSA), 4 nights each week (Ministry of Defence, 2023).

- CONUSE 1 – A vessel forward deployed, with the crew primarily embarked but are removed when the threat level reaches a given threshold. The time spent embarked is upwards of 16 days out of a month.
- CONUSE 2 – A vessel deployed on defence engagement, initially autonomous (e.g. for transit) and the crew are then embarked to complete specific tasks. The time spent embarked is between 5 and 16 days of a month.

- CONUSE 3 – A vessel deployed on environmental monitoring, with the crew only embarked for periodic maintenance. The time spent embarked is less than 5 days in a month.

3. Survive or Thrive

3.1 Enablers

3.1.1 Safety

When considering physical safety, the ship itself should not introduce risk to personnel. Crewed and autonomous vessels are certificated as appropriate for their class (Lloyds Register, n.d.) (Unknown, 2023), and it would be reasonable to assume that this would be the same for an optionally crewed vessel. As such, the ship itself would not endanger those on board. However, the certification of a Royal Navy vessel also considers its CONUSE, and the theatre in which it will be employed. If a ship is to be considered sacrificial (as in CONUSE 1), the question as to whether it is certificated for crewed operation in a hostile environment needs to be addressed. This will drive the risk appetite for the point of removal of the crew, as well as some fundamental design aspects and the equipment requirements of the vessel.

It is commonly accepted that a Royal Navy vessel may operate in a location where there is a level of danger or risk to the crew from external actors. However, this is dependent on the intended theatre, risk appetite, and whether the vessel is considered sacrificial – whilst it may not be reasonable due to the CONUSE of the vessel to incorporate the same level of threat detection and weapons systems as a crewed platform, a similar level of security could be provided through operation within a task group or another asset that provides detection and defence.

The majority of the psychological safety and security enablers of personnel on a ship are addressed by attitude and culture of both the ship and the organisation. However, there are aspects that can be incorporated to make individuals more comfortable. Soundproofed areas for making phone calls and discussing sensitive topics ensure that individuals have privacy, and can serve both a personal and operational purpose. Providing individuals with their own space to spend time in and personalise, no matter how small, allows that individual to create a sense of home within an alien environment – a place to call home brings an air of psychological safety, as well as somewhere to unwind when the day has been tough, thus facilitating an improved mindset and mental health.

3.1.2 Belongingness and Love

For those deployed on a vessel away from home, the primary enabler for belongingness and love is the ability to connect and communicate with those at home. There are several methods by which this can be achieved: post, voice calling, and internet connectivity (video calls and emails). The ability to receive post can be arranged without impacting the design of the vessel, and as such will not be considered further here. For voice calling, including phones with the ability to ‘dial out’ in all accommodation spaces would give personnel much greater ability to contact home, as well as providing the vessel with the ability to restrict those communications if required by the operating environment.

Having the ability to be able to video call loved ones is becoming the norm for anyone working away from home, but relies on internet connectivity with sufficient capacity. Access to the internet would also grant the use of online learning and resources for self-actualisation, and access to wider assistance for fault rectification from an operational viewpoint. There are numerous providers of systems that will work globally and in remote locations, though it is acknowledged that providing connectivity through a third party brings security challenges.

Another facet of belongingness is human interaction in the workplace – being able to speak with someone at a deeper technical, tactical, or strategic level than someone at home or outside the immediate scenario is reassuring and fulfilling, satisfying both the psychological safety and self-actualisation aspects of the hierarchy. Humans are naturally herd creatures and do not like being alone – our instincts tell us that it is safer to be in a group, even if that group is small. Ensuring there a multiple people on board the vessel satisfies this: the Royal Navy should not be considering optionally crewed vessels with only one person on board. A crew of multiple personnel also drives the culture of a Ship’s Company, working together to achieve tasks and outputs, and socialising when away from work – belonging.

3.1.3 Esteem

Esteem, much like the psychological safety, is primarily driven by the attitudes and cultures of the organisation, and other’s opinions of one another. The Royal Navy must ensure that the crew of an optionally crewed vessel still feel valued and are serving a purpose by being there. Whilst attitude, culture and opinion cannot be built into a vessel directly, building in aspects that make personnel feel valued and considered will significantly improve their esteem – these aspects are the thrive elements of the hierarchy.

Additionally, the Royal Navy should ensure that the ability to optionally crew the vessel does not render the crew under-employed when embarked. Having facilities on board that cannot be accomplished by a machine, for example a galley, decision making or approval, and maintenance activity, ensure that the crew feel a purpose for being there, and a sense of accomplishment and professional satisfaction when a task is completed.

3.1.4 Self-Actualisation

Crewed vessels naturally accumulate some of the enablers for self-actualisation over time, regardless of whether the design incorporated them, as the crew are permanent residents. This includes designated spaces to practise religious beliefs, small libraries, collections of musical instruments, and gym equipment and exercise spaces. The inclusion of these enablers post build on crewed vessels is a strong indicator that humans want access to these facilities whilst on board, and designing spaces in from the start will ensure they are in suitable locations.

Esteem and self-actualisation can be both found through career and professional development, which whilst not things that can be directly built into a vessel, are enabled by access to material to learn or study from, or by the ability to attend conferences and courses. This also incorporates self-learning, such as studying part time for a degree.

Considering the physical aspects of the enablers listed above only, they are themselves enabled primarily through designated, appropriate spaces or internet connectivity. Both can be incorporated during the design of the vessel. Although not necessarily a design feature, the Royal Navy could provide an allocation of money towards the vessel during its initial concept and build, to ensure that the spaces, resources and equipment to facilitate self-actualisation are furnished and ready to use as soon as there is a crew on board, as opposed to the crew accumulating them over time, or purchasing them through ship’s funds and other sources once in service.

As mentioned in belongingness and love, there are additional security considerations surrounding internet access. However, a system that has been procured and approved through a recognised route; incorporates the ‘Secure by Design’ philosophy (gov.uk, 2024), and can have access controlled by the chain of command for operationally sensitive theatres or scenarios is feasible for ship-wide incorporation. Alongside the design and electronic safeguards, a good security culture is key to facilitating widespread use of internet connectivity on board. It is noted that there are some areas of the Royal Navy where the option for internet connectivity whilst deployed will never be within the risk appetite due to the security implications.

3.2 Concepts of Use

3.2.1 CONUSE 1

This is the closest CONUSE to the current Royal Navy operating model with crewed vessels, and there are distinct similarities between a permanently crewed vessel, and one whereby the crew are onboard for a considerable proportion of their time. Humans want to thrive, as indicated by the accumulation and addition of enablers for self-actualisation, and belonginess and love, over the life cycle of a crewed vessel. From a human requirements viewpoint, provision should be made for an optionally crewed vessel as detailed in CONUSE 1, for the crew to thrive.

However, an advantage of an optionally crewed vessel is the ability to operate it autonomously; in CONUSE 1 the crew are removed at a certain risk level, implying that the vessel is sacrificial. Whilst the risk to life far outweighs the equipment risk, the Royal Navy must address the psychological safety of the crew if judging a ship to be sacrificial. When someone spends the majority of their life on the vessel, they have personal effects on board, a routine, and a schedule or plan of when to return home. Knowing that all could be destroyed with minimal notice because the ship is deemed sacrificial does not make a person feel safe or secure in the environment.

Additionally, can those making the decision to evacuate the crew guarantee the correct moment to do so? If the chosen point is too late on a vessel designed to be sacrificial, there will undoubtedly be fatalities. To ensure all personnel remain safe, the Royal Navy would need to have unquestionable faith in the intelligence used to determine that evacuation point, a metric by which to determine its validity, and a margin of safety to guarantee that the evacuation point meant survival. If the crew doubted the integrity of the data driving the decision that kept them alive, they would not be in a psychologically safe or secure state.

In this scenario, the vessel could enable the crew to thrive, without ever enabling them to truly survive.

3.2.2 CONUSE 2

This CONUSE draws comparison with personnel who stay at their place of work for a couple of nights a week, such as those in the military who commute. A military base has some enablers of thrive, such as a gym and internet connectivity, but the transient nature means many individuals do not personalise their space. Although it is not as psychologically comfortable, it is a pragmatic balance of survive and thrive. A vessel whereby the crew are on board for an extended period, but not necessarily on a permanent basis, should enable personnel to thrive, though it would be acceptable for there to be a reduction in the level of facilities and enablers compared to CONUSE 1 due to the shorter time periods of embarkation.

When considering which facilities should be drawn down on in the compromise of survive or thrive, consideration should be given to retaining the communal spaces such as the gyms and recreational spaces within accommodation areas – these encourage team ethos, which directly contributes to esteem and belongingness and love.

3.2.3 CONUSE 3

Akin to visiting a location for a short course, when the crew are onboard for a minimal number of days there is little requirement for the vessel to enable them to thrive. The crew are transient, and the vessel is little more than a staging facility for them to be able to carry out their task. As the vessel in this CONUSE would primarily be designed to be operated autonomously, there would be greater utilisation of the space and weight margins to provide redundancy in the systems than in the facilities for the crew to thrive.

It should be considered though, that where facilities are provided aspects of the task or operation, such as internet connectivity for fault diagnosis by maintainers when on board, whether these facilities could be easily modified to enable some aspects of thrive.

3.2.4 Tasking Consideration

Current Royal Navy vessels are exceptionally flexible in terms of their tasking, demonstrating repeatedly over their lifespan their versatility in being able to alter between counter-piracy, humanitarian aid, task group support and defence engagement. Whilst having a vessel that can be adapted relatively easily to meet a new task has its advantages, there is a cost associated with this, both financially and in the size of the vessel. These changes often do not affect the thrive enablers on the vessel, and the impact to the crew is on a programmatic front rather than a facilities one.

When designing an optionally crewed vessel, it is apparent that whether the vessel enables its crew to survive or to survive and thrive is dependent on the length of time spent on board, which in turn is driven by the CONUSE of the vessel. It is therefore critical that optionally crewed vessels are designed for a specific CONUSE, with a review of the facilities on board the vessel conducted if the CONUSE changes. Whilst the base vessel will be less flexible in terms of the tasking that can be achieved, there are savings to be made by not having equipment competing for space on the same platform to provide it the ability to conduct multiple tasks without refit, and may also allow for a more targeted employment of personnel on those vessels.

Navies are considering the use of modular vessels, payloads and equipment for a more cost effective but still quick change of use (Unknown, 2021) (Unknown, n.d.) (Smidt & Junge, 2014), an idea which is supported by industry concepts (Thomas, 2023) (DAMEN Naval, n.d.). Modularity can also be incorporated into optionally crewed vessels, provided the time spent on board by the crew was common across the CONUSE of the different modules.

3.3 Should Thrive Be Enabled?

There are disadvantages to including the enablers listed above into the design of optionally crewed vessels. By incorporating dedicated thrive enablers on board the vessel, there may be less space available for systems and payloads, or the vessel may be required to be larger to accommodate the additional requirements.

There is a cost increase with regards to personnel too – having more systems, facilities and designated spaces on the vessels will likely require an increase in, and potentially more specialist, personnel. An uplift in crew size to facilitate this will cost more in both wages and training overheads, and spirals into needing more facilities on board the vessel to ensure there is sufficient supply. There are also the security considerations with regards to internet connectivity, as discussed within self-actualisation.

However, the advantages to enabling the crew of an optionally crewed vessel to thrive far outweigh the disadvantages. This is reflective of other areas of industry – there have been significant numbers of papers written on the motivation of employees.

All the enablers lead to a more satisfied individual. Such individuals are likely to be more motivated, therefore perform better in the workplace and have a more positive attitude towards work. This positive attitude and sense of accomplishment from performing well set the culture required for esteem and psychological safety. Personnel who are both comfortable with their surroundings and performing at their peak will provide a greater output or quality of output, thus the Royal Navy will get a better service from them.

The crew will feel valued if the organisation enables their satisfaction and considers it from the start, as opposed to including it as an afterthought, which will encourage people to work for the aims and goals of the organisation – this again provides the Royal Navy with a better service. Additionally, these people will experience a higher job satisfaction, encouraging them to remain in the Royal Navy rather than looking at civilian jobs.

Retention of skilled, experienced personnel reduces the training burden on the organisation, alongside providing a natural training and supervisory capacity. By retaining more personnel, there is greater capacity in the system for personnel to explore and take advantages of the other opportunities available within the Royal Navy, such as adventurous training, Service sport, and part time education – this all feeds into self-actualisation. A workforce of motivated employees who enjoy their job will also reap rewards in recruitment – it is much more pleasant proposition to be recruited into an organisation with a satisfied workforce who are keen to see the goals of the organisation met than the opposite. In an ever competitive employment market, and with skilled personnel being more in demand, harder to recruit and more costly to train (Unknown, 2024), can the Royal Navy justify not investing in giving its personnel the opportunity to thrive when the benefits are clear and self-sustaining?

4. Conclusion

From the CONUSEs considered within this paper, it is apparent that there is no one answer to whether Royal Navy ships designed for optional crewing should only enable humans to survive, or also enable them to thrive. The length and percentage of time personnel are embarked for is the primary factor, which is wholly dependent on the planned use of the vessel.

Where the crew spends most of its time embarked, there is no doubt that the advantages of allowing them to thrive outweigh the disadvantages. If the crew are onboard for a minimal amount of time, including the enablers for them to thrive is unlikely to merit the associated reduction in redundancy or increase in size of the vessel. For the CONUSEs between, there is a balance to strike, but when a crew that is thriving leads to a more motivated, satisfied and organisationally focussed workforce, to tip that balance towards thrive is unlikely to yield negative results.

Additionally, it is likely that some of the systems required to operate optionally crewed vessels when the crew are disembarked will themselves provide opportunity to incorporate enablers. Many aspects of the design, function and regulation of vessels operated autonomously rely on continuous communications and data feeds, which may not be so heavily relied upon when the crew are embarked. When the systems have capacity, they could be utilised to enable the crew to thrive.

It is also clear that optionally crewed vessels will need to be used more exclusively than their crewed counterparts. Although this may seem negative as a reduction in flexibility, when applied correctly this can be a positive – a ship designed for a specific area of work will carry less ancillary equipment, so may be of a smaller and more cost-effective design. It may open a broader ship building market, increasing competition in the sector, whilst also providing more targeted employment of personnel who develop deeper specialisms, benefitting the Royal Navy and the ship building and design industries.

The biggest challenge for the Royal Navy with optional crewing lies within attitude and culture – when a vessel can be operated autonomously, how do they make the crew feel valued and purposeful? This becomes even more vital than on a crewed vessel; enabling them to thrive goes a long way to making personnel feel valued, but further research is required into the most appropriate theatres and uses of optionally crewed vessels to ensure Royal Navy personnel continue to feel purposeful.

References

Cambridge University Press and Assessment. (2024). *belonging*. Retrieved from Cambridge Dictionary: https://dictionary.cambridge.org/dictionary/english/belonging

Cambridge University Press and Assessment. (2024). *esteem*. Retrieved from Cambridge Dictionary: https://dictionary.cambridge.org/dictionary/english/esteem

Cambridge University Press and Assessment. (2024). *safety*. Retrieved from Cambridge Dictionary: https://dictionary.cambridge.org/dictionary/english/safety

Cambridge University Press and Assessment. (2024). *self-actualization*. Retrieved from Cambridge Dictionary: https://dictionary.cambridge.org/dictionary/english/self-actualization?q=self-actualisation

DAMEN Naval. (n.d.). *Crossovers*. Retrieved from DAMEN: https://www.damen.com/vessels/defence-and-security/crossovers?view=models

Eckstein, M. (2018, June 25). *Navy to Field 'Optionally Unmanned' Vessels to Supplement Future Surface Combatant*. Retrieved from USNI News: https://news.usni.org/2018/06/25/navy-looking-at-optionally-unmanned-vessel-to-supplement-future-surface-combatant-program

Garman, L. (2024, February 20). *'Optionally crewed' vessels provide VLS firepower for Tier 1 combatants*. Retrieved from Defence Connect: https://www.defenceconnect.com.au/naval/13647-tier-1-combatants-to-include-optionally-crewed-vessels

gov.uk. (2024, March 25). *Secure by Design*. Retrieved from security.gov.uk: https://www.security.gov.uk/guidance/secure-by-design/

Guy-Evans, O., & Mcleod, S. (2024, January 24). *Maslow's Hierarchy of Needs*. Retrieved from Simply Psychology: https://www.simplypsychology.org/maslow.html?ez_vid=2cae626a2fe896279da43d587baa3eb663083817#The-expanded-hierarchy-of-needs

International Maritime Organisation: Maritime Safety Committee. (2021). *OUTCOME OF THE REGULATORY SCOPING EXERCISE FOR THE USE OF MARITIME AUTONOMOUS SURFACE SHIPS (MASS).* London: International Maritime Organisation. Retrieved from https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/MSC.1-Circ.1638%20-%20Outcome%20Of%20The%20Regulatory%20Scoping%20ExerciseFor%20The%20Use%20Of%20Maritime%20Autonomous%20Surface%20Ships...%20(Secretariat).pdf

Lloyds Register. (n.d.). *Rules and Regulations for the Classification of Naval Ships*. Retrieved from Lloyds Register: https://www.lr.org/en/knowledge/lloyds-register-rules/rules-and-regulations-for-the-classification-of-naval-ships/

Maslow, A. H. (2017). *A Theory of Human Motivation.* Dancing Unicorn.

Ministry of Defence. (2023). 8 Substitute Service Single Accommodation. In M. o. Defence, *JSP 464 Tri-Service Accommodation Regulations Volume 2: Single Living Accommodation and Substitute Service Single Accommodation Part 1: Directive* (pp. 8-5). Retrieved from gov.uk.

Reilly, J. C., Guilmartin, J. F., Friedman, N., Scheina, R., & Eller, E. M. (2024, JAnuary 1). *warship*. Retrieved from Britannica: https://www.britannica.com/technology/naval-ship

Smidt, M., & Junge, M. (2014). A Modular Warship for 2025. *Proceedings*. Retrieved from https://www.usni.org/magazines/proceedings/2014/january/modular-warship-2025

Thomas, R. (2023, September 11). *Kongsberg eyes modular warship market with new mission bay handing system*. Retrieved from Naval Technology: https://www.naval-technology.com/news/kongsberg-eyes-modular-warship-market-with-new-mission-bay-handing-system/?cf-view

Unknown. (2021, October 8). *Thinking inside the box – the Royal Navy's containerised capability concept*. Retrieved from Navy Lookout: https://www.navylookout.com/thinking-inside-the-box-the-royal-navys-containerised-capability-concept/

Unknown. (2023, Feb 21). *BAE Autonomous RIB awarded LR Unmanned Marine Systems Certification*. Retrieved from Lloyds Register: https://www.lr.org/en/knowledge/press-room/press-listing/press-release/bae-autonomous-rib-awarded-lr-ums-certification/

Unknown. (2024, May 10). *Diminishing strength of the Royal Fleet Auxiliary undermines the Royal Navy's global reach*. Retrieved from Navy Lookout: https://www.navylookout.com/diminishing-strength-of-the-royal-fleet-auxiliary-undermines-the-royal-navys-global-reach/

Unknown. (n.d.). *Modular Warships: Pioneering the Future of Maritime Defence*. Retrieved from Cubedin: https://cubedin.com/news/modular-warships-pioneering-the-future-of-maritime-defence

Glossary of Terms

CONUSE	Concept of Use
IMO	International Maritime Organization
RN	Royal Navy
SSSA	Substitute Single Service Accommodation

‘Alternative Fuels’ or ‘Koolaid’?: Maintaining Focus and Perspective When Considering Options for Future Naval Fuels

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Synopsis

INEC 24’s core theme is ‘lean, mean and green’ navies, embracing the concept of reduced carbon emissions through new fuels. Literature abounds with shallow claims that navies must comply with IMO edicts or otherwise demonstrate ‘net zero’ performance. This is misleading, as legitimate as claiming that navies need do nothing. Navies adopting new fuels need navigate a sensible course, and avoid replicating the naïve, largely unconditional adoption of MARPOL regulations in the 1990s, a legacy saddling many navies with unnecessary regulatory burdens offering minimal environment protection while emasculating capability. Selection of future fuels must be based upon engineering evaluations, but reliance upon technical assessments in isolation would be inadequate. Effective, focused and technically literate naval engineering policy must always form the bedrock underpinning naval engineering deliberations, including for considerations pertaining to new fuels.

Warships, and the navies that operate them, exist for one fundamental reason – to fight and win at sea. There is no virtue in being ‘cleaner and greener’ if the fight is lost. No government will thank their navy for losing a ship and crew while doing so with lower carbon intensity than the adversary. This is an inviolable, and for some perhaps inconvenient, truth.

Amid societal expectations and the pursuit of ‘net zero’, in concert with an anticipated decline in diesel availability, navies must, in time, consider alternatives, preferably where there is parallel operational advantage. Fuels suitable for commercial use can be inappropriate for military applications. Realisation of the diminishing ubiquity of diesel should be the primary driver inducing navies to consider alternative fuels; any intent specifically related to emissions reductions should be subordinate, and any perceived benefit or temptation for ‘virtue signalling’ should not dictate the calculus. Whether naval transition is undertaken in an objective, informed manner, or in a less orderly and dysfunctional way in response to externalities may determine navies’ operational effectiveness and logistical overheads for decades to come. Navies are now at or approaching that threshold of decision, as warships currently in design are those that will be built into the 2040s and 2050s. Powertrains and energy sources are clearly a critical consideration for warship design. In the absence of any evident replacement for diesel, most navies are compelled to reply upon current fuels for new designs, or else significantly modify or prematurely decommission extant and nascent ship classes.

Technical assessments need to be bounded within objective engineering policy frameworks, in-turn linked to capability intents. Any ‘opportunities’ for alternative fuels adoption that may present as technically feasible must be rigorously evaluated in terms of the unique and exacting naval requirements. ‘Net zero’ does not mean ‘zero’, and the span of the ‘net’ need not be limited to fleet units. This gives opportunity and licence to develop innovative means of reducing carbon emissions while maintaining superior naval capability.

This paper explores how effective navy engineering policy can improve carbon efficiencies while safeguarding naval capability. Any quest for ‘net zero’ must be about what a navy needs to do, not what it could. Engineering policy must be in the vanguard of navies’ pursuits of alternative fuels, so that any aspired ‘green’ future does not render a navy as an ‘inconsequential and vanilla’ outfit rather than a ‘formidable and responsible’ maritime force.

Keywords: ‘net zero’; fuels; alternative fuels; IMO/environmental compliance; capability; navy mission; naval engineering policy

1. Proceed with caution: ‘Lean, mean and green’ or ‘fighting fit and fit to fight’?

> *I want to lead a Navy that ...... is a ready, agile, resilient and lethal fighting force .... that stands ready to execute our mission to ‘Fight and Win at Sea’.*
>
> (Noonan 2018)

Navies exist for one fundamental reason – to fight and win at sea! All else is secondary or peripheral. The maritime fighting service that fails to ‘think like a fighting navy’ (Noonan 2018) will significantly compromise its likelihood of success against the only metric that really matters if and when the need arises.

INEC 2024’s ‘lean, mean and green’ theme should be considered with reference to a navy’s purpose:

Author’s Biography

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> 'Lean' has merit, especially if resources do not match needs. 'Lean', not malnourished, is valid if it is an indicator of efficient and effective resource use in the realisation of maritime capability, as and when directed by government.
>
> A 'mean navy' is likely to be one to give pause to nascent adversaries, capable of controlled and targeted aggression when necessary and as directed.
>
> …….. but a 'green navy'! This concept borders on woolly-headed thinking and a dislocation from any serious navy's mission. It may be indicative of an organisation overly focused on social credentials and manifestation of a zeitgeist, embodying insouciant aspirations that would evaporate rapidly when lethality and survivability matter more than aggregate emissions. 'Environmentally responsible' certainly – but 'green' aspiration as anything but a lower order priority is a distraction and largely inimical to mission.

From oars and sail, to coal and steam through to diesels and gas turbines, the historic arc of naval propulsion and energy sources has invariably been one where new technologies generate improved performance and reliability and enhanced warfighting capabilities. The emerging paradigm of 'low' or 'no net' carbon risks being one where the step into the new realm may be retrograde!

No responsible navy should step blindly into alternative fuels, with all their implications, besotted or distracted by some desire to reduce carbon emissions, a singular focus upon peacetime taskings and diplomatic subtleties, or overwhelmed by ill-informed external forces insistent on change while heedless of the consequences for the navy mission, its ships and the men and women who serve in them. History suggests this sort of outcome is not only plausible but should be expected in some quarters, where understanding of core mission has been blurred, if not lost, in the seductive fog of competing, ill-conceived distractions diluting what naval forces really need to exist for. This 'pull' needs to be countered and whatever 'alternative fuels' potentially adopted, with their concomitant ramifications for naval designs and operations, should at least maintain, and preferably improve, capability. Navigating this complex maelstrom requires corporate fortitude abetted by robust naval engineering policy.

Naval engineering policy is about getting mission ready ships at the right place at the right time. A panoply of other factors and endeavours underlie that outcome, but naval engineering is an indivisible and pivotal element. By extension, engineering policy frameworks and processes need be precisely aligned with the central naval mission of fighting and winning at sea. These themes – not strictly of 'alternative fuels' and 'net zero', *per se*, but of how they need be considered and evaluated and the parallel realities – are the subject of this paper.

2. The legacy of heedless adoption of merchant ship marine environment protection rules and practices

The international community, chiefly via the International Maritime Organization (IMO), recognises the myriad threats to the environment from shipping. Accordingly, the IMO has introduced controls on multiple aspects of ship design and operation, spanning the life spectrum from design to disposal. These regulations, as reflected in parallel national legislation and classification society rules, are in constant flux, as the IMO deals with emerging marine environment protection (MEP) priorities or exploits evolving technologies. Most of these rules occur within the *International Convention for the Prevention of Pollution From Ships* (MARPOL), with parallel conventions dealing with allied matters, such as anti-fouling paints and ballast water. The IMO, as per its charter, does not regulate warships.

In its original 1973 iteration MARPOL concentrated upon oil pollution, expanding by the 1990s to also include, *inter alia*, regulations for garbage and later sewage. Thus, in the first part of the 1990s the only substantive intersection of MARPOL with warships could be distilled as ships needed an oily water separator and the disposal to sea of plastic was prohibited. All simple to understand and to abide – at that time. It was within this context that most navies first developed pollution prevention and 'MARPOL compliance' policies, signalling the intent to observe MARPOL regulations. For example, the first formal Royal Australian Navy (RAN) ship waste management policy, promulgated in 1994, committed the RAN to:

> *…. comply …. unless operational capability will be significantly compromised. These … require that ship operators meet international maritime* (environmental) *regulations at all times.*
>
> (RAN 1994)

This 1994 policy is reflective of just about any other contemporary navy. From these 'humble', unadorned and expedient 1990s undertakings to observe 'MARPOL' not much has changed in the policy arena, either in the context of stated compliance aspirations or in guidance related to the nuance of ' *…. unless operational capability will be significantly compromised ……* ' and the employment of those caveats. While naval policies have remained static, the span, depth and complexity of IMO MEP edicts have expanded exponentially, compounded by their accelerated rate of change. Yet, navy policies have not matured in concert with the IMO's deliberations and obstinately and naïvely remain largely wedded to the anachronistic and simplistic concept of 'full compliance'. United Kingdom policy, for instance, commits the Royal Navy (RN) as follows:

The default position is that within the UK we comply with all applicable ... environmental legislation.

(UK MoD 2024)

The sub-text of this edict is that the subject navy is bound to comply even if the potential or perceived 'risk' to the environment associated with any particular aspect of commercial ship design or operation is irrelevant to warships or compromises design and operational imperatives. In essence, these standard policy precepts commit navies to complying with commercial ship regulations, rather than protecting the environment.

These compliance commitments are largely unreserved in practice and thus at variance with the IMO's own expectations. All IMO environment conventions expressly exempt warships and naval auxiliaries, but rather seek consistency albeit only to the extent resonant with warship imperatives. MARPOL states:

> *The present Convention shall not apply to any warship, naval auxiliary ..... and used .... only on government non-commercial service. However, each Party shall ensure by the adoption of appropriate measures not impairing the operations or operational capabilities .... that such ships act in a manner consistent, so far as is reasonable and practicable, with the present Convention.*

This language is replicated in all other IMO environment conventions. While navies may volunteer to comply, or may be compelled by their governments to do so, warship compliance is not a given and was never intended.

Initial undertakings to 'comply with MARPOL' stemming from the halcyon archetype of observation essentially by the simple expedient of keeping plastic garbage separate have now morphed into a far more intrusive and demanding set of compromises. This historical legacy still saddles many navies with avoidable regulatory burdens emasculating capability while often, ironically, offering minimal protection to the environment. Examples abound of penalties where it may be considered that hubris exceeds practicable outcomes when balancing environment protection with warship exigencies. The chronicles of navy attempts to 'fully comply with MARPOL' are replete with ill-conceived excursions into ship design and fit:

- Protected fuel tanks: Rules formulated upon merchant ship designs and operations and subsequent inherent risks of oil fuel release in the event of merchant ship collisions and groundings have been shoehorned into warships. This is despite combatant warships not embodying the risk factors intended to be countered by the intricate IMO design rules, but which the advent of results in warships designed with different tank systems and/or reduced capacity – veritable 'frankentanks'. This is a patent example of 'engineering the rule' rather than engineering the risk. These modified designs generally require warships to refuel or conduct tank transfers more regularly - ironically the main reasons why warships lose fuel to the marine environment. Thus, application of a rule not intended for warships, inappropriately addressing an item of minimal risk, amplifies risks to the environment, in parallel with compromising operational effectiveness. This is an irredeemably perverse outcome (Polglaze 2018), arrived at under the banner of 'full compliance'.
- NO_x Tier III emissions systems: The most valuable commodity in a surface combatant is top weight margin. Sensors, weapons, countermeasures and other key elements of the combat suite are invariably mounted at or above main deck level. It is these systems that ensure a warship is lethal and can survive. Anything which occupies top weight or compromises its utility without contributing to combat capability disproportionately detracts from effectiveness. This very space is where standard NO_x Tier III emission control systems, weighing tens of tonnes for frigate-sized ships, must be located. As a result, designers are forced to forego inclusion of sensors and weapons, and top weight reserves which could be conserved for capability upgrades are sacrificed in the pursuit of inconsequential NO_x reductions. Some surface combatants have squandered top weight margin in preference to NO_x systems only rarely and intermittently used, yet the loss of combat capability is persistent.

The observation of MEP regulations is not always incompatible with warships, but in some cases strict adherence is discordant with a warship's *raison d'être*. This compels navies to evolve agile, nuanced, risk-informed approaches, applying lateral thinking presaging innovative, fit-for-purpose solutions. Much of the current debate surrounding alternative naval fuels is naive, ill-informed, poorly defined, ambiguously framed, and unjustifiably optimistic. This does not augur well that the past mistakes in futile pursuit of 'full compliance' will not be repeated. Examples given above provide salutary lessons about the folly of unfettered, myopic and dogmatic warship compliance. Smart navies, the ones that 'think like fighting navies', will avoid repeating these mistakes when considering energy efficiency options and alternative fuels.

3. 'What fuel?': Pivotal and fundamental naval engineering policy precepts

We will see a lot more disruptive solutions .... and .... we need to accommodate the challenge of green fuels, ... some are toxic, some are explosive, some take up more space, all of which will change design a lot too.

Einar Vegsund, Kongsberg Maritime (in McClellan 2024)

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Diesel has established itself as the standard naval fuel for good reasons. Realistically, however, it is not going to be available indefinitely in the manner and price range to which navies have become accustomed. Evolving technical and logistical factors mean that it is incumbent upon navies to consider how they intend to respond to this emerging shift in availability and utility. Rather than any simple technical questions or carbon-intensity assessments, however, the response to the anticipated supply constraints needs to consider a wide spectrum of factors, each of which needs to be anchored in the 'why' and 'what for' of a nation's navy. To this end, it is instructive to consider why diesel has become the ubiquitous naval fuel. This may be summarised as: availability, affordability, stability, transferability, storability, reliability, predictability, flexibility, low volatility, practicality, effectuality, and commonality.

Energy efficiencies and emissions reduction opportunities extend beyond the ambit of fuels alone, with avenues existing to realise efficiency gains by means other than novel fuels. IMO precepts include:

- clean hulls;
- proceeding by the most direct, optimal routes;
- proceeding at (constant) most economical speed;
- mandated maximum speeds; and
- installed engines with minimum power reserves.

Merchant ships have predictable and stable operating profiles: load, sail, steam at *x* knots for *y* hours, go alongside, unload (and refuel/plug in!); turn around; repeat: this poses a different set of requirements for merchant ship energy sources in comparison with warships. The commercial shipping world is assessing, testing and trialling at varying levels of technical maturity a range of technologies and energy sources in the quest for low emissions. These include, variously, hydrogen, ammonia, LNG, methane, electrification, 'hull lubrication', sails and on-board carbon capture systems. Some of these may offer potential for collateral operational advantages for warships, in terms of improved thermal or radiated underwater noise signatures, or simplified maintenance and logistics. Overall, it is difficult to reconcile the IMO energy efficiency construct with warship requirements. It is not suggested that warships should not optimise energy use, as doing so will enhance endurance, but any intent of adherence to IMO energy efficiency rules as an objective in itself is a futile proposition and a damaging distraction.

Whether alternative fuels may be suitable for warship application can only be determined when measured against criteria unique to or accentuated in the case of warships. These attributes encompass:

- Good energy density
- Flexible in application across engine types
- Employ manageable and maintainable machinery
- Effective over a range of environmental conditions
- Low volatility
- Low toxicity
- Affordable
- Available
- Able to be transported, stockpiled and transferred in bulk
- Suitable for rapid replenishment, including between ships at sea
- Not require extensive upperdeck allocations

Actual 'greenhouse' efficiency of any diesel replacement must be properly balanced with these attributes. Although consideration of alternative fuels may have a technical nucleus, deliberations must be leavened by considerations broader than those nested in climate change responses. They need to consider consequences for ship mobility, lethality, survivability, supportability, utility and flexibility, as well as fuel affordability and availability. Such evaluations and the decisions which stem from them must be founded upon disciplined application of objectives and the policy and doctrinal frameworks which coalesce and express these. This ultimately translates to getting the policy settings right, and given its inherent technical character, questions of alternative fuels and all that may go with them should primarily be distilled, harmonised and reconciled through the articulated prism of naval engineering policy, not navy environment policy.

4. 'Net zero' does not mean 'zero'

> *Net zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period.*
>
> (IPCC 2018: 535)

Beyond the platitudes and clichés, little is rudimentary in the 'net zero' sphere. Even the concept of any purported 'net zero' solution is typically contestable, if not controversial, once 'whole of life', 'scope two and scope three emissions', second and third order implications, and longer-term outcomes are taken into account. For example, an electric car charged from a grid powered by fossil fuels is not a utopian paragon of 'net zero' aspirations. So while in some cases driving an electric car may be a sop to the virtuous, much beyond the facade of sustainable energy use should not be considered as any universally accepted *fait accompli*. Accordingly, any quest or claim for 'net zero' operation of any ship, and not just any warship, should be recognised as involving intricacies, assumptions and contested claims. Any proposed 'net zero' solution is likely to represent some degree of compromise purely within the domain of it *really* being 'net zero', notwithstanding the implications for the ship's design, operation and ultimate effectiveness as a warfighting platform.

It is also clearly evident that 'net zero' should not be considered to mean that any individual ship should herself be required to be operated, let alone be built and sustained, with no net greenhouse gas emissions resulting from her use and upkeep. This provides latitude, elasticity and opportunity for innovative, indirect, novel and holistic approaches to 'net zero' that avoid detracting from capability. If this particular nettle is grasped boldly, shrewdly and effectively, enhanced scope should materialise in which navies can demonstrate energy efficient operations, even if not actually 'net zero', while limiting deleterious, if not catastrophic, effects upon warship effectiveness.

It is misleading to use commercial shipping as the yardstick by which navy 'net zero' performance or options should be measured. Effective, distributable fuels are required in a wide array of sectors, such as agriculture, mining, isolated settlements, and vessels operating locally from remote locations. Alternatives developed for commercial shipping and other applications are unlikely to be universally effective for these other uses, suggesting that some form of liquid fuel similar to diesel will need to be available to many users over an extended term.

If intended to have a 'net zero' fleet, then a navy should take the opportunity to think laterally and imaginatively. Superficially, 'net zero' warship operation may present as operating any individual warship with fuels that, purportedly at least, result in no ensuing increase in greenhouse gas emissions, with whatever design and operational penalties and impositions such an approach would inflict. This would represent a constraint on thinking and an orthodox and likely inappropriate approach – a 'green navy' at the expense of a 'mean' one.

The innovative navy will seek, develop, promote and exploit opportunities to have effective warships which nevertheless integrate desired energy efficiencies, consistent with the need to be able to fight and win at sea. Efficiency gains of this ilk can include elements such as: maintenance of a clean hull and propellers, with concomitant tactical benefit; use of low energy systems and fittings, such as solar absorbent paint, energy efficient lighting, and energy scavenging systems; and low drag above water profiles. None of these approaches detract from warship capability, but rather embody collateral benefit.

Expanding the form and reach of the 'net' provides further prospects. One foundation element could be to seek 'net zero' fleets in aggregate, rather than through the lens of individual fleet units, where low emission or 'net zero' units could be used to discount or offset the emissions of fleet units and naval activities which cannot sensibly be operated with low emission profiles while remaining credible warfighting platforms. Possible approaches of wider scope and span in the endeavour for a 'net zero' or 'near zero' navy may include, for example:

- Specialised support and general purpose harbour craft, such as tugs and launches, employing orthodox 'net zero' approaches, where activities are local and predictable and where compromises in design and operations would have no tangible affect upon a navy's overall combat capability.
- Naval auxiliaries dedicated to specific and predictable missions employing orthodox or otherwise palatable 'net zero' or low emissions design approaches.
- Ensuring shore supply services are of 'net zero' or 'net negative' origin, in parallel with ensuring that fleet units connect to shore supply as much as realistically achievable. Considering that a typical surface combatant is underway for only about 20% to 25% of total lifetime (compared with 80% or more for a typical merchant ship), the potential for realisation of greatly reduced aggregate emissions over a ship's lifespan by this measure alone cannot be understated.
- Navies linking with carbon capture and storage enterprises. This may include contributing to reforestation enterprises, or commercial arrangements with future carbon capture ventures. This would be a reversal of history, given that in times of sail navies managed forests as sources of ship materials, but in future it could be for carbon sequestration.
- Adopting a wider 'whole-of-government' or 'whole-of-nation' approach to the aggregation of total emissions accounting and the calculation of resultant net emissions. This approach would recognise the reality that a serious nation that wishes to have a serious navy cannot amortise 'net zero' down to individual fleet units or the navy in general, and that acceptance of net positive emissions by a navy in pursuit of the national good warrants emissions offsetting across the broader national economy.

Instead of defaulting to a base position of needing to find alternative fuels as a means of reducing emissions, a better option may be to pursue substitute 'net zero' sources for the same type of fuel. For example, diesel equivalent to that obtained from petroleum sources can be synthesised. Obviously more difficult to obtain at present and more expensive than the non-renewable alternative. In time, however, with sufficient demand – especially if like-minded navies approach the market collaboratively - and improvements in technologies and processes it is difficult to conceive that price would not decline as availability improved. Whatever additional cost which may be borne through purchase of this likely more expensive alternative would be offset significantly by the savings to be realised in not having to decommission and dispose of current diesel storage and distribution facilities and infrastructure, nor the delays and enormous costs which would need to be incurred in replacing them, even if we knew just ‘what’ they may need to be replaced with!

In reality, the ‘overall net zero’ navy will likely employ a combination of those options considered above, plus emergent opportunities, determined by factors such as fleet size and composition, operating tempo, mission profiles and operating areas. A critical determinant of the ultimate outcome will also be a navy’s risk appetite in alerting government, partner nations, and the wider public, to the incontrovertible fact that a nation can have an effective navy or a ‘clean and green’ one but most unlikely both. This requires a navy to step back from the comfort of ‘group think’ and to seek and stimulate, not shy away from, informed and objective, and likely robust, debate and discussion, drawing from a font of sensible, carefully formulated and pragmatic naval engineering policy.

The airline industry provides an exemplar for navies. Consider that alternative aviation fuels are not yet viable but a ‘net zero’ goal is sought through an assortment of means, such as carbon offsets, forestry, tailored technologies and modified procedures. Simultaneously, airlines are working towards Sustainable Aviation Fuels for long-haul flights and short haul aviation is innovating in hydrogen fuels and electric. A multi-pronged approach across industry is the model that is most likely to yield useful results. There is no suggestion that individual aircraft types will simply and rapidly switch to green fuels.

What is also obvious is that navies will need to shed any misapprehension that they should anticipate or be expected to ‘go it alone’. The serious, mission-focused navy, resolutely committed to being ‘mean’, possibly also ‘lean’, but only ‘green’ to the extent of consistency with maritime warfighting capability, cannot internalise ‘net zero’ or ‘low emissions’ endeavours. Government agencies - executive and legislative - at levels beyond the boundaries of a navy or its wider defence portfolio, and by extension the taxpaying public, need to be educated and informed clearly and soberly of the risks and implications of naval pursuit or expectation of ‘net zero’.

It may be expected that not all observers and commentators – especially purists - may agree with such approaches to a low emissions navy, but it should be accepted as axiomatic that whatever solution may be adopted will invariably have its detractors, benefits and disbenefits. It is therefore critical that navies also control the narrative on this and temper expectations, rather than be caught up in the hubris and ‘group think’ which may ultimately lead to disappointment as and when the reality dawns that navies can either be effective maritime fighting forces or green warriors, but most unlikely both.

This all points back to the inviolable necessity of a solid naval engineering policy foundation. Clearly, it is essential that the naval engineering policy framework of ‘mission first’ is established and consistently maintained, and that all proposed ‘net zero’ approaches be rigorously evaluated through this lens.

5. When should or must decisions be made?

The IMO’s vision is that zero / near -zero emission technologies will represent at least 5% (but striving for 10%) of the energy used in international shipping by 2030.

(Przytulski 2024)

The year 2030 is barely five years beyond INEC 2024, yet warships being built now are those designed 10 or 20 years ago! Indeed, warships being designed today will be built in 10 to 20 years’ time, or more, with some only newly into service by 2050.

Transition to CO_2-free fuels might increase the main dimensions of future new buildings.

Kristian Knappi, Deltamarin (in Reinikainen 2024)

In the absence of anything beyond speculation, it is not possible to design today the ‘net zero’ or alternative fuel warship. Any attempt to do so would represent significant technological, project and financial risk, notwithstanding the likely compromises of capability. Given that energy sources and associated systems and their layouts and configuration, as well as weight and space requirements, set many of the fundamental parameters of a warship’s design and fit, it is difficult to design the ‘alternative fuel’ warship today as would be necessary to start building in around 2035.

A rough, indicative timeline of a theoretical pathway to the design and build of an alternative energy warship may be derived. Assuming alternative fuel technologies for shipping, and their associated infrastructure recapitalisations, distribution networks and market supply capacities and resilience are not resolved until, say 2035, no clear guidance would be available to the future warship designer until that time at the earliest. Any attempt to design and build a ‘net zero’ warship before this juncture would invariably represent risk and more than likely result in a warship of qualified utility, if not a dead-end in design concept. Assuming an ambitious 10 year surface combatant design timeframe, followed by a five year build for the lead ship, suggests the prospect of a navy’s lead, and hence only ‘net zero class’ surface combatant in commission by 2050. This, patently, is far short of any goal for a ‘net zero navy’ if intended to be coupled to the IMO’s schedule for commercial shipping transition.

Given the usual warship lifespans, the obsessively determined ‘net zero’ navy may have half of the fleet at ‘net zero’ in the 2060 to 2065 timeframe, and maybe full ‘net zero’ by around 2075 to 2080. This hypothetical, and optimistic, timeline illustrates the unrealistic proposition that any serious navy could achieve a ‘net zero’ fleet posture in a manner synchronous with the IMO’s ambitions for commercial shipping. Furthermore, such ambition would invariably be realised by prematurely decommissioning other fleet units, with the sunk costs and inherent energy imposts and inefficiencies incumbent upon such a proposition – all detracting from and contradictory to the ostensible goal of ‘net zero’.

6. Conclusion

This paper does not purport to provide technical commentary about alternative fuels for warships. Rather, this paper springs from the precept that navy technical pursuits may be essentially meaningless, if not counter-productive, if they are not anchored to the purpose of developing, maintaining and sustaining naval capability and the pillars upon which that exists – lethality, survivability, supportability. Nowhere in these cardinal tenets does, or should, reside as key drivers facets such as ‘environmental responsibility’, ‘zero emissions’, ‘clean and green reputation’ or similar. These may be valid as collateral subordinate aspirations, but they cannot be fundamental drivers, or else the core navy role will be dislocated, if not dissolved. It is within this context that it is critical that effective, focused and informed navy engineering policy is developed and implemented to ensure that however navies may venture into alternative fuels, it is done so with the primary objective of delivering effective naval capability – not the pursuit of green credentials or emissions targets.

This paper is not advocating nor suggesting that navies need nor should do nothing about participating in the global pursuit towards ‘net zero’. Rather, it advocates that any intended responses be based upon lateral thought and sober, dispassionate, holistic analyses, and that any adopted responses be modulated and carefully calibrated to be synchronous with the core naval mission.

We really have no idea what technologies may emerge and be substantiated and refined in the next 15 to 25 years. The alternative fuel warship is not yet conceived, and certainly not built and proven, so any vision of a ‘net zero’ fleet by 2050 is arguably delusional. Navies would be better served by focusing upon mission, while recognising that whatever energy efficiency gains may be realised will not conform with the IMO’s timetable.

Ultimately, there is no virtue or solace in losing the fight at sea but doing so at a lower carbon intensity than the victor. Any rational government will not thank a navy for that, nor will the wives, husbands, mothers, fathers, sons and daughters of those who may be lost in vain in the process.

7. Acknowledgements

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8. References

IPCC, 2018. Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-562. https://doi.org/10.1017/9781009157940.008. p. 535.

McLellan, A. 2024. Marine Professional - On the Radar, 9 May 2024: Kongsberg’s Chief Ship Designer: ‘We will see disruptive solutions’. https://www.imarest.org/resource/mp-kongsberg-s-chief-ship-designer-we-will-see-disruptive-solutions.html, accessed 20 May 2024.

Noonan, M. 2018. Chief of Navy Change of Command Ceremony 6 July 2018: Vice Admiral Michael Noonan, AO, RAN. Canberra.

Polglaze, J.F. 2018. Instead of Simply Asking ‘What?’, Naval Engineers Need to Ask ‘Why?’: Environmental Compliance Challenges and Relevance in Warship Design. In Conference Proceedings of INEC 2 – 4 October 2018.

Przytulski, A. 2024. Marine electrification: Adjusting course for an electrified future, in The Naval Architect, February 2024, pp. 12- 13.

RAN 1994. DI(N) OPS 19-1: Policy for the Disposal of Shipborne Waste. Royal Australian Navy, Canberra.

Reinikainen, K. 2024. Cruise ships: Economies of scale powerful driver to build ever bigger cruise ships, in The Naval Architect, February 2024, pp. 26 -28.

UK MoD 2024. Policy Statement by the Secretary of State for Defence: Health, Safety and Environment in Defence. Secretary of State for Defence, 2 January 2024.

9. Glossary

IMO: International Maritime Organization

LNG: Liquefied Natural Gas

MEP: Marine Environment Protection

Designing in reconfigurability and adaptability to deliver lean and mean naval combatants

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Synopsis

As an enterprise we need to deliver naval combatants that can pack the biggest punch for the lowest cost whilst taking the strategic advantage of emerging and developing technologies. Modularity has been hailed as a key enabler in achieving this due to increasing requirements for the use of off-board systems, uncrewed assets, and the need to re-role naval combatants.

Terms such as modular, adaptable, flexible, and reconfigurable have been used in the context of warship design for decades, but what is meant by these is sometimes confusing. As an enterprise we need to learn the lessons of their adoption to repeat the good and stop the bad.

In the current climate where the threat is fast evolving and highly diverse the need to operate ships that can maximise capability across several different and often conflicting missions is highly desirable. The conflict in Ukraine along with recent issues in the Red Sea, show how traditional methods of war fighting and protection of commercial routes is in danger of becoming cost ineffective. For example, it is not economical to expend million-dollar missiles for the defence against small low-cost drones. How does this relate to requirements for further modularity and reconfigurability, and does flexibility and adaptability play a part in solving these issues?

This paper looks to discuss modularity and reconfigurability along with key enablers such as adaptability and flexibility, to establish what this means for design and associated impacts on the holistic cost of capability. It aims to promote the use and standardisation of definitions in the context of modern naval ship design and explore the breadth of these features to expose how a holistic approach to integrating systems is required to ensure they remain more than buzz words. If collective enterprise-wide agreement can be sort in defining what is truly meant by modularity and reconfigurability, a more collaborative and coherent wholeship design approach can be provided to increase efficiency when implementing these adaptability and re-configurability paths.

Keywords: Adaptable; Flexible; Reconfigurable; Modular; Arrowhead 140

1. Introduction

Over the past 20 years the need for naval ships that can undertake multiple roles and provide utility across a broad spectrum of operations has been made clear, with many new ship procurement programmes requiring multi-purpose or adaptable ships. Examples include the T31 General Purpose Frigate and T26 Global Combat Ship both of which are marketed as modular and adaptable.

The war in Ukraine and recent attacks to allied navies in the Red Sea, seem to validate the push towards technologies such as drones / un-crewed systems, which are now being used in conjunction with ani-ship missile and new ballistic missile threats, requiring a change in the defensive approach. These fast developing and rapidly changing technologies therefore impart a demand on the current and next generation of naval vessels to be flexible enough to carry high end radar and interceptors for the hypersonic and ballistic missile threat, as well as cost effective methods of dealing with the drone threats. This can provide a challenge to customers who specify the capability required for the vessels but whose design and build programmes are overtaken by rapid developments in technology. Therefore, it has become common to hear reference to terms such as modular, adaptable, flexible and re-configurable used in ship specifications, requirements and marketing literature, giving acknowledgement that future warfighting capabilities will need to evolve at a pace faster than the procurement cycle of vessels and that these requirements are largely unknown. This gives rise to vessel designs that must allow for the ability to change their topside arrangement, operational spaces and mission spaces to account for current unknowns and uncertainties associated with future sensor, communications, command & planning and weapon systems to keep pace with their technological developments.

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As an enterprise of ship designers, builders and equipment suppliers we all have our own understanding of what is meant by modular, adaptable, flexible and re-configurable. However, with little agreed common definition it can be easy to focus on the key equipment enablers necessary to embark 'modular' systems i.e. allowing Space, Weight and Power (SWAP), but lose sight of the holistic ship design required to fully support and operate a series of changing systems over the period of a vessel's life. As a result some of the core tenets of ship design often get overlooked, i.e. integration with communications, combat management, bridge and platform management systems. The importance of integration is becoming more widely acknowledged as demonstrated by the first Sea Lord coining the term *"Digital Integration"* (Allison, 2024) at the 2024 Sea Power conference.

As customers strive to identify the new technologies and systems needed to fight the changing landscape of war, it is likely that the demand for vessels with even more modularity, flexibility, adaptability, reconfigurability and interoperability will be required. This approach allows the unknowns and uncertainty associated with identifying future capabilities at the time of a ship procurement programme to be mitigated, resulting in a change in mind set from designing ships based on past conflicts and a fixed capability requirements, to designing vessels capable of meeting future threats, where the requirements are more ambiguous.

As this demand increases an effort should be made to agree on the key definitions of the terms that may govern the requirements of the future and draw out how they impact the design of a vessel, so as not to lose sight of the wholeship impacts that these requirements place on the naval designer. Afterall put a system in a box is just the first step, fully integrating that system into the ship to provide reliable capability over a series of campaigns should be considered the complex part.

This paper is intended to promote a series of existing definitions, which could be agreed and cause a pause for thought over the impact of integrating new technologies within a vessel. A further aim is to aid in informing future specifications or requirements, that allow the naval ship designers to offer a more collaborative and coherent wholeship design approach, which can be provided to increase efficiency when implementing these adaptability and re-configurability paths for our navies.

2. A definition of terms

The terms *Modular*, *Flexible*, *Adaptable and Reconfigurable* appear all too often in marketing literature associated with ship design and within requirements from navies for new ship procurement projects, including recent example such as the UK Defence Ministers announcement for 6 new Multi-Role Support Ships (UK Royal Navy, 2024). The inclusion of these features is clearly regarded as highly important in delivering capability to modern navies and allowing them to leverage new technologies on their ships. However, the definitions of these terms vary as shown through research across some key published standards and publications, for example:

- Lloyd's Register Naval Ship Code Technical Committee – Ship design and applications – Modularity (Draft);
- NATO ANEP 91 & 99;
- Royal Navy Maritime Modularity Concept; and
- DSTL Proposed way ahead on modularity.

What becomes apparent when reviewing the meaning of these terms and subsequently discussing them with learned colleagues is the overlap of the potential definitions or interpretations, modularity being a prime example. Used as an umbrella term modularity can have a series of different meanings covering either the way a vessel is constructed leading a ship to be described as modular build, a feature in a vessel that allows modules to be used e.g. a large mission bay or refers to a systems or equipment within a box that can be transported and embarked on a vessel, i.e. a modular system. Each of these can be argued to be a form of modularity that also overlaps with adaptability, flexibility and re-configurability.

The UK Royal Navy defines modularity within their Maritime Modularity Concept (UK MOD, 2022) as: '*adaptation through the timely addition or substitution of specialist or new capabilities at home or deployed; fully integrated to execute specified missions.'* This definition is further explained with the use of five subcategories of modularity: Build Modularity, Integral Modularity, Installed Modularity, Team Modularity and Digital

Modularity. In each instance a description provides some context as to what is meant by the term however these descriptions fall short of an unambiguous definition. These terms also overlap with others, for example Integral Modularity is stated to be a capability with a defined boundary both in application and installation. It relies on locations within a vessel designed specifically to accommodate modules allowing the capability to be fitted or removed depending on the mission demands, for example the Danish STANFLEX System. However, this could just as easily be described as either adaptability or re-configurability.

Therefore, to progress on a common understanding, it important that we become specific in the use of our terminology when describing features and function of the ships we design and systems we which to embark. To help this the following definitions are recommended based on the discussions held and publications examined.

In reviewing the aforementioned publications the definitions as stated within Dr Courts' paper (M.D.Courts, 2014) (Table 1) stand out as a comprehensive set of terms that are well bounded and meet with the authors' experience within the context of ship design. However, it is worth noting that modularity as a definition is not included, as these terms were intended to support the description of what was holistically meant by 'modularity'.

Term	Description	Example
Producibility	A measure of the ease with which a design can be manufactured and assembled. This may be enabled by both reducing work content and improving the efficiency of the work required. This may be achieved by breaking items down into sub-assemblies that can be built and tested separately before coming together or by re-designing assemblies to have fewer components requiring little effort to assemble.	- Structure with few components and weld lengths - Raft mounted engineering and auxiliary systems
Operability	A measure of the ease with which a ship or system can be operated by its crew.	-Ship that has easy access to all manned areas and living spaces separate from spaces allocated to fight and move functions.
Supportability	A measure of the ease with which a ship can be supported by maintaining equipment in situ or by removal and replacement.	- Clear vertical removal routes that can be opened easily. - Access for maintenance around equipment
Flexibility	Describes the ability of a complete entity to perform more than one function without major change.	- General purpose frigate able to contribute effectively against all threats in a battle space.
Reconfigurability	Describes the ability of a complete, or part of an, entity to be easily altered during its life to perform different functions.	- Deck space that can accommodate functionally complete portable containerised systems.
Adaptability	A measure of the ease with which a ship or system design can be changed to produce	- Ship design that has spaces already allocated

	variants optimised to perform additional or different functions.	for in-service additions together with in-built system capacity to support such additions.

It becomes apparent that in defining these terms, modularity becomes mostly redundant as a descriptor of ship capability and that it is in fact simply an enabler of re-configurability, flexibility, and adaptability. However, if the term modularity is replaced by re-configurability both the terms of modular and module do not become redundant and can be simply defined as stated in Table 1.

Term	Description	Example
Modular	Describes a system or capability, which can be assembled or constructed from multiple standardised parts or modules.	- A field hospital capability constructed from individual medical modules, e.g. labs, CT scanner, wards, stores, sanitary facilities etc
Module	Describes a defined item constrained to a size envelope, which can be transported and integrated to a larger assembly or host to enhance capability.	- Equipment installed within a container or standardised interface specification.

Table 1: Modularity definitions

3. Reconfigurability Case Studies

The following case studies provide examples of reconfigurability within a ship design that have enhanced capabilities and are reviewed to learn the lessons of their adoption to repeat the good and stop the bad.

RFA Argus

RFA Argus demonstrates reconfigurability at probably one of the extreme ends of the scale. Originally launched in 1981 as a commercially owned and operated freight, RORO and container ship, it was taken up from trade during the Falklands War and converted (adapted) for use as an aircraft transport before further conversion (adaptation) in 1985 to an aviation training ship with extended accommodation, flight deck and aircraft lifts. In 2009 further changes were made to incorporate a primary casualty receiving facility (PCRF) (UK MOD, 2024). The key enabler for this dramatic change in role was the overall size of the vessel and arrangement, which allowed for the reconfiguration of the design adapting it to the unique capability it now has.

The first PCRF adaptation of the vessel was achieved by reconfiguration of existing spaces within the vessel and in installation of a modular containerised hospital capability. This was completed during a re-fit period and within the bounds of the existing weight and stability limitation of the design. After being in service for several years the modular containerised hospital section was identified as being sub-optimal in layout and suffering from deterioration, but the value of the capability had been demonstrated and there was a wish to make the capability permanent. Implementing the improvements and making the PCRF fit permanent, resulted in a change to the classification of the ship, from class VII cargo ship to passenger ship requiring significant changes to provide sufficient escape and evacuation routes. This illustrates the need to consider the holistic impact of adapting a vessel with a modular fit and consideration if a system may become permanent, requiring a more holistic design approach from the outset including safety and certification.

This example also shows that reconfigurability is not necessary a short term or transient thing and with adaptable and flexible designs substantial change during a vessel’s life is possible.

Figure 1: RFA Argus (image credit Wiki commons)

RDN Absalon and Iver Huitfeldt Classes

The Royal Danish Navy's Absalon class and later designed Iver Huitfeldt class were designed from the outset as flexible and adaptable vessels, utilising a 'wide beam' design mentality, which provides additional volume beyond that required by the as built capability. This allows ease of maintenance and future reconfigurability of spaces. HDMS Absalon has a large flex-deck capable of accommodating multiple different vehicle types, stern ramp for launch and recovery and a large flight deck. In addition the vessels also utilised the Danish STANFLEX modular weapon systems. Designed from the outset as frigates opposed to auxiliary vessels enabled a credible combat capability as well as the inherent ability to change role, an example of which being the reclassification in October 2020 as Anti-submarine Warfare (ASW) Frigates through fitment of towed sonars and ASW helicopters (U.S Naval Institute, 2021).

The Iver Huitfeldt followed a progressive development on from the Absalon design providing an Anti-Air Warfare (AAW) primary capability, but also embraces reconfigurability through a number of means including utilising a mission bay capable of hosting four twenty-foot ISO standard sized containers and the integral design for interchangeable STANFLEX modules. The versatility has been seen firsthand by the authors whilst visiting HDMS Niels Juel, where the level of flexibility of the design becomes apparent as well as the level of integration that was required to enable the complex weapons (STANFLEX modules) to function. Discussions with the crews highlighted the process required to integrate these modules once they are fitted to the ship and although this now represents a streamlined process, the complexity of the design to allow integration with the combat system, communications system and ships sensor systems was clear.

Figure 2:HDMS Absalon (Left) HDMS Iver huitfeldt (Right) (Images credit wicki commons)

Arrowhead140

The Arrowhead 140 has evolved from the HDMS Iver Huitfeldt design adopting the wide beam design methodology and incorporates modern classification and NATO standards, along with increases to ship survivability. These ships have purposefully been designed to allow reconfigurability through life via a spiral capability acquisition programme, or to embrace the ability for the baseline design to be customised by the customer Navy, this can be seen when open source specifications for the UK RN Type 31 and Polish Miecznik programme vessels are compared.

The design has the ability to be reconfigured through a series of options to enhance capabilities such as Anti-Surface Warfare, Anti-Air Warfare, Anti-Submarine Warfare, Land Strike, as well as provision to embark modular capabilities e.g. Humanitarian Aid and Disaster Relief (HADR) or Mine Countermeasures (MCM), etc. Designed with a substantial adaptability margin the AH140 can facilitate significant capability changes (Howard & Johnson, 2022) (Babcock International Group, 2024) . These integral design features provide reconfigurability options that consider a wide variety of system interfaces allowing for the interfacing and addition of critical supporting systems beyond the primary capability, e.g. provision for additional HVAC and chilled water associated with a mission system equipment upgrades, which may be necessary for the inclusion of advanced radars or Mk 41 Vertical Launch Systems. The design also considers aspects such as the Integrated Platform Management System (IPMS) within the adaptability margins to ensure whichever system enhancements are selected the IPMS can be integrated.

In developing a variant of the AH140 tailored towards embarkation of modular systems, a series of discussions were held with Lloyd’s Register to establish the most appropriate means of meeting safety regulations for large enclosed multi-use mission bays. The conclusions of these discussions were that the rules do not currently consider these spaces in the new manner of which they could be used. Instead, they are reliant on extant regulations for vehicle decks or hangars to cover elements such as firefighting, etc. They do not fully consider simultaneous stowage of hazardous materials (e.g. batteries, fuels, munitions etc) or the requirements for general access/ egress / escape and evacuation through these spaces. Therefore it was key in the development of the AH140 that the solutions and safety case for the vessel consider these aspects in order to deliver a platform that is safe to operate without overly restricting the use of modular systems.

Figure 3: Arrowhead 140

4. Reconfigurability in the context of a ship design

To fully exploit a design and ensure that it can be reconfigured it is important to understand the different ways reconfigurability can impact a design. Broadly speaking these can be divided into two categories, Embarked and Integrated, which cover the different aspects of reconfigurability.

Embarked reconfigurability:

Embarked reconfigurability is where a vessel’s capability is reconfigured or supplemented through the embarkation of systems and equipment. This leverages the use of standardised modular system concepts, which conform to common design and integration standards e.g. NATO ANEP 99 (NATO, 2019) and NATO ANEP 91 (NATO, 2017) or utilises embarked vehicles or vessels e.g. drones. These systems are embarked into mission bays to either enhance the ship’s capability or be used to enhance the overall naval / military capability, through deployment from the ship. In order to be effective the ship must be designed to both accommodate and facilitate their operation by supplying key services to them (water, power, cooling, networking, etc) and accommodating the operators and/or maintainers. It is this form of reconfigurability that has been more widely known as modularity.

The benefits of providing embarked reconfigurability are well documented and the use within multi-role vessels established. However, the ability to host a module should only be regarded as the first step in true reconfigurability of capability, as the module and more importantly the equipment and systems hosted within must be fully integrated into the ship systems beyond allowance for Space, Weight and Power (SWAP) to function effectively.

This leads to a key trait of reconfigurable modular systems, which is that for the benefits to be fully realised they are reliant on being capable of being shared across multiple vessels and in some instances between navies, and therefore be designed to a single interface standard. This may sound obvious, however the ability to gain multi-organisation and multi-nation agreement on highly complex system design is fraught with difficulty. For example, the task of agreeing the size of a module, build standards and interfaces (ANEP 99) took NATO a significant number of years, and this was based on well-established ISO Containers. With standards for communications, interfacing and network infrastructures still to be decided amongst a wide variety of competing systems from both industry and government research institutes alike, the realisation of true interoperability of capability via a reconfigurable fleet is very much a continued journey.

These can be short cut through adoption of a common system by many customers, thus making it the adopted standard e.g the use of Hendrickson Hook for quick release boat, although this is a prescribed standard many navies and small vessel manufactures have adopted it or are compatible with it. Another approach could be a single 'best for navy' approach where one navy adopts a system and does not worry about the ability of sharing capabilities with other nations, e.g. the Danish STANFLEX system (DANYARD, et al., 1992). However, this approach brings a significant development cost for a nation compared to leveraging a wider pool of research and development from other nations and the wider equipment supplier market. This approach also blurs the line between embarked and integrated reconfigurability.

Integral reconfigurability

Reconfigurability of a vessel can also be facilitated through bespoke integral design solutions for systems and equipment in a single ship or class of ships. This can either be through specific design features that allow alteration of the vessel to meet different capability demands and uses, e.g. large office spaces that can be subdivided with partitions, additional space to fit either extra or larger equipment e.g. chiller plants, or specific interfaces for a particular system type, e.g. fit to receive a Lockheed Mk 41 Vertical Launch Silo, or the Danish STANFLEX system.

There are many advantages of integral reconfigurability from provision of flexible accommodation and planning areas to the ability to cost effectively add capability such as upgraded radars or weapon systems, without significant modification to the ship during refits. Having a design with integral reconfigurability provides the benefits of ship commonality for training, maintenance and spares whilst allowing the provision of capability differences, e.g. different vessels in a fleet geared for different mission types. There is also no reliance on the need to gain international agreement of standard interfaces or conform to large boxy volume requirements when smaller equipment can be accommodated, saving space.

The principal disadvantage associated with integral reconfigurability lies in the potential extended time to reconfigure ships if a standardised system is not used. Although reconfigurable in design the nature of the integral reconfigurability inevitably has a cost impact when compared to embarked reconfigurability due to the up-front development costs, therefore it is important that the solutions are thought through so the capability gains outweigh the associated cost burden.

Integrating reconfigurable spaces need to be carefully considered as they can affect ship size and cost of procurement to accommodate this specific feature. There is also a risk that, this capability may only be utilised once or twice during the lifetime of the ship or not at all e.g. fit to receive towed array sonar bay. This type of reconfigurability can also bake-in the interface requirements or standards for modules and systems that may not be adaptable for future technology developments, e.g. energy magazines for Directed Energy Weapons (DEW).

In summary regardless of the type of reconfigurability utilised within a vessel design, careful thought is needed on how it will interface with the ship. Which systems need to be provided? Where the additional design margin is required? How will a change of role / capability be undertaken so the associated costs are manageable and proportionate to the capability increases envisioned?

5. Reconfigurability impact on Cost

With little empirical data available to compare across the different vessels that provide reconfigurability in different ways it is difficult to draw fully factual conclusions. However, in the experience of the authors, elements such as mission systems equipment, survivability requirements and the required rules and standards typically make up the principal elements of a ships cost during the initial procurement. Reconfigurability therefore can aid in reducing this by allowing spiral acquisition programmes to be effective in adding capability at a later stage during a ship's life cycle noting equipment can make up to 60% of the ships cost. This can be applied to both types of reconfigurability provided that the holistic integration considerations are addressed effectively, and all future integration risks are mitigated.

The cost of reconfigurability at the design stage varies depending on the approach taken in design. Vessels that leverage a high degree of Embarked reconfigurability would expect to have costs that vary / scale proportionate to the volume of mission bay, as this forms the principal vessel size driver. Vessels that utilise Integral reconfigurability is more sensitive to the equipment cost of items designed into the vessel e.g. Missile or ammunition costs and the requirements to integrate these systems which are more significant than that of the platform costs.

Through life costs however will vary between the two types of reconfigurability as the investment will need to be either placed in the design of the embarked equipment i.e. modules, their transportation, stowage and maintenance (Harris & Thatcher, 2023) or invested during refits of a vessel, where integral reconfigurable spaces are modified to integrate new equipment and systems. The important factor in both cases is that reconfigurability provides the customer multiple options to manage the cost of the capability over the lifetime of a vessel.

6. Conclusion

The terminology associated with a ship's ability to be reconfigured is currently ambiguous and confusing. In order to provide succinct communication of requirements and capability an enterprise-wide agreement of common terms such as adaptable, reconfigurable, flexible, modular, etc. should be agreed. The term modularity is particularly misleading and only seems to cover part of a broad spectrum of capability drawing focus on embarked systems as opposed to the many ways a vessel design can facilitate changes in roles or capability.

This paper therefore recommends that as an enterprise we use the term reconfigurability in place of modularity and categorise it as either Embarked or Integral as it is the key enabler for adaptability and flexibility. The following statement aims to conclude the relationship of the common terms in the context of enhancing a naval capability:

> *'To provide a cost-efficient naval capability, the ship designer and builder should ensure high producibility, supportability and reconfigurability, which in turn allows for an operable, adaptable and flexible naval platform capable of exploiting modular systems.'*

It is also important to realise that although it is easy to focus on the new technologies being developed and embarked via modules and their associated handling systems, to truly leverage an increase in capability and provide reconfigurability the wider ship design aspects must be fully understood and considered. Aspects such as integration to the combat system, platform system and communication system cannot be overlooked or underestimated in complexity. Appreciation of the way large internal reconfigurable spaces can be operated and designed safely has also not been fully tested, with classification rules dependant on requirements for either vehicle decks or hangars to manage multi-use mission spaces. This means that the design of any reconfigurable spaces needs to carefully consider the safety challenges and justifications for their muti-use, the level of effort of which should also not be underestimated.

Many aspects associated with common integration of modular capabilities are yet to be defined or agreed resulting in an inability to fully standardise embarked reconfigurable capabilities. Therefore, it is key that the ship design and system integration beyond simply the physical aspects is fully considered in future reconfigurable designs and that integral reconfigurability can also provide substantial capability increases without the reliance on modular systems.

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8. References

Allison, G., 2024. *UK Defence Journal: Historian Dan Snow Talks to the First Sea Lord.* [Online] Available at: https://ukdefencejournal.org.uk/historian-dan-snow-talks-to-the-first-sea-lord/ [Accessed 20 05 2024].

Babcock International Group, 2024. *Arrowhead 140.* [Online] Available at: https://www.arrowhead140.com/ [Accessed 01 May 2024].

DANYARD, NobelTech & TERMA, 1992. *StanFlex 300 The True Multi-role ship.* [Online] Available at: https://www.marinehist.dk/orlogsbib/h/StanFlex.pdf [Accessed 22 May 2024].

Harris, A. & Thatcher, C., 2023. *The Challanges in Supporting modular capability, today and in the future.* Bristol, IMarEST - EAAW.

Howard, M. & Johnson, J., 2022. *Type 31 Frigate: Complex Warship Design for a Dynamic Operational Environment.* s.l., IMarEST.

M.D.Courts, D., 2014. *DTSL/TR75915 Proposed UK Way Ahead on Modularity.* 1 ed. s.l.:Defence Science and Technoloy Laboratory.

NATO, 2017. *Allied Naval Engineering Publication 91: Standard Interfaces for Mission Modules,* s.l.: NATO.

NATO, 2019. *Allied Naval Engineeriung Publication 99: Design and Infterface Stabdards for Containerised Mission Modules,* s.l.: NATO.

U.S Naval Institute, 2021. *U.S Institute November 2021 Proceedings Vol. 147/11/1325: Denmark's Absalon-class Flexible Frigates.* [Online] Available at: https://www.usni.org/magazines/proceedings/2021/november/denmarks-absalon-class-flexible-frigates [Accessed 01 May 2024].

UK MOD, 2022. *Maritime Modularity Concept.* s.l.:UK Ministry of Defence.

UK MOD, 2024. *Royal Navy organisation units and squadrons RFA Argus (A135).* [Online] Available at: https://www.royalnavy.mod.uk/organisation/units-and-squadrons/support-ships/rfa-argus [Accessed 01 May 2024].

UK Royal Navy, 2024. *Royal Navy: Six new amphibious warships to be built for Royal Marines operations.* [Online] Available at: https://www.royalnavy.mod.uk/news-and-latest-activity/news/2024/may/14/20240514-six-new-amphibious-warships-to-be-built-for-royal-marines-operations [Accessed 14 May 2024].

Ensuring Maritime Cyber resilience

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The views expressed in this paper are the author's views and do not necessarily reflect those of his organization

Synopsis

The Maritime Industry, keeping in line with recent technological developments is moving from stand-alone computer-based systems to integrated computer systems. Be it a dynamic positioning system, integrated platform management system or integrated bridge system, critical process are getting automated and integrated. Though the technology presents numerous advantages, the risks and challenges faced by the industry especially in cyber security with specific focus on addressing the risks in new builds and existing vessels, needs special attention and in-depth analysis. For new builds cyber risks are to be assessed from design stage and require in depth risk assessment, resilient design and use of secured control systems. However, implementation of cyber security controls in existing vessels with legacy systems, is a challenge and requires specific methods, approach and strategies to address cyber risks.

Key words. Cyber security, Maritime cyber resilience, cyber risks

1.Introduction

New Technologies and developments in the field of artificial intelligence, blockchain, IoT and automation are resulting in increased digitalisation. With increased digitalisation, data is being used for real time control of process, decision support, monitoring and analysis. The stand-alone ship control systems for propulsion, power generation, steering etc. are being gradually integrated for better control and reduction in manpower.

Electronic Data Exchange through removable drives or internet has become the normal mode of data exchange between ship to shore and vice versa. The International Maritime Organisation (IMO) goals for decarbonisation and use of alternative fuels are also leading to increased digitalisation and automation. While shipowners have various options to meet the goals, the quicker measure would be digitalise the process and use data for increased operational efficiency. Though industry has been using cyber technology for its various operational systems, typically termed as Operational Technology (OT) systems for several decades, the focus was more on their usage, than on issues of cyber security, the latter term being generally associated with information technology (IT) systems. However, the vulnerabilities created by accessing, interconnecting or networking these systems either for data transfer, software updates, control, and for maintenance can lead to cyber risks, which are required to be addressed. Cyber-attacks on ship critical Machinery Control and Navigational systems can pose significant risk to vessels. The attack can affect safety of vessel, safety of personnel and of the environment.

The paper aims to bring out challenges in addressing cyber security aspects for ship control systems and initiatives taken to address these challenges for new builds and for existing vessels. The paper also highlights the challenges faced by implementers while trying to incorporate cyber risk mitigation controls in existing vessels equipped with legacy systems and discusses the strategies for effective management of cyber risks in such vessels.

2. IMO's initiative

Cyber security is high on the agenda of IMO and is being actively discussed at the Maritime Safety Committee (MSC) and at the Facilitation Committee. The Committee deliberated on papers submitted by the member States on the subject and in June 2016, the Maritime Safety Committee approved Interim Guidelines on Maritime Cyber Risk Management vide MSC.1/Circ.1526. These high-level guidelines present the functional elements that support effective cyber risk management. The Guidelines were superseded by MSC-FAL.1/Circ.3 which recommend a risk management approach to counter cyber risks and subsequently as per IMO Res. MSC 428(98) the cyber risk management is being addressed through safety management system.

Authors' Biography

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3. Initiatives by the Indian Register of Shipping (IRS) to address Cyber Risks

For safeguarding ships from current and emerging threats, Indian Register of Shipping (IRS) has developed Rules for Cyber Resilience based on two unified requirements for cyber resilience published by International Association of Classification societies (IACS). The Rules for Cyber Resilience of ships specify the minimum requirements aimed to protect the vessel's cyber systems against cyber incidents. The requirements are mandatory for ships contracted for construction on or after 1st July 2024 and address the five functions 'Identify, Protect, Detect, Respond and Recover' to ensure cyber resilience. The Security capabilities of Systems and Equipment are to be designed and verified as per rules for Cyber Resilience of On-Board Systems and Equipment.

One of the key features of the new requirements is segregation of Computer Based Systems (CBS) into zones. All CBS in one zone have the same security requirements and can communicate with other zones only through conduits which have necessary data flow controls. The network housing all the CBS in scope are termed as Trusted Network and the rules specify additional cyber security requirements when CBS in trusted network(s) has to communicate with untrusted network(s).

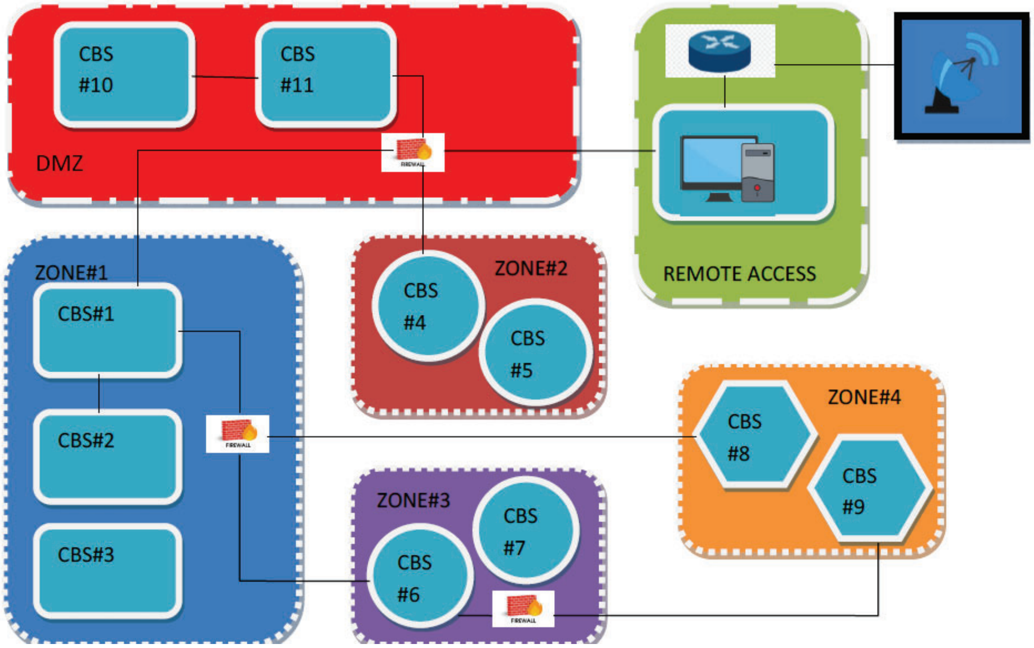

Figure 1: Zones

The requirements for Cyber Resilience of On-Board systems and equipment are applicable to computer based systems under the scope of the Rules for "Cyber Resilience of ships" which defines 30 Security capability requirements and a further 11 additional security capabilities to be complied with for CBSs which can communicate with un-trusted networks The requirements cover following areas**:**

- Identification and authentication controls
- Use control
- System integrity
- Data confidentiality
- Timely response to events
- Resource availability

To assist the maritime industry in identification of cyber risks and designing a suitable cyber risk management system for various types of vessels, both new build and existing, IRS published "Guidelines for Maritime Cyber Safety", based on IEC 27001, IEC 62443-3-3 and industry best practices. Further, for addressing the security requirements for control system components, IRS published classification notes on "Cyber Secured Control System components" which defines five levels of cyber security. Notwithstanding the type of vessel, if any owner desires to protect the onboard computer based systems with additional cyber safety features, to address cyber risks due to increased system integration, including connectivity outside the vessel, additional Class notation as per guidelines can be assigned when requirements as stated in the IRS guidelines for cyber safety are complied with. For new construction ships which are not required to comply with rules, but the owners voluntarily intend to secure their vessel against cyber-attacks, a class notation to state that the vessel meets the minimum cyber security requirements as per Class rules will be assigned.

4. Addressing Cyber Security in New Build Vessels

All new builds, under the scope of applicability of the new rules, are required to comply with requirements of cyber resilience, which are to be implemented from design stage. For countering ‘single point failures’ a ‘Defence in Depth’ approach is encouraged whereby detection and protection measures, designed to prevent or slow down the progress of a hacker are implemented, thereby enabling an organisation to detect and respond to a cyber-attack. In cases where equipment and systems are not ‘type approved’, they can be certified ‘specific to project’, through review of manufacturer’s documentation and witnessing of tests.

4.1 Compliance verification

The Class surveyor would verify compliance to the approved documents for following stages of ship life cycle

- Equipment product certification
- Vessel design phase
- Installation
- Commissioning before delivery
- First annual survey and subsequent annual survey
- Special survey

In the event a particular system does not meet the specified cyber security requirements, counter measures can be applied. Changes to hardware and /or software would require submission of updated plans and subsequent onboard verification.

4.2 Cyber Risk Assessment

Cyber risks can be defined as those risks that arise from the loss of confidentiality, integrity or availability of information in IT and OT systems, the consequences of which can severely impact an organisation and/or ship’s critical operations. Ship-critical systems are to be designed, installed, tested and maintained to mitigate the risks arising out of use of such technologies. Therefore, evaluating the risks is essential for smooth operation of control and information systems. The National Institute of Standards and Technology (NIST) of the United States defines risk as a measure of the extent to which an entity is threatened by a potential circumstance or event. Risk therefore is a function of:

- Adverse impacts that would arise if the circumstance or event occurs, and
- Likelihood of occurrence.

4.3 Attack surface

One of the important aspects to be considered in assessing cyber risk is the ‘attack surface’. An attack surface is typically the exposed area for cyber-attack and depends on the extent to which the system can be accessed either locally or from another location. For example, open USB ports on the PC give an easy access for the intended or unintended user to plug in a corrupted USB stick with virus. Similarly, when the system has provision for remote login the chances of attack increase as the asset can be connected from shore. The extent of attack surface available to the threat to exploit the vulnerability will determine the likelihood of cyber-attack on a particular equipment /system.

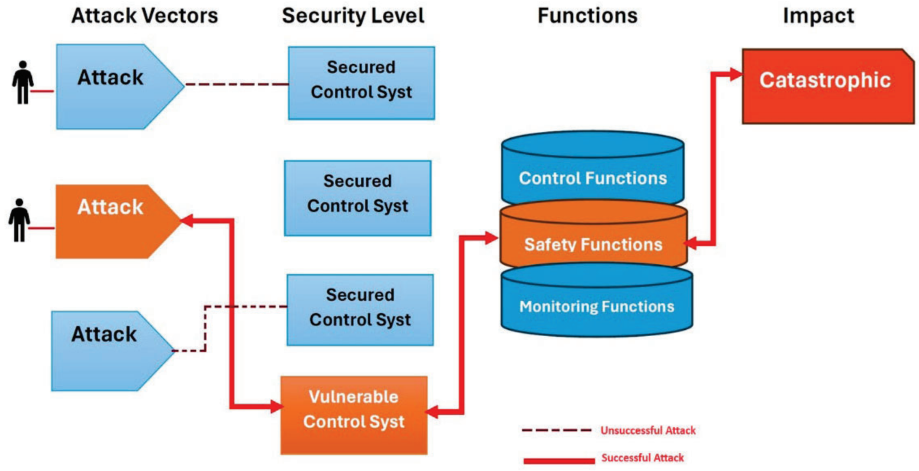

Figure 2: Attack Surface

For Ships built as per IRS guidelines, the yard /system integrators are required to provide a detailed risk assessment of ships IT and OT systems and a proposal for risk mitigation methods, which could be a combination of technical, procedural and managerial controls. The document is to be supported by network diagrams clearly identifying zones and conduits, vessel inventory and testing methodology towards verification of rule requirements.

Once identified, organizations should prioritize risks based on their potential impact and likelihood of occurrence. Based on the results of the risk assessment, organizations should develop and implement risk mitigation strategies to reduce the risk of successful cyberattacks. Vessel operators should view cyber risks along with the physical, human factor, and other types of risks. It is essential to protect critical systems and data with multiple layers of protection measures which should include role of personnel, procedures and technology. It is imperative to note that it is not a linear exercise and requires a holistic approach to protect critical assets, considering all interconnections, dependencies and upgradations.

5. Cyber Security in Existing Vessels

5.1 Challenges

While it is comparatively easier to implement the cyber security requirements for new builds, implementation of cyber security requirements for existing vessel i.e. vessels in operation**,** is a challenge.
Some of the critical challenges are presented below**:**

5.1.1Outdated Hardware, Software

Legacy OT systems typically consist of outdated hardware and software which were not designed with security perspective**.** Hence, they may not support modern algorithms, communication protocols, encryption algorithms or secure communication protocols. These factors increase their vulnerability to cyber-attacks. Legacy OT systems may also use insecure communication protocols that can be exploited by attackers.

5.1.2 Lack of Security Awareness

Operators who manage the systems may lack security awareness and training, making them vulnerable to social engineering attacks. Social engineering attacks can be used to gain access to sensitive information or systems by exploiting human vulnerabilities.

5.2 Strategies for cyber risk management of existing vessel

To overcome the abovementioned challenges and especially to secure legacy OT systems, the following approach is suggested

5.2.1 Conduct Gap Assessment

Implementation of new controls would require a detailed analysis of existing systems and the Gap with respect to the desired security level.

Gap assessment should be aimed to identify gaps existing in technical and procedural controls and may be categorised accordingly in two groups; one group identifying Gaps in policies and procedures, while the second group identifying Gaps in controls. Identification of CBS in scope and review of available documentation /information on the CBS would be the first step in assessment of gaps in existing controls. Vulnerability of identified systems are to be assessed based on:

- Extent of connectivity i.e. integrated or stand-alone
- Number of systems with which asset is integrated
- Remote connectivity (ship-to-shore connectivity)
- Criticality of the equipment/system
- Software update methodology
- Possibility of remote operations / monitoring etc.

The above-mentioned activity would help in arriving at the risk level for each vulnerable system. Documentation verification and analysis is to be followed by onboard assessment of identified vulnerable systems. The methodology consists of verification of Policies, Procedures and Controls for each identified vulnerable system and interaction with concerned ship personnel. One of the objectives of the interaction is to ascertain their commitment and clarity in their roles and responsibility towards implementation of cyber risk management. Identified vulnerable systems are assessed towards compliance with requirements of following functional domains, as applicable. The requirements are broadly grouped into 2 groups.

Group A

- Governance
- Procedures
- Risk Management
- Training & Awareness,
- Reports and Review procedures

The requirements of above functional domains, generally require policies and procedures to be defined at Company level and implemented onboard and ashore.

Group B

- Access Control
- Network Security
- System Security Controls
- Software Configuration
- Backup and Recovery

Towards implementation of the requirements of the abovementioned controls, generally assistance of manufacturers could be required.

5.2.2 Conduct Risk Assessment

Risk assessment is the process of identifying, evaluating, and prioritizing risks to legacy OT systems. This includes identifying vulnerabilities, threats, and potential consequences of a successful cyber-attack. Once identified, organizations should prioritize risks based on their potential impact and likelihood of occurrence. Based on the results of the risk assessment, organizations should develop and implement risk mitigation strategies to reduce the risk of successful cyber-attacks.

Vessel operators should review cyber risks along with the physical and human factors, as well as other types of risks. It is essential to protect critical systems and data with multiple layers of protection measures which should include role of personnel, procedures and technology.

5.2.3 Enforce Access Control

Access control involves implementing mechanisms to control access to legacy OT systems. Access controls should include strong authentication, authorization, and accountability mechanisms. Organizations should limit access to critical systems only to authorized personnel with a legitimate need to access them. The first step in implementing access control is to identify the assets that need to be protected and the individuals or roles that require access. Access control policies should be developed to define the rules and procedures for granting and revoking access to these assets. Authorization mechanisms should be implemented to define what actions users can perform on the system and which resources they can access.

5.2.4 Carry out System Hardening

Hardening legacy OT systems involves implementing security controls to reduce the attack surface and improve the security posture of the systems. This could include implementation of firewalls, intrusion detection and prevention systems, access controls, and other security measures to limit the potential for successful cyber-attacks. In addition, unnecessary or unused services, protocols, and applications that could be exploited by attackers, should be removed. Disabling unnecessary ports, removing default accounts and passwords, and restricting access to critical systems and components, could be some of the methods. It is important to note, however, that hardening should be performed in a careful and deliberate manner, as any misconfigurations or errors can result in unintended consequences or downtime.

5.2.5 Conduct Training

Implementing security awareness and job specific training programs for OT systems is essential for reducing the risk of cyber-attacks caused by human error or oversight. These programs should include training on basic cyber security principles, regular cyber security awareness training, and clear policies and procedures for reporting potential security incidents or threats.

By establishing effective security awareness and training programs, organizations can improve the overall security posture of their critical infrastructure and reduce the risk of successful cyber-attacks. It is important to note that security awareness and training should be an ongoing process and that organizations should regularly review and update their programs to ensure that they remain effective in the face of evolving cyber threats and attack techniques.

5.2.6 Implement Change Management

System security can be maintained by regularly carrying the software updates and patches. Operating critical, essential system by outdated software and hardware, can make them vulnerable to cyberattacks. All the patches are to be tested prior to deployment and change management process has to be defined and documented. Procedures shall be implemented for testing the patches before deployment. Updation and patching of legacy OT systems can be challenging due to the potential for disruptions to critical operations and are to be carefully planned, taking into account the manufacturer’s recommendations.

5.2.7 Implement procedures for Monitoring and Incident Response

Identification of incidents that are more likely to occur, would be the first step in development of Incident Response Plans. The Plan should outline the steps that should be taken in response to each type of incident. This plan should include procedures for detection, containment, eradication, and recovery. A desirable feature in vessels with increased integration and remote connectivity would to use tools and techniques to identify and respond to potential cyber threats and attacks in real time. This includes implementing network and system monitoring tools, intrusion detection systems etc.

5.2.8 Implementation of Procedures for Backup & Recovery

Implementing data backups and recovery plans is an important aspect of securing legacy OT systems. These systems handle critical data that is essential for vessel operations and a loss or corruption of this data could have serious consequences on the safety of the vessel. Organizations should develop a data backup and recovery plan to address the procedures for scheduled backups of critical data including testing of backup and recovery procedures. Procedures for Secured storage of backups and periodic testing to ensure that it can be recovered in the event of data loss or corruption are to be implemented.

6. Conclusion

Cyber-attacks are on the rise and it is important to address the cyber risks from design stage through a holistic approach. It is not sufficient to address the risks only through procedural controls and requires, in addition, that control systems components also have features to address cyber risks. Risk assessment forms a fundamental and important step in addressing cyber risks. A holistic approach addressing various threat actors and threat paths are to be considered along with the overall impact on the safety of the vessel and the environment when the subject system is compromised. Awareness and system specific training is essential for successful implementation of cyber risk management.

References

- IMO guidelines on Maritime Cyber Risk Management
- ISO/IEC 27001 standard on Information technology – Security techniques
- National Institute of Standards and Technology(NIST)

- IRS Guidelines on Maritime Cyber Safety
- IRS Classification notes on “Cyber secured Control system components”
- IEC 62443-3-3 Industrial Communication Networks - Network and System Security - Part 3-3: System Security Requirements Security Levels

Bibliography

- United States National Institute of Standards and Technology's Framework for Improving Critical Infrastructure Security (the NIST Framework).
- Code of Practice - Cyber security for ships by Department of Transport UK
- IEC 62433-2-1 Establishing an Industrial automation and control system security program
- NIST Special Publication 800-30
- ISO 31000 – Risk Management-Principles and Guidelines
- IRS Rules and Regulations for the Construction and Classification of Steel Ships
- IACS UR E26 Cyber resilience of ships
- IACS UR E27 Cyber resilience of on-board systems and equipment

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Maritime Autonomy and Safety at Sea

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Synopsis

Safety at sea is the protection from harm to people, property and the environment. Safety assurance in the case of autonomous sea going vessels is nontrivial due to the pace of change in enabling technologies and their disruptive impact. Historically accidents and incidents at sea have often been attributed to human error but the safety implications of a machine rather than a human making decisions whether fully or in part, is yet to be understood. Although the development of regulation of autonomy at sea is in its early stages, there is much activity to address safety of autonomy in maritime and elsewhere, along with a wealth of established safety practices from before its advent with good read across. One recent and significant development is the European Maritime Safety Agency commissioned study into autonomous vessel safety risks and their assessment tool, 'RBAT'. Meanwhile the umbrella body, MARITIME UK is up to the seventh edition of its code of practice for industry players and the major ship classification societies have each published guidance documents in the intervening period. Two general purpose guidance documents are the UK's Safety-Critical Systems Club "Safety Assurance Objectives for Autonomous Systems" and the "Safety Assurance of autonomous systems in Complex Environments (SACE)" from the Assuring Autonomy International Programme. Leaning on earlier established principles and practice, management of safety risk to a tolerable level and subsequent demonstration of safety case remain pivotal to safety assurance of maritime autonomy. Functional safety is the mitigating risks of system or component failures that would otherwise cause harm. Here the well-established and general-purpose standard IEC 61508 applies and in addition, failure and hazard analysis techniques abound. Finally, where applicable, good practice should be read across from safety initiatives beyond maritime and self-driving road vehicles in particular are considered.

Keywords: Hazards, Risk, Uncrewed, Unmanned, Remote

1. Introduction

The maritime industry is experiencing a significant paradigm shift with the increasing adoption of autonomous technologies. Autonomous vessels, equipped with advanced sensors, Artificial Intelligence (AI), and automation systems are reshaping traditional maritime operations. This transformation is driven by the pursuit of improved efficiency, safety, and sustainability in maritime transportation.

The broad interpretation of autonomy assumed by the authors of this paper is a machine acting in place of the human although with the human potentially remaining in the loop to some variable degree either in situ or remotely. Numerous classifications of autonomy exist but no further consideration of these follows. Prevention of harm and the safety imperative remain front and centre irrespective of the "flavour" of autonomy.

Reflecting available maritime related literature, many of the references sources here that follow pertain to surface vessels and commercial shipping however the authors of this paper have sought to extract transferable principles rather than case detail.

1.1. Accidents aboard conventionally crewed vessels

Despite advancements in maritime safety practices, accidents and incidents continue to occur aboard conventionally crewed vessels; which highlights the inherent risk associated with maritime operations. The European Maritime Safety Agency Annual Overview of Marine Casualties and Incidents 2022 report (EMSA, 2022) considers all accidents and incidents occurring involving ships flying the flag of a European Union (EU)

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member state and occurring in an EU Member State's territorial sea or inland waters. Data presented in this report shows that of the accidents and incidents occurring at sea between 2014 and 2021, "Human Action" was the most significant event type, making up 68.3% of contributing factors. Contributing factors catalogued as Human Behaviour, and contributing factors related to human action accident events are considered as influenced by human behaviour. When considering contributing factors influenced by the human element, the study found that 81.1% of all contributing factors were influenced by the human element. Whilst autonomy is sometimes heralded as panacea to human error, its role in accidents and contribution to safety at sea can only truly be understood from experience over prolonged period of introduction and maturation. The significant use of technology to supplant the human may lead to many new and poorly understood causal mechanisms, different potential hazard events and demand added barriers to these then resulting in harm.

1.2. Safety nuances of autonomous systems

The introduction of autonomous systems in maritime operations brings new safety considerations and challenges. Unlike conventionally crewed vessels, autonomous vessels rely on sensors, algorithms, and communication networks to navigate and operate autonomously. While autonomy offers the promise of improved safety through reduced human error, it also raises concerns regarding system reliability, cybersecurity vulnerabilities, and regulatory compliance. The adoption of autonomous systems is relatively immature and their technology building blocks, AI for example, are still developing. As a result, operational insight of autonomy specific causes to hazards at sea, is severely limited. Several other nuances of autonomous systems are now discussed and their implication to safety at sea.

The scope of functionality for autonomous systems is much broader than conventional systems and so the safety analysis must go far further. As illustration, looking to the "SUDA" (Sense, Understand, Decide, Act) characterisation of system functionality, an autonomous system spans the entire spectrum whilst conventional systems do not and tend instead to fall at either end.

For a role of any complexity, the human must act in concert or team with the machine in a dynamic manner that is contingent on varying conditions of both the system and its operational environment. There is thus the potential for ambiguity over the delineation of responsibility between human and machine. Furthermore, the human factors of such teaming raises additional concerns well documented elsewhere with potential safety implication.

In maritime, a future blurring of responsibility is at odds with the historical delineation between the supplier focus on assuring that a system is safe to operate versus the user focus on assuring that the system is operated safely. Indeed, the overwhelming conclusion from workshops held by the UK's Society of Maritime Industries (SMI) last year on assurance of autonomy was the pressing need for intimate collaboration between the two communities to achieve success (SMI, 2024).

Given that the blurring of responsibility is relatively recent, current regulation intended to impose safe operation has been written exclusively for human consumption and enaction. At the highest level these include International Maritime Organization (IMO) instruments such as the International Convention for the Safety of Life at Sea (SOLAS), the International Regulations for Preventing Collisions at Sea (COLREGs) and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). Two ramifications are firstly that without some interpretation they cannot be applied in isolation as written to autonomous systems and secondly, the widely adopted threshold is that they should then demonstrate equivalent safety to the human. This is potentially less familiar, more ambiguous or difficult to evidence whilst less demanding than the engineering convention of As Low As Reasonably Practical (ALARP).

With conventional systems, the handling of unforeseen circumstances typically falls to the human operator who adapts their use of systems at their disposal or otherwise mitigates the consequences. For safety assurance of autonomous systems and reduced human fallback, then increased emphasis is placed on identifying foreseeable excursions from the system's intended use or "Operational Design Domain". However, if adopting the well-established risk-based approach to safety then a safety related event of low likelihood and so not "reasonably" foreseeable that however has disastrous consequences, should not be neglected. Conventional bottom-up safety practice focuses on functional safety, so system faults or failures, and autonomous systems have given rise to the notion of functional insufficiency (particularly looking to self-driving and "SOTIF", Safety of the Intended Functionality) as source of hazardous situations hitherto neglected.

Having asserted requirements have been correctly set for the autonomous system including the off-design performance just mentioned (so called validation) then demonstration that the system implementation correctly meets these requirements (so called verification) may be similarly fraught depending on technology choice.

Autonomous systems that learn on the fly and are opaque in underlying nature for instance, may be difficult to verify. In the case of autonomous systems, risk assessment must address far more software failures, for which failure rates are much harder to quantify if indeed they can be, than the equivalent for hardware. Software failures are a result of human error but frustratingly, these can occur anywhere in the lifecycle from requirement setting through to implementation.

Ensuring the safety of autonomous vessels requires a multidisciplinary approach that encompasses technological innovation, regulatory oversight, and risk management strategies. Addressing these safety nuances is essential to building trust and confidence in autonomous maritime technologies and realizing their full potential to revolutionize the maritime industry for the better.

2. Maritime autonomy and safety, significant position pieces

The following subsections summarise the status of key position pieces on safety in autonomy at sea and attempt to draw out their unique slants.

2.1. European Maritime Safety Agency (EMSA)

Undertaken by the consultancy arm of Norwegian classification society Det Norske Veritas (DNV), the EMSA has commissioned development of a Risk Based Assessment Tool (RBAT) for the autonomous and remote control of sea going vessels. Four reports are available with the fifth and final still outstanding. The fourth report (DNV, 2022) explains the current status of RBAT and describes its application to three hypothetical case study vessels with varying onboard autonomy: a short-sea cargo vessel, small passenger ferry and Ro-Pax ferry. Given the significant detail published and its endorsement by EMSA, a summary of component parts to RBAT now follows.

RBAT part 1 is the detailed description of the use of autonomous and remote control by subdivision of a vessel's "mission" into phases, operations, control functions and control actions, and allocating both the undertaking and the supervision of these actions at the lowest level to human/machine and onboard/remote.

RBAT part 2 is then a hazard analysis of all control actions. Unsafe conditions are first identified by considering a provided list of control action deviations from design intent, similar to conventional HAZard and OPerability study (HAZOP) "guidewords", such as the control action occurring too early. Causal factors which can trigger unsafe conditions are then identified with candidate categories provided to assist their identification. The worst foreseeable outcome of an unsafe condition/mode assuming no mitigation is then selected from a list of potential accident categories such as collision and flooding. The severity of the worst-case outcome is determined from tables of consequences such as fatalities/injuries and environmental damage.

Part 3 of RBAT is a mitigation analysis of part 2's unsafe conditions. This entails understanding any Fault Detection, Isolation and Recovery (FDIR), particularly identifying independent prevention and mitigation measures and ranking their effectiveness. RBAT part 4 is a risk matrix evaluation and departs from the convention of considering event likelihood (given the difficulty in quantifying this) and consequence severity to instead consider consequence severity (from RBAT part 2) and mitigation effectiveness (from RBAT part 3). Each unsafe condition is thus ultimately categorised as high risk (intolerable), medium risk (tolerable) or low risk (As Low As Reasonably Practical, ALARP). RBAT part 5 is driving risk down to tolerable and ALARP by for example, increased control action integrity, introducing operational restrictions, and better mitigating the unsafe condition and the hazard severity.

The RBAT is effective in removing the need to assign a quantitative likelihood to risks relating to autonomous systems, instead looking to the effectiveness of mitigation layers. This allows for risks to be assessed where a quantitative likelihood cannot be reliably assigned. Furthermore, it is the authors' opinion that the RBAT has a wide applicability which could as it is adopted by the industry, promote common understanding across all stakeholders involved in the maritime safety process, for example an equipment manufacturer's safety work can be understood by any party who may want to install the equipment on their vessel.

The RBAT technique refers to mitigations that "for the assessed scenario can prevent losses regardless of failure cause". This post failure mitigation aims at preventing the undesirable consequence once a failure has occurred. Standards such as IEC 61508 (covered later in the paper) could be used in conjunction with the RBAT, to developing a system to a safety integrity level which will give assurance that there is mitigation against the failure occurring in the first place.

2.2. *Horizon2020 AUTOSHIP*

Bolbot and Theotokatos (2021a) present the safety approach developed by EU Horizon 2020 collaborative project AUTOSHIP and its application to hypothetical cases studies of remote and autonomous operation of short sea shipping cargo vessel and inland waterways barge. They compare eleven different risk and hazard analysis methods and ultimately advocate Preliminary Hazard Analysis or HAZard IDentification (HAZID) citing its applicability irrespective of the maturity of design and its support from class societies. The AUTOSHIP safety analysis steps are similar to those endorsed by EMSA (DNV, 2022) and described above, indeed the use of similar HAZOP like guidewords are proposed (function provided wrong, not provided etc.). Several major departures of the AUTOSHIP from the EMSA approach are as follows. It considers security and cyber-security implications along with consequences beyond safety such as reputation, it does not specifically emphasise vessel control, and the final risk assessment is based upon the estimated frequency of unmitigated cause and its likelihood of becoming a hazard.

2.3. *Classification Societies and others*

On behalf of an industry collective, MARITIME UK (2023) describe a voluntary code of practice now in its seventh edition, signed up to by many suppliers and relevant other parties. In terms of safety of autonomy, the code steps back and proposes element of a safety management system to include policy, appropriate responsibilities, culture, risk management, procedures for safe operation and emergency response, personnel and training, equipment maintenance. It then offers good practice recommendations including systems that should be risk assessed (Table 1) for failure implication and perhaps uniquely, recommended sense and avoid capability according to vessel category. Numerous classification societies undoubtedly have a view on the safety of autonomy at sea with only a few notables commented on below. An overview of notable positions is presented in Table 1 but this is not comprehensive survey and other classification society positions are omitted.

Lloyd’s Register (LR) was early to develop a design and construction code for Unmanned Marine Systems (Lloyd’s Register, 2017). The LR code attributes required system “levels of integrity” in light of the consequence of system failure to people safety, namely high (unacceptable), medium (conditionally acceptable) or low (unconditionally acceptable). Although no specific criteria or guidance is given for deciding between integrity level, the degree of safety verification then imposed by LR matches these three categories and specific verification methods are distinguished in the code annex both for each category and each lifecycle stage from design through to in-service operation. Systems drawn out for consideration as represented by headings in the code are given in (Table 1) for comparison.

Bureau Veritas (BV) proposes potential hazard types associated with vessel functional groups (see Table 1) and define risk as an additive combination of indices for causal event frequency and severity of hazard consequence (Bureau Veritas, 2019). The former ranges from 1 (extremely unlikely) to 7 (frequent) whilst the latter ranges from 1 (negligible) to 5 (catastrophic) for implications to the human (injury and death), the ship (damage) and the environment (pollution). The selection of index in each case is aided by tabulated distinctions. Guidance is not however offered on the acceptability of resulting risk with responsibility for this placed on the relevant administration.

The American Bureau of Shipping (2021) assigns risk category of high, medium and low according to the consequence of a functional failure (distinguished as not dangerous, potentially dangerous and immediately dangerous) and both whether human supervision is onboard and remote, and whether it continuous, periodic or on-demand. The risk categorisation assumes that risk increases if human supervision is remote rather than onboard and as attention becomes less frequent. In addition to vessel generic hazards, the ABS suggest hazard types for oil and gas vessels so for example, topside production and underwater drilling.

DNV set out assurance expectations according to four areas of navigation, engineering/platform systems, remote control and communications (DNV, 2021) with contributing functional groups listed in Table 1. As DNV’s guidance pertains to both autonomous and remote operation, they are unique in advocating explicit analysis of human factors related risk via dedicated methods beyond the conventional. As the longest list of functional groups by item count, the entries against DNV in Table 1 are compared for consistency with items proposed by others as interpreted by the authors of this paper, a tick suggesting duplication and empty entry suggesting omission. Table 1 suggests a patchwork of safety topic coverage but also potentially inconsistency of terminology both of which should be carefully considered in any safety argument.

MARITIME UK	**LR**	**BV**	**ABS**	**DNV GL**
Platform control		✓		Remote control
✓		✓		Communication
Autonomy decision making	✓	Voyage, Navigation	✓	Navigation/ manoeuvring
✓	✓		✓	Propulsion
✓				Steering
Electrical connectors;	Electrical			Electrical power
Sensors, Actuators	Control	Detection		Control / monitoring
	Structure, Stability			Watertight integrity
Fuel / hydraulic	✓	Ship machinery		Fire safety
	Auxiliary		✓	Ballasting
			Environmental protection	Drainage / bilge
			Mooring, Docking	Anchoring
				Maintenance
		Cargo / passenger management	✓	Cargo handling
			Industrial processes	
		Security		

Table 1 Comparison of autonomous vessel functional or system groups

2.4. Regulation and Standards

The Maritime and Coastguard Agency (MCA) is responsible for implementing UK and international law and policy, with safety being central. Their Workboat Code applies to vessels in commercial use less than 24m in length and Edition 3 (MCA, 2023), specifically annex 2 addresses remotely operated unmanned vessels. This will dictate on regulatory compliance in UK waters until the Maritime Autonomous Surface Ships (MASS) Code of the IMO takes mandatory effect planned for 2028.

Workboat Code Annex 2 covers: general code exclusions by virtue of the vessel being unmanned (e.g. machinery space fans), equipment restrictions (e.g. no flame appliances), data requirements (e.g. positional information), equipment protection measures (e.g. fire containment, alerts), operational requirements (e.g. remote connectivity, checks, distress call obligations), navigational and anchoring stipulations (e.g. remote watchkeeping provision), and finally health and safety provisions for boarded personnel.

Overarching policy for safety management in UK defence is governed by JSP 815 with DSA02 DMR focussing on maritime defence. Defence regulations interpret statutory instruments such as the MCA code in a defence context and add military deltas and DefStan 00-56 then dictates how systems are acquired in response. The UK's Naval Authority and Technology Group (NATG) are actively considering rules for the certification of autonomy at sea.

Three key standards are briefly mentioned, the first already well adopted given the increasingly software intensive nature of complex systems and second much more recent but with significant future potential implication. IEC 61508 dictates Safety Integrity Level (SIL) for safety critical systems and the specification, design, implementation and testing processes that should be followed to ensure the required integrity is met. IEC 61508 was intended for the implementation of simple safety function and does not for instance deal with AI such as machine learning. The upcoming IEC 63187 standard is touted to build upon 61508 but with a defence and pan-lifecyle focus. ISO/IEC TR 5469 addresses the functional safety of AI systems and AI specific concerns such as transparency, explainability and adversarial attacks.

3. Safety of autonomy beyond maritime

The following two subsections cover positions on safety in autonomy that are first generic in nature and second originate from the ground-breaking automotive domain.

3.1. Domain independent safety assurance

Coordinated by the University of California Los Angeles, the Norwegian University of Science and Technology (NTNU) and the University of Stuttgart, the International Workshop for Autonomous System Safety (IWASS) has been running for several years and Correa-Jullian et al. (2023) put forward a scene-setting white paper for last year's event. These authors note that "safety cases" have been "central to the regulation of multiple safety-critical systems, including nuclear, railway, oil and gas, automotive, industrial automation, and aerospace" with maritime notably absent. Here, a safety case is "a structured argument and the corresponding evidence that a system can operate safely for a given context". Correa-Jullian et al. (2023) note limitations in the use of natural language to present safety cases in reports and adoption instead of graphical notations "CAE" (Claims, Arguments, and Evidence) and the similar "GSN" (Goal Structuring Notation).

GSN can be traced back to the University of York who have proposed "SACE" (Safety Assurance of Autonomous Systems in Complex Environments), a set of safety case GSN "patterns" to structure the safety argument of an autonomous system (Hawkins et al., 2022). The top-level goal or claim is that the autonomous systems will sufficiently mitigate all hazards both within and outside of its defined operating context and a recurring GSN pattern then applies at each level of system decomposition, that safety requirements are met and any potential hazardous failures are managed. The steps to SACE might be summarised as follows:

1. Operational domain (context) and scenarios (autonomous system activities) defined completely and correctly.
2. All hazardous scenarios identified by considering all autonomous system interactions with its environment.
3. Safety requirements or a reduced operational domain are determined sufficient to mitigate hazardous scenarios.
4. High level safety requirements are decomposed in a tiered manner to reflect design decomposition into its component parts.
5. The design at each tier ensures safety requirements are met, that decisions are appropriate, a process has been followed and the design has been checked.
6. Hazardous failures/deviations (by HAZOPS, FMEA) are identified and sufficient mitigations put in place.
7. The autonomous system is aware of excursions outside its operational domain and remains safe both when in this occurs and during transitions.
8. The meeting of safety requirements is sufficiently verified.

A third initiative of note is the UK's Safety Critical Systems Club (SCSC) and its Safety of Autonomous Systems Working Group (SASWG). The group proposes 46 safety principles across three categories: computational, architectural, and platform or vehicle related (SASWG, 2024). The first and largest category covers data, requirements (functional, performance and test), algorithms, software and hardware.

3.2. Driver-assistance and self-driving developments

The development of ANSI/UL 4600 Standard for Safety for the Evaluation of Autonomous Products has been led by Carnegie Mellon University's Professor Koopman with road vehicles predominantly in mind although with application beyond. Whilst not strictly a process, numerous assessment criteria are proposed to help determine the acceptability of a safety case. It covers process such as risk assessment, testing and tool usage along with solution specifics such as autonomy functions and environment interactions. ANSI/UL 4600 provides a potentially useful checklist of considerations to confirm the exhaustiveness of a safety case.

The automotive domain has led on handling hazards in the absence of equipment faults. The ISO/PAS 21448 SOTIF standard considers the mitigation of risk due to unexpected operating conditions, gaps in requirements and foreseeable misuse. Valuable safety insight is anticipated from the application of SOTIF to maritime autonomy. Clear bounding of a vessel's concept of operation has long been common precursor to safety assessment irrespective of particular method chosen and rigorously identifying foreseeable excursions beyond this boundary is the kick-start to such SOTIF thinking.

Beyond SOTIF, functional safety and hazard analysis, there are one or two safety topics raised within the self-driving sector that read across to maritime but not featured in the maritime autonomy safety literature covered earlier. The term "behavioural safety" adopted for instance by Waymo (2021) and Siemens (2020) is described as "basic and defensive" driving by Koopman (2022) and concerns following the expected norms including adhering to traffic rules. The parallel in maritime is observance of good seamanship and compliance with the COLREGs, which particularly the latter, has been keenly pursued as feature of autonomous navigation. A second topic is crash safety or crashworthiness and lessening the severity of harm, a collision having occurred. This safety topic has clear relevance to safety at sea but could be interpreted more broadly across the range of accidents that might occur and not merely limited to vessel collisions.

4. Conclusions

The increased adoption of autonomy at sea will introduce different specific hazards to seafaring and new causal event chains. Despite a prevailing view that autonomy will reduce accident occurrences that arise due to human error, there are multiple nuances of autonomous systems that make safety assurance more challenging than for conventional systems.

This paper has reviewed the safety assurance nuances of autonomy at sea, relevant responses across the maritime domain and key contributions from further afield. A coalescing of the different positions is advocated to ensure coverage and comprehensiveness of safety philosophy and practice. Ultimately, the adequacy of safety assurance can only be evidenced by continuous at sea operation free from incident and accidents. Given the disruptive impact of autonomy adoption, unsafe events are inevitable, and safety assurance must be iterated in response.

Current safety thinking is that with a shift of emphasis on the balance of responsibility between human and machine, then the well-established risk-based approach still serves its purpose. Promising steps forward have been taken on the European continent to tailor such an approach to the nuances of autonomy. Classification societies and similar are then forthcoming on prescribing levels of safety verification although the coverage of topics would benefit from alignment.

Drawing on different perspectives including from adjacent domains should continue to be exploited to ensure safety at sea remains as a forefront priority. Developments in the driverless car domain are good examples such as dealing with foreseeable excursions from intended functionality and accident severity management. A continued emphasis on safety assurance is essential to seeing that autonomy at sea serves its full potential.

References

American Bureau of Shipping, "Guide for Autonomous and Remote Control Functions", July 2021.

Bolbot V., Theotokatos G., "Risk assessments, fail-safe procedures and acceptance criteria", Deliverable D2.4 of AUTOSHIP WP2, November 2021.

Bureau Veritas, "Guidelines for Autonomous Shipping", Guidance Note NI 641 DT R01 E, October 2019.

Correa-Jullian C., Grimstad J., Dugan S.A.: "The Safety Case for Autonomous Systems: An Overview", White paper for the 4th International Workshop on Autonomous System Safety (IWASS 2023), August 2023.

DNV (Det Norske Veritas), "Autonomous and remotely operated ships", Class Guideline DNVGL-CG-0264, September 2021.

DNV (Det Norske Veritas), “Testing of RBAT on specific cases of mass concepts, Report 4”, Report No. 2022-0481, Rev. 0, September 2022.

EMSA (European Maritime Safety Agency), “Annual Overview of Marine Casualties and Incidents 2022”, Ref. Ares(2022) 8241169 – 29/11/2022, 15th October 2022.

Hawkins R., Osborne M., Parsons M., Nicholson M., McDermid J., and Habli I., “Guidance on the Safety Assurance of Autonomous Systems in Complex Environments (SACE)”, Assuring Autonomy International Programme (AAIP), University of York, Version 1, July 2022.

Koopman P., “How Safe Is Safe Enough for Autonomous Vehicles?”, Carnegie Mellon University Lecture 131, November 2022.

Lloyd's Register, “LR Code for Unmanned Marine Systems”, ShipRight Design and Construction Additional Design Procedures, February 2017.

MCA (Maritime Coastguard Agency), “The Workboat Code Edition 3. The safety of small Workboats and Pilot Boats - a Code of Practice”, November 2023.

MARITIME UK, “Maritime Autonomous Ship Systems (MASS) UK Industry Conduct Principles and Code of Practice”, Version 7, November 2023.

SASWG (Safety of Autonomous Systems Working Group), “Safety Assurance Objectives for Autonomous Systems”, SCSC-153C, February 2024.

Siemens, “Delivering safe automated driving systems”, Siemens Digital Industries Software Whitepaper, June 2020.

SMI (Society of Maritime Industries), “Creating a Leading Edge – Accelerating Autonomous Assurance to Unlock the UK Opportunity”, January 2024.

Waymo LLC, “Waymo Safety Report”, February 2021.

Application of Commercial Advances to Support the Naval Energy Transition

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Synopsis

Developments in the commercial marine industry to support the energy transition away from fossil fuels is picking up pace. There is a division within the industry of the future fuel selection and the application of Energy Saving Technologies (ESTs).

With no clear “winner” coming out front, ship owners in various parts of the world are hedging their bets with different technologies.

Naval Platforms are more complex to shift to future fuels for a number of reasons, one primary reason is fuel energy density and range requirements. This paper explores developments in the commercial marine industry in the EST space and assesses the impact on fuel selection on BMT’s Venator 110 concept platform.
Future fuel availability is also becoming increasingly regional of type and bunkering locations. The impact on vessel range and currently available and predicted future bunkering locations is also considered.

Keywords: ESTs; Decarbonisation; Future Fuels; Fuel Transition.

1. Introduction

Across commercial shipping there is pressure to meet incoming and future environmental regulations; the introduction of IMO’s Carbon Intensity Index (CII) and the European Commission’s FuelEU Maritime Regulation has incentivised ship owners to start reducing their vessel’s carbon intensity. With forthcoming stringent regulations, commercial shipping is on the eventual path to decarbonisation. A significant number of new build commercial vessels are being specified as dual fuel, providing owners with flexibility into the future. In June 2023, the shipping giant Maersk had 25 methanol-enabled vessels on order (Maersk, 2023).

To support future fuel adoption, Energy Saving Technologies (ESTs) can enable the reduction of carbon intensity of a vessel whilst maintaining or improving performance. Existing ship owners are increasingly turning to ESTs to meet current CII legislation, this legislation dictates the pace of EST adoption across the maritime industry. ESTs can be broadly categorised as warm, wet and windy:

- Warm: Improvements to thermal efficiency or the recovery of waste heat.
- Wet: Hydrodynamic improvements.
- Windy: Wind assisted propulsion or aerodynamic improvements to the super-structure.

Naval vessels can benefit from commercially available ESTs, providing an environmental benefit, cost saving and increased capability. Alongside regulations, energy security will also govern naval strategic thinking and future capabilities; ‘transitioning from fossil fuels to renewable energy yields more electrified, decentralised, and digitalised energy systems’ (IRENA, 2024). To maintain current capabilities, navies must proactively transition towards implementing ESTs and the incorporation of future fuels.

Whilst navies may be content with operating fossil fuels such as F-76, a distillate marine fuel, regulations are enforcing the transition to future fuels for the global merchant fleet. Demand for maritime fuel is dictated by the commercial market; therefore, fossil fuel availability for naval applications could consequentially suffer.

This study explores the currently available ESTs that could be integrated on to naval vessels using BMT’s light frigate concept Venator-110 as the baseline vessel, assessing both F-76 and methanol variants of Venator-110.

By incorporating selected ESTs onto Venator-110, this study demonstrates that a conservative 13% reduction in the energy demand across the proposed operational profile and a 21% reduction at a 15kn cruising speed could be achieved.

Author’s Biography

Benjamin Scott is a Naval Architect at BMT UK. Ben is actively involved in research associated with the energy transition, having recently published an investigation into the feasibility of molten salt reactors for the propulsion of surface ships. His previous work includes research quantifying the added resistance due to biofouling using a fully turbulent flow channel.

William Ayliffe is a Graduate Marine Engineer at BMT UK. Will’s academic background at the University of Bath is in mechanical engineering specialising in advanced manufacturing technologies. Whilst at BMT Will has since worked on naval retrofit and in-service support projects.

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2. Baseline Vessel

BMT's Venator-110 is a general-purpose light frigate able to provide adaptable and cost-effective capabilities for various mission needs such as: maritime security, naval boarding, and consort defence (BMT, 2024).

Venator-110 is powered by F-76, a NATO fuel standard, which is similar in makeup to marine gas oil (MGO) (Ministry of Defence, 2013) and has a Combined Diesel and Diesel propulsion solution with two independent shaft lines. Each shaftline is powered by x2 MTU 16V8000M91L diesel engines and fitted with a controllable pitch propeller. Principal particulars for Venator-110 are detailed in Table 1.

Figure 1: Render of BMT's Venator-110 light frigate (BMT, 2024).

Table 1: Principal particulars of Venator-110.

Item	Value
Length (m)	117
Beam (m)	18
Draught (m)	4.3
Displacement (t)	4000
Range at 15kn (nm)	6000
Top Speed (kn)	> 25
Main Engines	x2 MTU 16V8000M91L
Electrical Generation	x2 MTU 16V2000
Crew	85
Total Personnel	106

Figure 2 illustrates the operational profile for Venator-110. This profile has been generated assuming transit speeds of 10kn, with Venator-110 spending most time at sea patrolling with the occasional sprint.

Based off this the operational profile, every year Venator-110 will consume 4892t of F-76 over 73550nm, and emit 15,190t of CO_2 whilst underway at sea for 5000hrs/year.

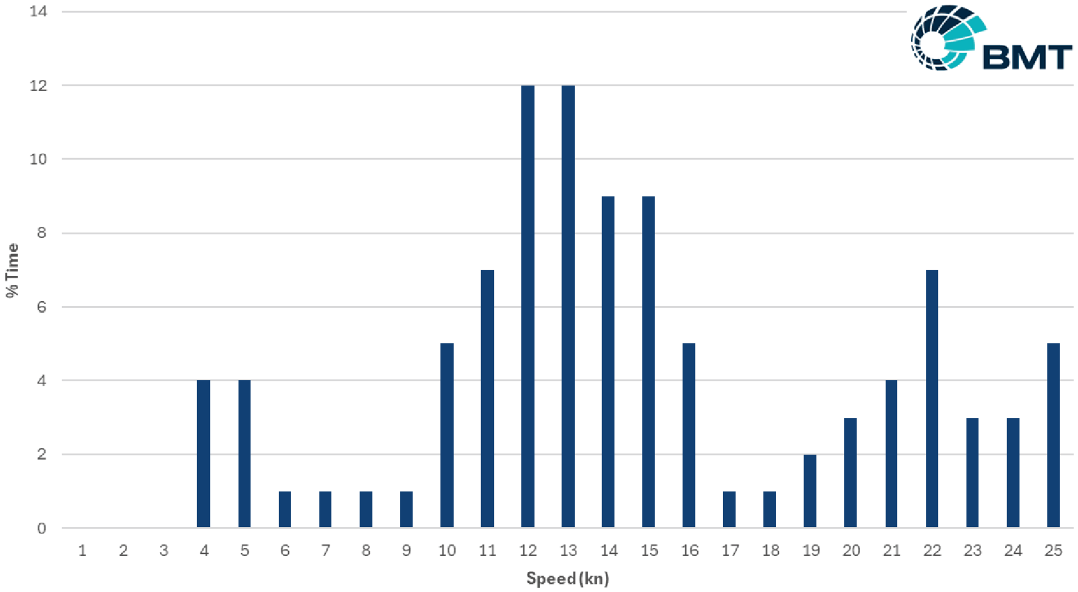

Figure 2: Typical operational profile for Venator-110.

3. Energy Saving Technologies

3.1. Options

Whilst the list is non exhaustive, Table 2 provides a classification of available ESTs with suitable Technology Readiness Level (TRL) 6 and above. The methodology used for assigning TRL was taken from TWI's TRL scale diagram (TWI, 2024). Notably, TRL 6 implies the EST has been demonstrated in the commercial shipping domain, and TRL 7+ have been utilised in a naval setting.

The effect of combining multiple ESTs of a similar categorisation type has seldom been explored, this may adversely affect performance and is a clear gap in the literature. For example, installing hull air lubrication may hinder the effectiveness of a Hull Vane®. By categorising ESTs into warm, wet and windy, the EST selection process for Venator-110 allows for segregated selection.

Table 2: Classification of available ESTs

Category	Energy Consumer	EST	TRL
Warm	Ship Services	Absorption Chiller Plants	7 (Spector, 2017) (Heinen & Hopman, 2024)
		Variable Frequency Drives	9 (General Electric, 2020) (ABB Marine and Cranes, 2012)
		Wärtsilä Low Loss Concept (power distribution)	6 (Wärtsilä, 2024)
Wet	Hull Resistance	Hull Air Lubrication	6 (Alfa Laval, 2024) (Silverstream Technologies, 2024)
		Hull Vane	7 (Hull Vane®, 2024)
		Fixed/Retractable Bow Foil	6 (Wavefoil, 2024) (AQUILA, 2024)
Windy	Propulsion	Flettner Rotor	6 (ANEMOI, 2024) (Norsepower, 2024)
		Fixed/Deployable Sails/Wings	6 (BAR Technologies, 2024) (Oceanbird, 2024)
		Deployable Kites	6 (Airseas, 2023) (Beyond the sea®, 2024)

3.2. Selection

For naval vessels, complex requirements can be broadly simplified into ‘Fight, Move, Float’; one EST from each category summarised in Table 2 was selected based on suitability for these requirements.

The effects of combining hull air lubrication with Flettner rotors on Venator-110 have previously been assessed by BMT, providing “a conservative estimate of 6% reduction in fuel” (Buckingham, 2023). For this reason, the addition of hull air lubrication and Flettner rotors on Venator-110 has not been reassessed during this study.

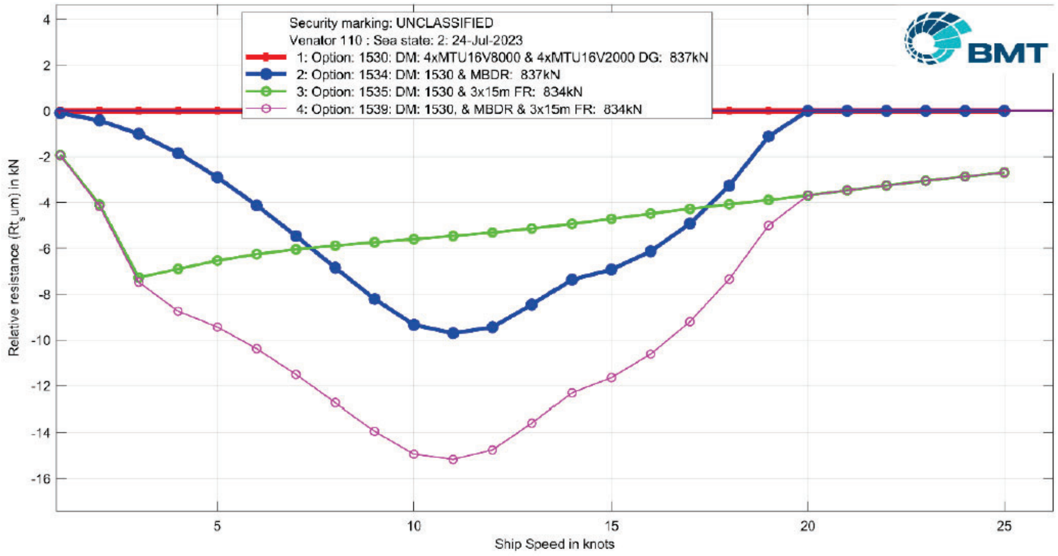

Figure 3: Reduction in relative ship resistance (kN) at sea state 2 with 3 Flettner rotors and micro bubble drag reduction (Buckingham, 2023).

3.2.1. Warm

Through power electronics, variable frequency drives alter the frequency and voltage of electrical supply to motors, subsequently controlling motor speed and torque to match system demands. These drives have a high TRL and are proven to provide fuel savings (ABB Marine and Cranes, 2012).

The Wärtsilä low loss recovery concept reduces the need for supply transformers to frequency converters, this configuration can result in a 2-3% higher system efficiency (Wärtsilä, 2024). Whilst substantial, the low loss concept was not investigated as it is best suited for ships with electric propulsion and has a lower TRL (Table 2).

Both variable frequency drives and the Wärtsilä low loss concept significantly impact system design and outfit, with variable frequency drives demanding additional volume onboard.

Through waste heat recovery there is the potential to save energy by incorporating an Absorption Chiller Plant (ACP) without significantly impacting the vessel's layout and outfit; an ACP could potentially replace a Chilled Water Plant (CWP) (Section 3.3.1). ACPs and CWPs are both used to provide cooling for various ship services. CWPs use a vapour-compression refrigeration cycle, which is electrically driven, to absorb heat from the chilled water loop and subsequently release the heat into a condenser. In contrast, ACPs are predominantly driven by heat and use an absorption process instead of a compressor, as a mixture of water and lithium bromide enables the cooling.

3.2.2. Wet

The energy saving performance of fixed/retractable bow foils is dependent on wave energy, wave direction and vessel route (Bowker & Townsend, 2022), which are less predictable when considering the operational requirements of a light frigate. Operationally, the bow foils are also likely to negatively impact the capability of the sonar dome. Hydrodynamically, Venator-110's waterline length is only optimal for bow foil performance in certain wave conditions (Bowker & Townsend, 2023). As Venator-110 is required to operate globally and maintain a sonar capability, bow foils were deemed unsuitable.

Fixed/retractable bow foils are reliant on wave energy; in contrast, a Hull Vane is dependent on vessel speed. A hull vane can be optimised for the specific vessel and corresponding operational profile. A Hull Vane can also reduce pitching accelerations, which can improve crew comfort and potentially increase the operational window for naval operations. Therefore, a Hull Vane fitted to the stern on the vessel, was considered most appropriate for application on a light-frigate.

3.2.3. Windy

Despite being able to provide significant thrust and energy savings (Buckingham, 2023) (Shukla & Ghosh, 2009) (Hussain & Amin, 2021), deployable/fixed sails and Flettner rotors were not considered for this study due to their large physical envelope and significant deck area requirements. Instead, deployable kites were selected for investigation, offering access to faster wind speeds through high altitude flight (Formosa, et al., 2023).

3.3. Analysis

3.3.1. Warm

Venator-110 requires four Chilled Water Plants (CWPs) to provide sufficient cooling. During chemical, biological, radiological, and nuclear closedown, there is a maximum cooling requirement of 2600kW. This load must be met with just three of the four CWPs, as the fourth CWP is required for redundancy for the chilled water system. For Venator-110, the air treatment unit and CWP sizing calculations state each CWP must therefore have a minimum cooling rating of 867kW, with approximately 250kWe electrical load per plant.

One of the four CWPs could be replaced by an ACP of an equivalent rating. ACPs convert low-grade heat into chilled water, requiring a significantly lower electrical load compared to CWPs, as ACPs are predominantly powered by thermal energy.

The feasibility of running an ACP is dependent on waste heat availability, and a large source of waste heat is generated by the main engines. Currently, waste heat is removed from the main engines via the exhausts, High Temperature (HT) lines and intercooler lines. As most ACPs at sea are either hot water or steam driven (Johnson Controls, 2019) (York, 2018) (Heinen & Hopman, 2024), it was investigated whether 90°C hot water from the HT lines could power a suitable ACP, and at which vessel speeds there would be sufficient waste heat available from the HT lines.

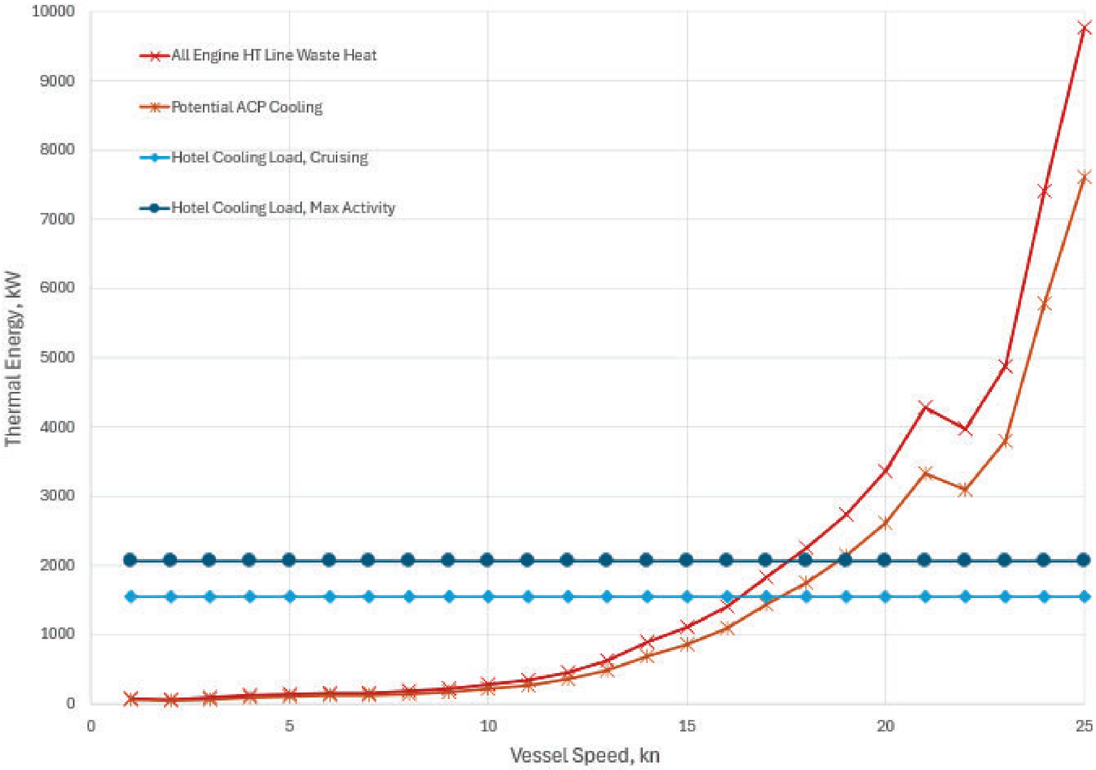

Figure 4: Graph of Thermal Energy Availability vs Vessel Speed for the Absorption Chiller Plant.

As each CWP is required to deliver 867kW cooling capacity, a replacement ACP must also provide at least 867kW of cooling. When considering the coefficient of performance for a Heinman & Hopman maritime ACP can be up to 0.8, a coefficient of performance of 0.78 was assumed implying the SWM-320 model would suffice (Heinen & Hopman, 2024).

At 15kn and above, there is sufficient waste heat available from the HT lines for this ACP to deliver the 867kW cooling requirement (Figure 4). This implies the SWM-320 could only be fully utilised for 43% of the vessel's operational profile (Figure 2), which would limit the redundancy in the chilled water system. Nevertheless, the ACP could be operated at vessel speeds lower than 15kn, but the subsequent effects to coefficient of performance during partial load were not explored.

Each CWP currently consumes 250kWe at full load. In contrast, the equivalently rated ACP consumes <10 kWe (Heinen & Hopman, 2024). The potential electrical load saving is therefore ~240kWe, which equates to a 3% fuel reduction when the ACP is running at full load, and a 1% reduction across the operational profile. For this study, waste heat from the main engine exhausts was not considered as available due to other ancillary pre-heating requirements during chemical, biological, radiological, and nuclear closedown. However, maritime ACPs can be set up to receive waste heat from multiple sources (Figure 5), which implies the ACP selected could sufficiently operate at lower loads for vessel speeds below 15kn.

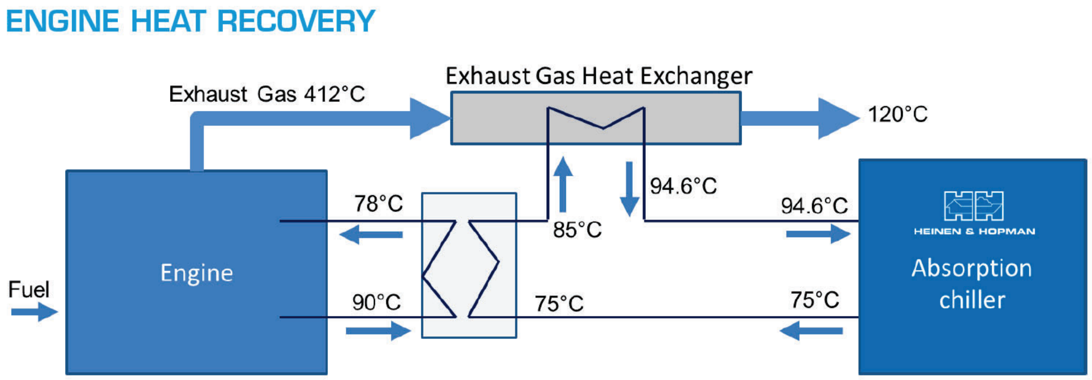

Figure 5: Optimised system layout for maritime absorption chiller plants (Heinen & Hopman, 2024).

3.3.2. *Wet*

Located on the stern, a Hull Vane creates a low-pressure region to suppress the stern wake (Çelik & Danışman, 2023). By accelerating fluid flow at certain speeds, a Hull Vane can generate forward thrust, stabilise trim and reduce the vessel's stern wake (Figure 7), all of which contribute to reducing overall hull resistance. A reduction in resistance and subsequent effective power requirements can further allow for reduced propeller loading and improved propulsive efficiency accordingly.

The energy saving potential from a Hull Vane depends on vessel type, waterline length and nominal operating speeds; vessels equipped with a Hull Vane and of similar characteristics to Venator-110 were identified, with the corresponding reported resistance reduction profiles captured in Figure 6.

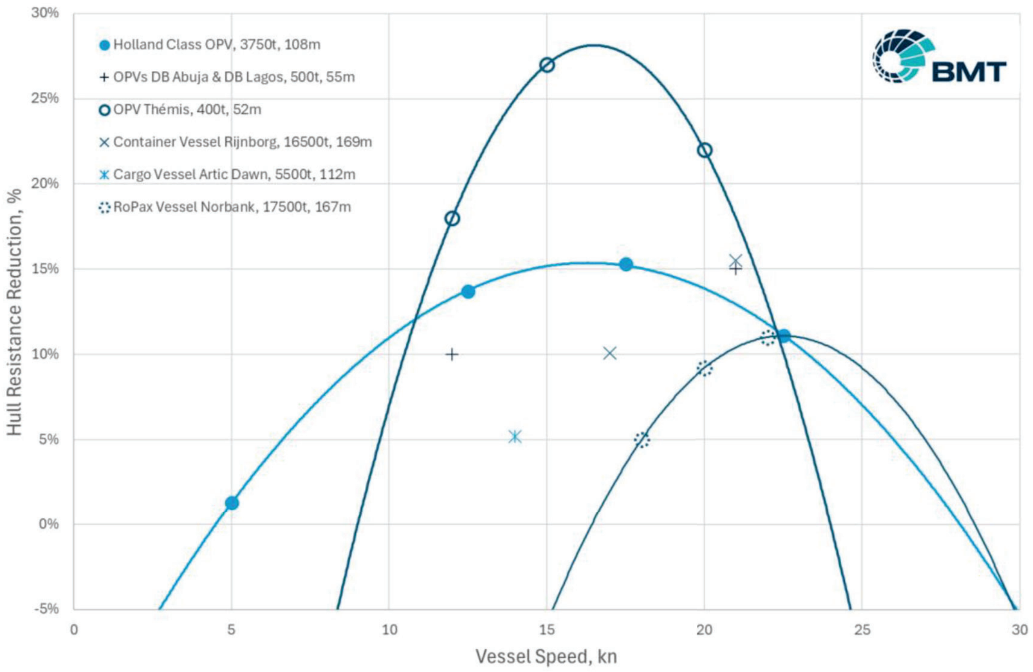

Figure 6: Graph of Hull Resistance Reduction vs Vessel Speed comparing vessels fitted with a Hull Vane (Hull Vane®, 2024)

There is poor convergence across the different vessels (Figure 6), caused by the appended (or simulated) Hull Vane being optimised for each specific vessel. However, the resistance reduction profiles all follow a negative second-degree polynomial in shape, going negative at the extremities of the vessels' nominal speed ranges. Of the vessels identified, the 108m Holland Class OPV is the closest match to Venator-110 in terms of vessel type, length and tonnage; therefore, it was assumed that a comparative resistance reduction profile could also be achieved for Venator-110.

Figure 10 illustrates the potential power saving of appending a Hull Vane to Venator-110. From this analysis, a Hull Vane could potentially reduce hull resistance by approximately 9% across the defined operational profile. . Whilst a Hull Vane can damp pitch accelerations, there is minimal impact to roll dampening implying naval manoeuvrability requirements could still be achieved (Bouckaert, et al., 2016).

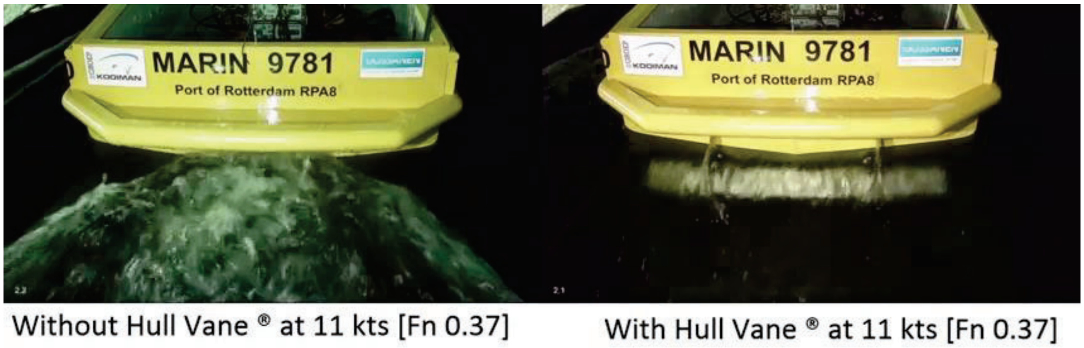

Figure 7: Demonstration of Hull Vane stern wake reduction (Van Oossanen Naval Architects, 2020)

3.3.3. Windy

Wind has been harnessed to propel ships for centuries, and contemporary sports such as kite surfing and kite boating exemplify the potential to use kites for at sea propulsion in the modern era. Unlike fixed/deployable sails and Flettner rotors, kites provide a compact and deployable solution which is perhaps more suited for warships. Companies such as 'Airseas' and 'Beyond the seas' are utilising kite assisted propulsion for medium-large vessels, offering up to 1000m^2 and 1600m^2 sized kites respectively (Airseas, 2021) (Beyond the sea®, 2024).

Kites can provide vessels with both thrust and lift, there are various approaches for determining these aerodynamic forces. Whilst physical experimentation and computational fluid dynamics are desirable for validation, there is also merit in implementing a simple Newtonian approach. NASA provides a guide for determining the aerodynamic forces acting on a kite (NASA, 2021), which supplemented the analysis conducted in this study when deriving kite thrust (Figure 8). Table 3 contains the particulars for the assumed kite installed on Venator-110; a 900m^2 kite surface area was deemed most appropriate when comparing vessel tonnage to commercial ships also utilising kite assisted propulsion.

Table 3: Kite Particulars.

Item	Value
Kite Surface Area (m^2)	900
Kite Aspect Ratio	4.5
Wind Speed over Oceans @ 100m - 300m (m/s)	10
Air Density at flight altitude (kg/m^3)	1.21
Angle of Attack (degrees)	5< AoA < 20

Kites only provide forward thrust in a tailwind, forces generated in headwinds would contribute to overall resistance. It was assumed that the probabilistic wind direction in relation to vessel direction was equal in all directions, implying Venator-110 only experiences tailwinds 50% of the time.

The useful component of kite thrust depends on the angle between prevailing wind direction and the vessel's direction of travel, so a Centreline Angle (CA) was used to account for the useful kite thrust component; a perpendicular crosswind provides no useful thrust component (Figure 8). Also, as vessel speed increases, the apparent wind speed diminishes, so a linear reduction to apparent wind speed was incorporated (Figure 9).

The kite generates both lift and thrust, the vessel could subsequently experience unwanted heave and surge. At this stage, a study into the total seakeeping impact was not conducted.

The kite's Angle of Attack (AoA) also effects the useful thrust generated; the kites lift coefficient must be greater than the drag coefficient for the kite to remain airborne under stable flight conditions. For this kite (Table 3), an AoA higher than 24° would cause back stall and lower than 0° would cause front stall. The safe operating range was determined to be AoAs between 5° to 20°, with 20° providing the optimum thrust point (Figure 8).

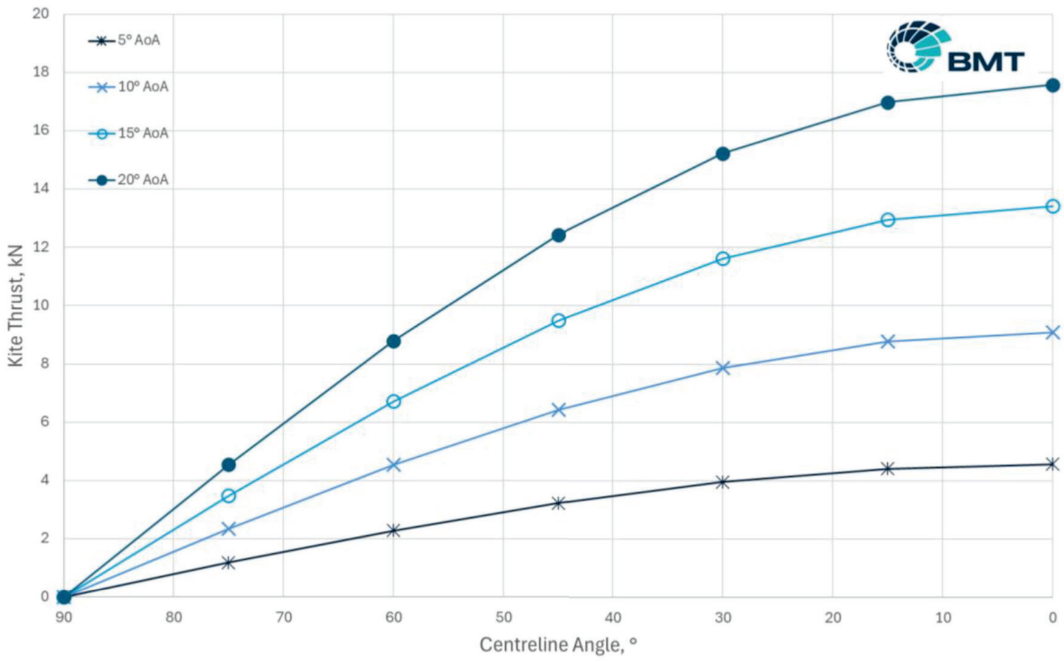

Figure 8: Graph of Kite Thrust vs Centreline Angle.

With a 50% chance of tailwinds, Figure 9 shows this kite could significantly contribute to reducing the vessel's delivered power demand for vessel speeds below 10kn. By contributing thrust, the kite reduces the vessels overall resistance and effective power requirements at a given speed, further allowing for reduced propeller loading and improved propulsive efficiency accordingly. The benefit of deploying a kite quickly diminishes beyond Venator-110 speeds of 10kn, as the apparent wind speed continues to reduce linearly and required power increases exponentially (Figure 10).

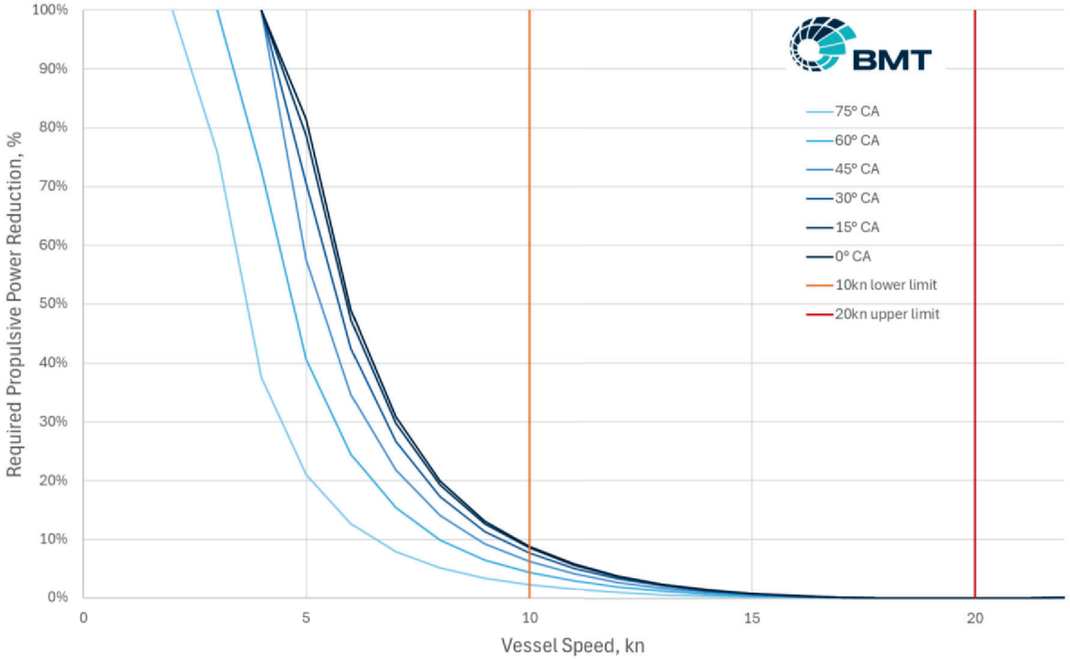

Figure 9: Graph of Required Propulsive Power Reduction vs Vessel Speed for kite assisted propulsion, at 10m/s wind speed.

Whilst this kite only offered favourable fuel savings at low speeds, several articles suggest that the Irish Navy were investigating the use of kites to extend passive radar range (Engineers Ireland, 2015) (Irish Independent, 2015). This highlights a potential strategic advantage for early warning detection, but there is limited evidence to suggest these kites have been developed further. Realistically, fuel savings at low speeds have a negligible impact to overall power reduction, especially for a medium-high speed operational profile (Figure 2).

For this kite, a theoretical 10% average power reduction could be achieved across the operational profile. This analysis assumed the kite is in static flight, whereas ‘Airseas’ suggest a parafoil wing forced to fly in “figure of 8 loops” can multiply the dynamic flight speed and subsequent thrust (Airseas, 2023).

However, when considering naval operational limitations, the kite would not be deployed for speeds lower than the in-harbour pilotage speed of 10kn, or above the sprint/pursuit speed of 20kn when Venator-110 is travelling with urgency (Figure 9). Naval operational limitations for when the kite could be deployed result in a <1% energy saving across the operational profile.

3.4. Performance Overview

Figure 10 illustrates the potential benefits when an ACP, Hull Vane and kite is incorporated into the design of Venator-110. Across the operational profile, a Hull Vane is expected to represent the largest efficiency gain, and the kite the least. For vessel speeds of 4kn and below, the Hull Vane has a negative efficiency impact, whereas the kite is most effective at these speeds; the kite could potentially offset the Hull Vane losses at 4kn and below if deemed suitable for naval operations at these speeds.

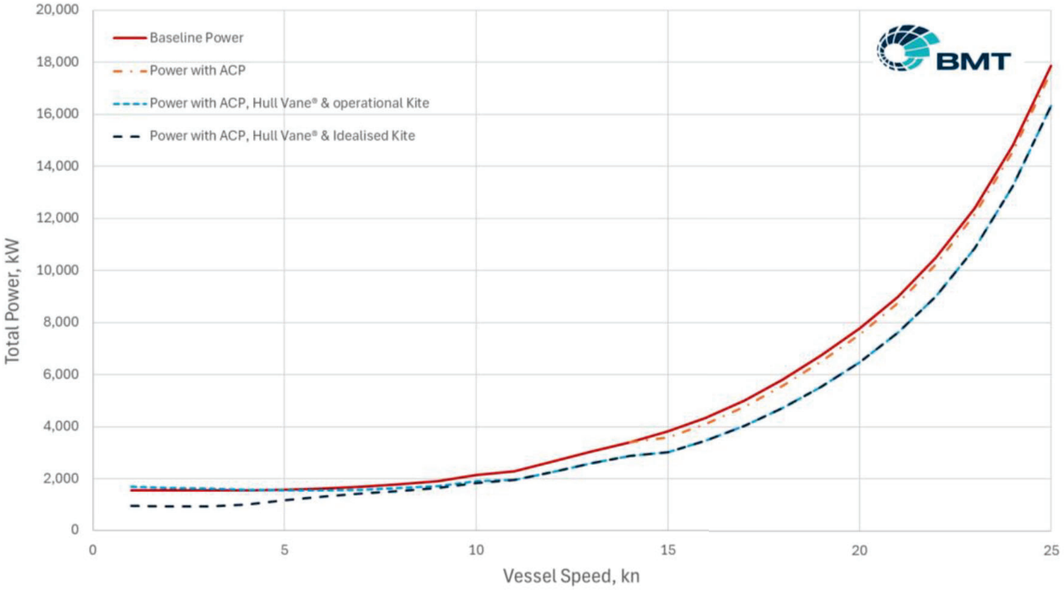

Figure 10: Graph of Total Power vs Vessel Speed for Venator-110 comparing the selected ESTs.

When considering the operational profile, potential fuel savings peak at 15kn, caused by the Hull Vane resistance reduction and the ACP operating at full cooling capacity (Figure 11). Due to the added drag of the Hull Vane at low speeds, additional fuel would be required for vessel speeds below 4kn as shown (Figure 11). Fortunately, when time spent at each speed is also considered (Figure 2), these losses are negligible.

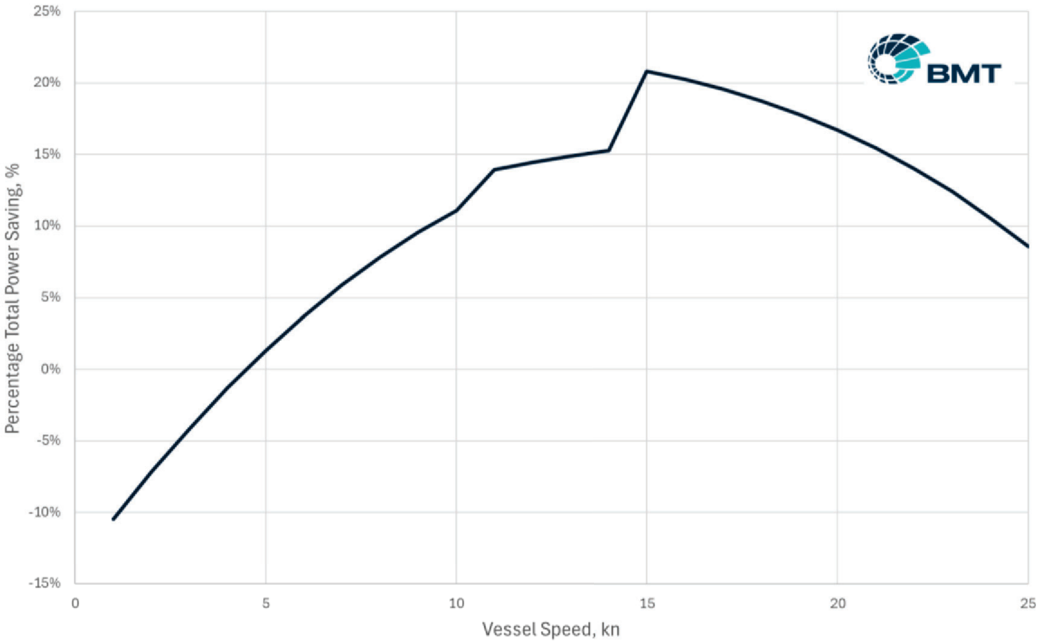

Figure 11: Graph of Percentage Total Power Saving vs Vessel Speed for the selected ESTs.

4. Future Fuels

4.1. Overview

Figure 12 illustrates the bunkering availability of methanol, ammonia, hydrogen, and LNG. With future fuels offering reduced bunkering availability compared to commercial marine fossil fuels, the range in terms of nautical miles of future fuel powered vessels, alongside potential for Replenishment at Sea (RAS) must reflect this fuel availability.

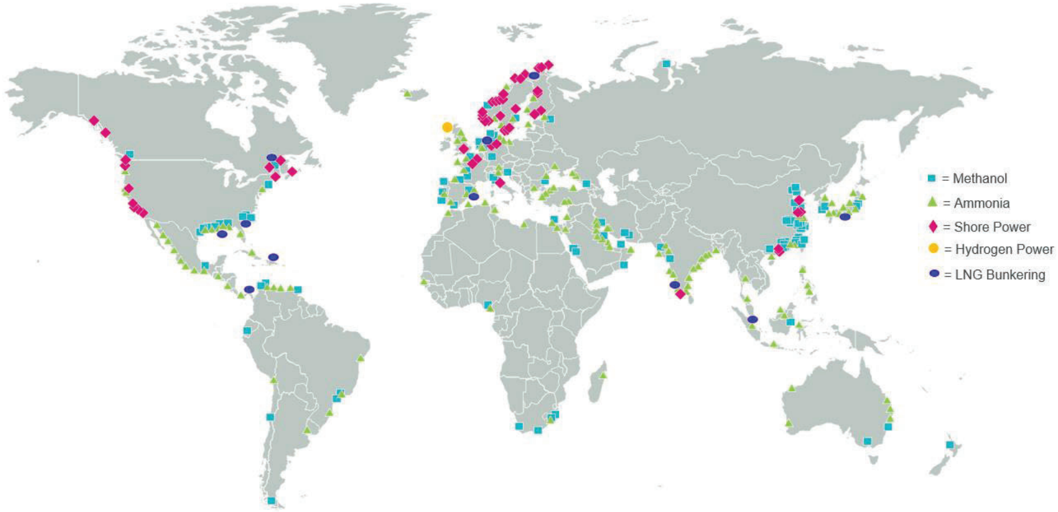

Figure 12: Future fuel availability (Dr Beard, 2023).

In January 2023, 105,500 ships of 100 gross tonnes or more were registered in the global fleet (UNCTAD, 2023). In comparison, the UK's Royal Navy and Royal Fleet Auxiliary (RFA) consisted of a combined 71 vessels in 2022 (House of Commons, 2022).

Switching to future fuels could represent a significant cost yet represent minimal environmental benefit for the Royal Navy in comparison to the environmental impact of the commercial fleet.

However, if a switch to an alternative energy source is not made, the Royal Navy may face future fuel availability implications, especially considering IMO's Green House Gas (GHG) reduction strategy which aims to achieve net-zero GHG emissions for commercial shipping by 2050 (International Maritime Organization, 2024). Therefore, to maintain operational capability it is imperative to assess the impact that future fuels will have upon naval vessels.

Whilst drop-in fuels could be integrated into Venator-110, Table 4 offers a comparison of Ammonia, Methanol and Hydrogen.

Table 4: Fuel Suitability for naval vessel (Dr Beard, 2023).

	Hydrogen, H_2	**Liquified Natural Gas (LNG), CH_4**	**Ammonia, NH_3**	**Methanol, CH_3OH**	**F-76**
With Tank (Gross) Volumetric Energy Density (MJ/l)	2.7-7.9	13.2	11.5	14.2-15.1	27.3-31.0
General Storage Conditions	Cryogenic or Pressurised	Cryogenic	Cryogenic or Pressurised	Ambient	Ambient
Space Requirement	7.7-15.7	3.2	3.4-6.4	2.3	1.0
Flast Point (°C)	-253	-162	-33	+12	+61.5
Minimum Ignition Energy in Air (mJ)	0.02	0.29	8.0	0.14	20.0
Explosion Risk	Large flammability range with low ignition energy	Medium flammibility range with reasonable ignition energy	Medium flammibility range with high ignition energy	Medium flammability range with high ignition energy	Small flammibility range with high ignition energy
Toxixity	None	None	Highly toxic to humans and aquatic life	Toxic to humans, but very low toxicity to aquatic life	Refence Fuel
Combustion Emissions	NO_X	NO_X & Lower CO_X	NO_X	NO_X & Lower CO_X	CO_X, NO_X, SO_X & PM

4.2. Future Fuel Performance Assessment

Before the impact that both ESTs and future fuels has upon Venator-110 can be assessed, a baseline performance assessment of a future fuel powered Venator-110 is required. This baseline assumes that ESTs are not implemented.

The future fuel baseline for Venator-110 is based on methanol, which offers both good TRL and integration into the Venator-110 platform. This paper does not offer a performance comparison for Ammonia or Hydrogen variants.

4.2.1. Methanol Assumptions

When assessing the performance of a methanol Venator-110 variant, the following assumptions have been applied:

- Venator-110 methanol retains the same capabilities, other than range, as the base vessel Venator-110 F-76.
- Current F-76 tanks have been converted to methanol, cofferdams are needed where methanol tanks are not adjacent to ballast water tanks (Lloyd's Register, 2023). Although, companies are developing solutions which significantly reduce cofferdam size requirements.
- Venator-110 methanol retains the same displacement and installed power as the base vessel.
- Venator-110 methanol uses 95% methanol and 5 % diesel as a fuel emulsion to improve combustion (Shukla, et al., 2021).
- The methanol combustion engines have a SFC of 380g/kWh (Shukla, et al., 2021).

- The dual fuel methanol engines have a comparable or improved delivered density when compared to the current MTU 16V8000M91L installed on Venator-110 F-76 (Shukla, et al., 2021).
- Values for the annual bunkering frequency are based on the operational profile (Figure 2) assuming tank capacities do not drop below 40% for typical operation.

4.2.2. Performance Baseline

Table 5: Comparison of Venator-110 Methanol and F-76 variants without EST Installed.

Item	**Value**		**Performance of Methanol as a Percentage of F-76 (%)**
	Methanol	**F-76**	
Range at 15kn (nm)	*2880*	*6000*	*48*
Annual Bunkering Frequency	*30*	*20*	*150*
CO_2 Emissions Per Nautical Mile (tCO_2/nm)	*0.0103*	*0.2065*	*5*

Assuming green methanol is bunkered, CO_2 emissions are associated with the use of the 5% diesel fuel as an emulsion, as methanol internal combustion technology matures this proportion should significantly decrease (Shukla, et al., 2021). However, even when 100% methanol is combusted, CO_2 emissions will still be generated by the ship; therefore, green methanol must be used. This will create a carbon cycle, meaning that the resulting CO_2 ship emissions are net-zero.

Without the use of ESTs, Venator-110 methanol offers a significantly reduced range, and increased bunkering frequencies when compared to the F-76 variant.

ESTs are imperative to mitigate the need to trade-off operational capabilities when integrating future fuels into the future naval fleet. Table 6 and Table 7 provide insight into the need for ESTs at 15kn cruising speed and across the operational profile accordingly.

4.2.3. Performance of Venator-110 with ESTs.

Table 6: Venator-110 EST Comparison at 15kn

Total EST Saving	**Range at 15kn**	
	Methanol (nm)	**F-76 (nm)**
All Off, 0%	*2880*	*6000*
All On, 21%	*3480*	*7260*

Table 7: Venator-110 Methanol EST Performance Based on Operational Profile

Operational Profile (nm)	*73550*	
Total EST Saving	*All Off, 0%*	*All On, 13%*
Annual Bunkering Frequency	*34*	*30*
Total CO2 Emissions (tCO2)	*759.5*	*660.8*

At 15kn, Table 6 shows that the assessed ESTs can provide a conservative increase in range of 600nm and 1260nm for methanol and F-76 variants accordingly. This both significantly increases the viability of future fuel powered variants and allows for increase operational capability of F-76 powered variants.

Across the operational profile of 5000hrs/year underway at sea, Table 7 shows the that the use of ESTs reduces the annual bunkering frequency from 34 to 30, further improving the viability of a methanol variant of Venator-110.

Across the operational profile, ESTs offer a reduced energy saving when compared to when the vessel is underway at 15kn. If the operational profile was optimised for this speed, the difference in EST energy saving could be significantly less.

5. Conclusions

Commercially available ESTs can be integrated onto naval vessels to enable improved operational capability, reduced running costs and lower emissions via efficiency improvements.

For this study, the effects of adding an absorption chiller plant, a Hull Vane, and a deployable kite to Venator-110 powered by both F-76 and methanol were investigated. No detailed physical ship integration or interface studies were undertaken.

The assessed combination of ESTs reduced the power requirements of Venator-110 by 13% across the defined operational profile. The Hull Vane provided the greatest potential energy savings for Venator-110; however, this may not be the same for all vessel types with EST suitability and selection being unique for every vessel type.

With all of the selected ESTs being utilised, at 15kn the F-76 powered Venator-110 has a range of 7260nm; a 21% improvement when compared to the 6000nm range when the assessed ESTs are not engaged. This study also investigated the performance of a Methanol powered Venator-110, and without ESTs, Venator-110 running on methanol at 15kn offers a range of 2880nm; this range is increased to 3480nm when utilising all of the assessed ESTs. Therefore, ESTs will significantly contribute to the successful integration of future fuels onto naval vessels. By implementing ESTs alongside future fuels, the need to trade operational capabilities is reduced when developing future fuel powered vessels; however, even with all assessed ESTs being utilised, the range of the methanol powered Venator-110 at 15kn is only 58% that of the range of the F-76 powered Venator-110 with no ESTs.

To mature this study, further technical development of the Venator-110 methanol variant is required. This would enable the selected ESTs to be further optimised for Venator-110's operational profile. To validate the potential fuel savings, CFD or model towing tests of a bespoke Hull Vane designed for Venator-110 is required.

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References

ABB Marine and Cranes, 2012. *Using Variable Frequency Drives (VFD) to save energy and reduce emissions in newbuilds and existing ships,* s.l.: ABB.

Airseas, 2021. *Airseas' Seawing sets sail on Louis Dreyfus Armateurs' Ville de Bordeaux, chartered by Airbus.* [Online]
Available at: https://airseas.com/en/airseas-seawing-installation/

Airseas, 2023. *SEAWING.* [Online]
Available at: https://airseas.com/en/seawing-system/

Alfa Laval, 2024. *Ocean Glide.* [Online]
Available at: https://www.alfalaval.com/products/process-solutions/fluidic-air-lubrication/oceanglide/
[Accessed 15 March 2014].

ANEMOI, 2024. *Rotor Sail Deployment Systems.* [Online]
Available at: https://anemoimarine.com/flettner-rotor-ship/
[Accessed 20 March 2024].

AQUILA, 2024. *Which Aquila model can be retrofitted with after-market Hydro Glide™ foils?.* [Online]
Available at: https://www.aquilaboats.com/aquila-enquirer/question-fourteen
[Accessed 20 March 2024].

BAR Technologies, 2024. *Wind Wings.* [Online]
Available at: https://www.bartechnologies.uk/project/windwings/
[Accessed 9 March 2024].

Beyond the sea®, 2024. *Beyond the sea: by Yves Parlier.* [Online]
Available at: https://beyond-the-sea.com/en/seakite/

BMT, 2024. *BMT VENATOR-110 Frigate.* [Online]
Available at: https://www.bmt.org/projects/project/3353/bmt-venator-110-frigate

Bouckaert, B., Utihof, K., Moerke, N. & Oossanen, P., 2016. *Hull Vane® on 108 m Holland-Class OPVs : Effects on Fuel Consumption and Seakeeping,* s.l.: s.n.

Bouckaert, B. et al., 2015. *A Life-cycle Cost Analysis of the Application of a Hull Vane® to an Offshore Patrol Vessel.* Washington, DC, 13th International Conference on Fast Sea Transportation.

Bowker, J. A. & Townsend, N. C., 2022. A probabilistic method to evaluate bow foils for realistic seas and shipping routes. *Applied Ocean Research.*

Bowker, J. & Townsend, N., 2023. *The effect of ship length scale on bow foil efficiency gains in waves,* s.l.: s.n.

Buckingham, J. E., 2023. *The Impact of Dual Energy Saving Technologies on a Frigate's Duties.* s.l., s.n.

Çelik, C. & Danışman, D. B., 2023. *Powering performance prediction of a semi-displacement ship retrofitted with Hull Vane.* s.l., Ocean Engineering.

Dr Beard, T., 2023. *Maritime Alternative Fuels.* Bath: BMT.

Dr Beard, T., 2023. *Maritime Alternative Fuels.* Bath: BMT.

Engineers Ireland, 2015. *Ship kite system to enhance efficiency and communications unveiled by Defence Forces.* [Online]
Available at: https://www.engineersireland.ie/Engineers-Journal/News/ship-kite-system-to-enhance-efficiency-and-communications-unveiled-by-defence-forces

Formosa, W., Sant, T., Muscat-Fenech, C. D. M. & Figari, M., 2023. Wind-Assisted Ship Propulsion of a Series 60 Ship Using a Static kite Sail. *Marine Science and Engineering.*

General Electric, 2020. *GE Powers US Navy's 1st Full-Electric Power and Propulsion Ship.* [Online]
Available at: https://www.ge.com/news/press-releases/ge-powers-us-navys-1st-full-electric-power-and-propulsion-ship

Heinen & Hopman, 2024. *Maritime Absorption Chiller.* [Online]
Available at: https://www.heinenhopman.com/products/absorption-chiller/
[Accessed 16 March 2024].

Hou, H. et al., 2020. *An experimental investigation of the impact of retrofitting an underwater stern foil on the resistance and motion.* s.l., Ocean Engineering.

House of Commons, 2022. *The Royal Navy's Surface Fleet.* [Online]
Available at: https://commonslibrary.parliament.uk/research-briefings/cbp-9697/

Hull Vane®, 2024. *108m Offshore Patrol Vessel Holland Class.* [Online]
Available at: https://www.hullvane.com/project/108m-offshore-patrol-vessel-holland-class/

Hull Vane®, 2024. *Hull Vane®.* [Online]
Available at: https://www.hullvane.com/naval-patrol-vessels/

Hussain, D. & Amin, O., 2021. A Comprehensive Analysis of the Stability and Powering Performances of a Hard Sail–Assisted Bulk Carrier. *Journal of Marine Science and Application.*

International Maritime Organization, 2024. *International Maritime Organization (IMO) adopts revised strategy to reduce greenhouse gas emissions from international shipping..* [Online]
Available at: https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx#:~:text=The%20revised%20IMO%20GHG%20Strategy%20includes%20an%20enhanced,well%20as%20indicative%20check-points%20for%202030%20and%20204

IRENA, 2024. *Geopolitics of the energy transition: Energy security,* Abu Dhabi: International Renewable Energy Agency.

Irish Independent, 2015. *Fuel costing too much? Follow the Navy's example... use a kite.* [Online]
Available at: https://www.independent.ie/regionals/herald/fuel-costing-too-much-follow-the-navys-example-use-a-kite/30924379.html

Jimenez, V. J., Kim, H. & Munim, Z. H., 2022. A review of ship energy efficiency research and directions towards emission reduction in the maritime industry. *Journal of Cleaner Production.*

Johnson Controls, 2019. *Johnson Controls Marine Case Study - Absorption Chillers.* [Online]
Available at: https://www.johnsoncontrols.co.uk/insights/2021/case-studies/marine-hvac-case-study---absorption-chillers

Landon, C. D., n.d. *Tac Talks: Fight, Move, Float - It is Time to Simplify Command.* [Online]
Available at: https://seapower.navy.gov.au/media-room/publications/tac-talks-11

Lloyd's Register, 2023. *LR, SDC Ship Design and Consult develop innovative space saving concept for methanol-fuelled vessels.* [Online]
Available at: https://www.lr.org/en/knowledge/press-room/press-listing/press-release/lr-sdc-ship-design-and-consult-develop-innovative-space-saving-concept-for-methanol-fuelled-vessels/

Maersk, 2023. *Maersk orders six methanol powered vessels.* [Online]
Available at: https://www.maersk.com/news/articles/2023/06/26/maersk-orders-six-methanol-powered-vessels

Ministry of Defence, 2013. *Fuel, Naval, Distillate NATO Code: F-76 Joint Service Designation DIESO F-76.* Bristol: Ministry of Defence.

NASA, 2021. *Aerodynamics of Kites.* [Online]
Available at: https://www.grc.nasa.gov/WWW/k-12/airplane/kiteaero.html

Newman, S. & Beard, T., 2022. *The Viability of Low-Carbon Fuels for the Front-Line Naval Vessel.* Bristol, RINA.

Norsepower, 2024. *Product.* [Online]
Available at: https://www.norsepower.com/product/
[Accessed 15 March 2024].

Oceanbird, 2024. *Oceanbird.* [Online]
Available at: https://www.theoceanbird.com/
[Accessed 16 March 2024].

Sahoo, P., Andrews, I., Avala, V. K. & Ramakrishnan, S., 2015. *Resistance Characteristics For High-Speed Hull Forms with Vanes.* Washington, DC, s.n., pp. SNAME-FAST-2015-012.

Shukla, P. C., Belgiorno, G., Di Blasio, G. & Agarwal, A. K., 2021. *Alchol as an Alternative Fuel for Internal Combustion Engines.* Singapore: Springer.

Shukla, P. & Ghosh, K., 2009. Revival of the Modern Wing Sails for the Propulsion of Commercial Ships.

Silverstream Technologies, 2024. *The Silverstream® System: Market Leading.* [Online]
Available at: https://www.silverstream-tech.com/
[Accessed 20 March 2024].

SkySails Marine, n.d. *A PIONEER REACHING FOR NEW HORIZONS.* [Online]
Available at: https://skysails-marine.com/#:~:text=The%20wind-assisted%20ship%20propulsion%20system%20from%20SkySails%20uses,2MW%20of%20propulsion%20power%20from%20the%20main%20engine.

Spector, M. S., 2017. *Waste Heat Recovery in Military Applications.* [Online]
Available at: https://arpa-e.energy.gov/sites/default/files/2d%20-%20Spector%20%28final%29.pdf

TWI, 2024. *What are Technology Readiness Levels (TRL)?.* [Online]
Available at: https://www.twi-global.com/technical-knowledge/faqs/technology-readiness-levels
[Accessed 2 March 2024].

UNCTAD, 2023. *Merchant Fleet.* [Online]
Available at: https://hbs.unctad.org/merchant-fleet/#:~:text=In%20January%202023%2C%20the%20world%E2%80%99s%20merchant%20fleet%20consisted,which%2056%20500%20ships%20were%20over%201000%20gt.
[Accessed 2024 March 10].

Van Oossanen Naval Architects, 2020. *RPA8.* [Online]
Available at: https://oossanen.nl/project/rpa8/

Wärtsilä, 2024. *Electric Propulsion Systems: Low Loss Concept (LLC).* [Online]
Available at: https://www.wartsila.com/marine/products/ship-electrification-solutions/electric-propulsion-systems/low-loss-concept#:~:text=The%20Low%20Loss%20Concept%20%28LLC%29%20is%20a%20power,the%20frequency%20converters%2C%20especially%20those%20supplying%20electri

Wavefoil, 2024. *Retractable Bow Foils.* [Online]
Available at: https://wavefoil.com/
[Accessed 18 March 2024].

York, 2018. *The New Era of Absorption Chillers.* [Online]
Available at: https://www.york.com/-/media/Project/JCI-Global/York-Sites/United-States-York/Insights/Files/Article-PDFs/Chillers/CHI_Article_Absorption_Chiller_Technology_Moves_Forward.pdf

Dual Fuel Technology: A route to reduce emissions

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Synopsis

Naval vessels have a set of key requirements that should be kept to ensure operational capability. Whilst we design vessels for war, the reality is that many are used for various other roles and rarely see combat. How do we ensure navies can play their part in reducing emissions without impacting on capability in times of conflict? Utilising dual fuel arrangements provides the opportunity to reduce emissions during peace time operations whilst also providing an increase in survivability during combat as well as ensuring fuel availability has a reduced impact on the vessel. This paper will explore the work conducted to integrate dual fuel methanol on the BMT concept Ellida vessel an amphibious transport vessel.

Keywords: Dual Fuel; Propulsion; Integration; Marine systems

1. Introduction: Moving away from fossil fuel

The need to meet Net Zero 2050 is widely accepted now, but there are many hard to abate sectors one of which is maritime. The maritime sector are striving to reach this target for the majority of commercial vessels (International Maritime Organization, n.d.). Whilst many areas of the commercial sector are making inroads to reduce emissions, the only way to fully meet the target is by changing fuel away from fossil fuel derivatives.

The commercial sector are investing in a variety of future fuels; electric, hydrogen, ammonia and methanol are all options on the table. As stated by Steve Gordon, Global Head of Clarkson Research: *"2023 was a hugely significant year in the shipping industries decarbonization pathway, with new regulation entering into force and a net zero commitment agreed at IMO. And while we remain only at the start of a vital and unprecedented fleet renewal investment program, a start has been made with 49% of current orderbook tonnage now alternative fuelled*," (Offshore Energy, n.d.).

Whilst biofuel is currently being considered the reality is that it would be impossible to produce the quantities required, especially when in competition with other sectors such as aviation. This then gives a future maritime fuel mix that is significantly varied. Methanol is a fuel that has significant interest from the Commercial sector with several vessels operating on methanol fuel across the globe, although this only supports emission reductions when created from non-fossil fuel sources.

Future naval vessels may well have targets to reduce emissions, whilst there may be the opportunity for Government dispensation. The UK Government has set a target for Net Zero 2050 which includes defence (Department for Energy Security & Net Zero, 2023). What cost does this come at? Some of the potential impacts from this are:

- Reduced operating areas, at least in peace time;
- Lack of fossil fuel availability;
- Long term lack of suppliers;
- Public opinion.

It is envisaged that there could be a requirement to transition from fossil fuel (F76) for naval vessels. This then poses the question about what could be the fuel and how best to integrate them whilst maintaining capability and operational reach.

A potentially leading fuel for naval vessels is methanol, most likely synthetic rather than bio-derived. This is technology that is already available, with commercial vessels operating on methanol at the moment (DNV, 2024). The use of methanol could support a naval energy transition. It is postulated in this paper that rather than pure methanol the use of dual fuel has advantages in the near term as well as ensuring minimal impact on capability and operations. This concept is explored further within this paper, including the vessel considerations and operational impacts.

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2. Methanol as a Fuel

Methanol is a carbon based fuel, containing a single carbon atom, that as stated earlier could be Net Zero depending on the source of this carbon atom. Currently most methanol production is from fossil fuel, which is not practical and ‘green’ production requires significant scaling. High-level details of methanol are provided in Table 1 with greater detail covered in the following subsections.

Table 1 Comparison of some properties of Methanol & Diesel (Newman & Beard, 2022)

	Methanol	**F-76 (MGO)**
With Tank (Gross) Volumetric Energy Density (MJ/L)	14.2 – 15.1	27.3 – 31.0
General Storage Conditions	Ambient	Ambient
Flash Point (°C)	+12	+61.5
Flammability Limits in Air (vol%)	7.3 – 36.0	0.7 – 5.0
Minimum Ignition Energy (mJ)	0.14	20.0
Toxicity	Humans & Aquatic Life	
Emissions	Low COx, NOx	Standard

2.1.1. Storage

Methanol like almost all of the alternatives has a lower volumetric energy density compared to diesel, ~14.5 MJ/L compared to ~29.2 MJ/L, when including tankage. This equates to ~2.3 times more volume required for fuel. However, methanol is a liquid at ambient conditions which means it can be stored in a similar manner to diesel and that standalone tankage is not required.

The main requirement for methanol tanks is to be able to withstand the corrosive nature, requiring either specialist coatings or stainless steel to mitigate. Currently there is a requirement for cofferdams to be used which is included in the spatial requirements stated before. But there are now solutions becoming available to reduce this spatial requirement, such as the Sandwich Plate System (SRC , n.d.). The cofferdams are not required if methanol is stored below the water line at the shell, because methanol is soluble in water. Unlike the double bottom required for diesel tanks on commercial vessels, which could alleviate some of the spatial constraints mentioned.

2.1.2. Safety

Methanol has a flashpoint of +12°C which means that vapours will be released that in sufficient concentrations could ignite in air. Therefore methanol is classed as a low-flashpoint fuel and a vessel would need to comply with the IGF code (IMO, 2022), it should be noted that the criteria for low flashpoint is +61°C. To mitigate against this tanks should utilise nitrogen inerting to minimise the accumulation of vapours.

Flammability is a concern with methanol as it has a wide flammable range, 7.3 – 36.0 vol%, although it should be noted that the Lower Flammability Limit (LFL) of methanol is greater than the Upper Flammability Limit (UFL) of diesel. This means that diesel vapour could ignite at lower concentrations compared to methanol, but also that it only has a small range to ignite in comparison to methanol. The other factor to consider with flammability is the ignition energy, these are generally parabolic functions. The saddle-point of which is known as the minimum ignition energy and is generally at the stoichiometric mixture, which for methanol is extremely low at 0.14 mJ compared to diesel at 20.0 mJ. Either side of this point it is more difficult to ignite as the concentration increases or decreases. Methanol also burns with a pale blue flame that is almost invisible.

Toxicity is the other significant risk to crew on-board. As stated in Table 1, methanol is toxic to humans and aquatic life, although for aquatic life toxicity is low. The thresholds for humans is 30-240 mL (ingestion), which can occur via ingestion, inhalation or skin contact. However there are methods to mitigate methanol toxicity, including fomepizole or ethanol (National Library of Medicine, 2023).

2.1.3. Availability

Methanol currently has limited availability across UK & Europe compared to diesel, although has slightly better availability globally. This is shown in Figure 1.

Figure 1 Methanol Bunkering Locations (DNV, 2024)

2.1.4. Prime Movers

There are two main methods to release energy from methanol, combustion or chemically. Combustion is via either Internal Combustion Engine (ICE) or possibly a Gas Turbine (GT), whilst chemical release of energy is via Fuel Cell (FC).

Currently methanol ICE is still in the infancy although more OEMs are providing solutions for this and there are ships in operation with methanol. The engines can come as dual fuel rather than pure methanol (DNV, 2023). Regardless of the approach used, methanol is likely to require a pilot fuel which would support the use of dual fuel instead of just methanol.

Fuel cells involve a chemical reaction to create the energy. There are various types of fuel cell, although many of these are only suitable for pure hydrogen (99.999% purity). This would then require ‘cracking’ of the methanol to release the hydrogen for use in a fuel cell. Solid-Oxide Fuel Cells (SOFC) which operate at higher temperatures do not require ‘cracking’, although these are low-medium TRL at the moment.

2.1.5. Emissions

Methanol will still produce COx emissions regardless of the prime mover, although it could be captured to support a carbon cycle for synthetic production. If methanol is combusted then NOx would be produced as well. There may also be other emissions which would be associated with lubricants that are used.

However, methanol produced from non-fossil fuel sources, i.e. bio or synthetic derived, would be net-zero. This is currently accepted within several regulations including FuelEU Maritime.

This then means that when operating the vessel in dual fuel mode, methanol with diesel pilot fuel, then the emissions would be reduced by circa 85%. Localised carbon emissions still occur but the overall impact on the environment is only from the pilot fuel, although this may be negligible if this is also synthetic or bio derived. This route also significantly reduces the quantity of bio or synthetic diesel that would be required.

3. Ship Integration

3.1.1. Dual-Fuel System Arrangement

Dual-Fuel marine engines allow for operating in two modes (Diesel Only & Methanol), noting the Methanol mode does require a small amount of Diesel as a pilot fuel as detailed earlier in this paper. Each type of fuel requires its own dedicated fuel supply system (pumping arrangement, pipework) to transfer the fuel from the storage/service tanks to the engine for combustion. This typical arrangement, results in duplicate of fuel supply systems as well as dedicated fuel tanks for each type of fuel, which on commercial vessels can be accommodated within the design, but is a challenge for warships given available space is a premium.

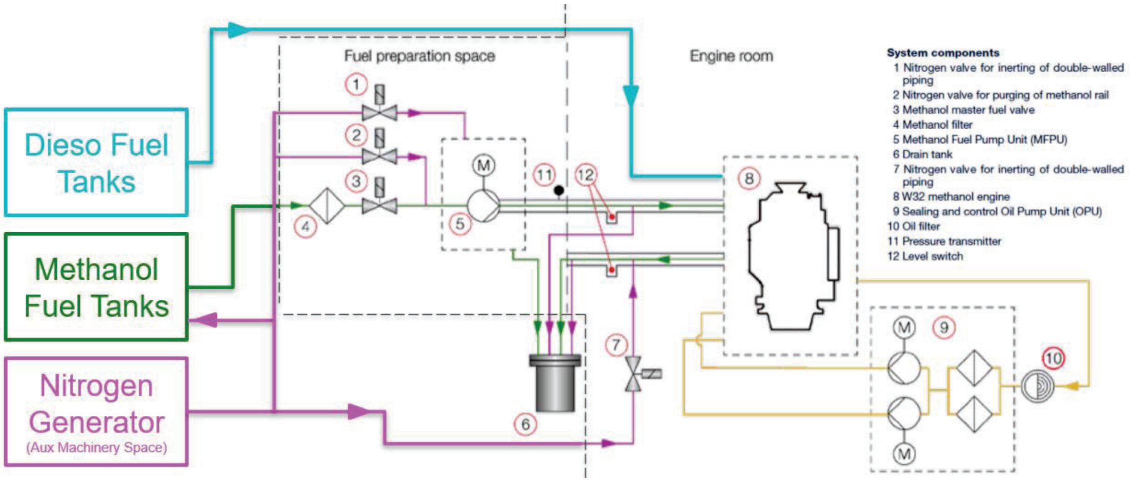

Figure 2 Dual-Fuel System Layout for Methanol & Diesel supplied Marine Engine (Wartsila, n.d.)

3.1.2. Design Considerations

It has already been stated that a methanol vessel would need to align with the IGF code. This means that the vessel design needs to be adapted to conform to these additional standards, above the typical standard applied for warships (e.g. Lloyds Rules for Naval Ships).

Methanol has similar storage requirements to Diesel (i.e. non-cryogenic or compressed storage). The amount of design change to incorporate compared to Diesel is considerably less than any fuel requiring stand-alone (cryogenic or compressed) storage. This provides the opportunity to potentially consider retrofit installation of methanol as an alternative fuel within a vessel, rather than new-build only.

Noting, a new-build design that has already accounted for a methanol fuel can be optimised to minimise any impacts. The following areas of design are impacted by combining a methanol fuel on board a vessel:-

3.1.3. Tank Design & Arrangement

Current engine technology for Methanol requires a pilot fuel to support the combustion process within the engine, requiring a continued supply and storage of Diesel within the vessel arrangement.

Commercial vessel design has adapted to provide independent fuel storage tanks for the two types of fuel (either Methanol or Diesel). For vessels dedicated to operating on methanol fuel, and typical pilot fuel consumption of 15%, fuel storage tank capacity would likely be split to match the 85:15 ratio to optimise fuel capacity for maximum range of the vessel. This is shown in Figure 3.

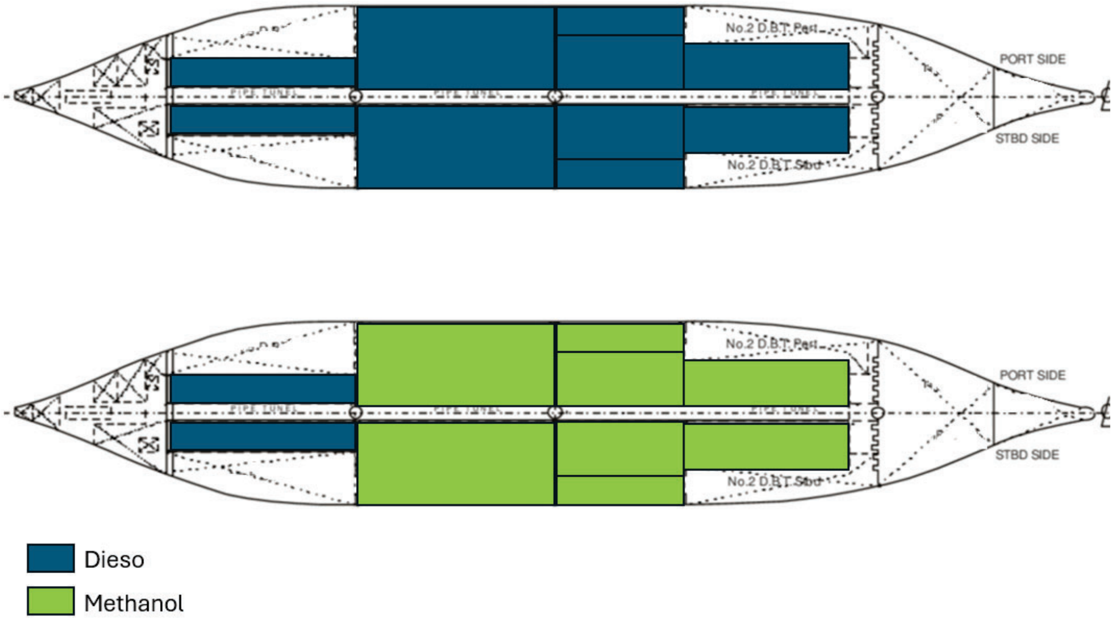

Figure 3 Typical Tank Arrangement Diesel Only v Methanol & Diesel

Although Methanol can be stored at the same ambient temperature and pressure as Diesel, the corrosive nature of the fluid is not supported by a standard bare steel tank. To mitigate this, either a specialist coatings (Zinc Sulphate) can be applied to the standard steel tank, or alternatively the use of a different material (e.g. Stainless Steel). The latter is considered a very expensive alternative due to the size of these tanks within a naval vessel, but may be more appropriate for fuel header tanks or service tanks.

Design guidelines for Methanol fuel tanks within commercial vessels require protective cofferdam with vapour and liquid leakage detection. However, as Methanol is soluble in water , the cofferdam arrangement is not required below the waterline, unlike double hull requirements for Diesel Tanks, see Figure 4. This has been mitigation for commercial vessel to store additional Methanol within their design, given Methanol has a lower volumetric energy density than Diesel.

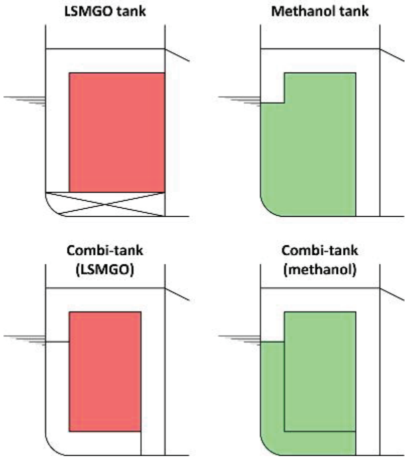

Figure 4 Cross section of Fuel Tank Arrangements (Royal IHC, 2024)

This would unlikely be a mitigation for Naval vessels, as they are typically single skinned hulls with no accommodation for double hull due to the spatial constraints. The inclusion of inboard cofferdams would actually result in less storage capacity within the vessel. However, new technology is in development to replicate the cofferdam protective arrangement in the form of a sandwich construction plate to separate the tank boundaries (SRC , n.d.).

These tanks are also not to be vented to the open deck (via air escapes) for natural ventilation, as Methanol vapours in the tank need to be managed. Nitrogen purging (section 3.1.4) is required, and results in the tank being pressurised, with a need for a pressure relief valve on each tank directed to the open deck within a safe area that is not near air intakes into the vessel.

3.1.4. Methanol Fuel Supply System

Methanol combustion with current Dual Fuel Marine Engines requires higher pressure injection into the combustion cylinder in comparison to Diesel only. Each engine supplier has differing concepts (Low Pressure Methanol Supply, ~10-25Barg, or High Pressure Methanol Supply ~400 Bar). Either fuel supply process begins with Methanol being pressurised at a dedicated Pump Module mounted separately to the Engine. This Methanol Fuel Pump System will be housed in dedicated compartment (Fuel Preparations Compartment), and be gas and water tight to surrounding spaces and vented to the open air following the same requirements as tank venting.

Pipework for Methanol in comparison to Diesel has further requirements for its design and construction, for pipework that passes through enclosed spaces then the use of double-walled pipes is required. The fuel pipe is enclosed in an outer pipe or duct that is both gas and liquid tight. Such double walled piping is not required in cofferdams surrounding fuel tanks, fuel preparation spaces or spaces containing independent fuel tanks as the boundaries for these spaces will serve as a second barrier.

IMO MSC.1/Circ.162*1INTERIM GUIDELINES FOR THE SAFETY OF SHIPS USING METHYL/ETHYL ALCOHOL AS FUEL* provides a set of key requirements and standards for designing suitable pipework within a vessel for handling Methanol, however their applicability to Naval vessels may require review and agreement for non-compliance. Notably, *5.7.1 Fuel pipes should not be located less than 800 mm from the ship's side,* will unlikely be compliant within naval vessels due to spatial constraints (typical pipe runs (all services) run along the ships sides).

3.1.5. Fire detection & Fire-Fighting

Methanol is a methyl alcohol (CH3OH) that burns in a completely different way than hydrocarbon fuels and has a much lower flashpoint of 12°C. Methanol fires are nearly invisible to the naked eye during in daylight, and there is little or no smoke direct from the flame, posing a great issue in attempting to detect and extinguish the fire. Early detection of methanol fires requires different technology from early detection of gasoline and diesel fires, utilising Vapor Detection and Thermal Imaging.

Current naval vessel typically have Aqueous Film Forming Foam (AFFF) as one form of fire-fighting onboard, however this means of tackling a Methanol fire is not appropriate for use, as solvent properties of Methanol cause the foam to degrade. IMO's interim guidelines for ships using methyl or ethyl alcohol as fuel, MSC.1/Circ.1621, establish a requirement for an approved alcohol-resistant foam system for ships running on methanol, expected to be alcohol-resistant Film-Forming FluoroProtein (AR- FFFP). This is required for bunker stations, fuel preparation rooms, tank top and bilge wells in the engine room. However, a CO2 system may substitute the foam system in the engine room, which is more common on later naval vessels (e.g. Type 45 Destroyers).

Managing the safe storage of Methanol onboard in all tanks (storage and service) and piping requires nitrogen purging.

In addition to integrating systems specifically dedicated fight methanol fires, the design of the vessel should aim to restrict and segregate Methanol from as many areas of the ship as possible, and provide protection boundaries (e.g. airlocks) when entering methanol areas (Methanol Fuel Pump Rooms, bunker stations) from non-hazardous areas.

Minimising vapours in tanks and double-wall pipework though Nitrogen purging, the vessel can either accommodate sufficient storage of Nitrogen to support its operation (with the requirement to re-supply) or generate Nitrogen locally as required. The latter provides a greater capability for the vessel and reduces any limitation or demand for re-supply on for naval vessel, especially when in conflict.

However, Nitrogen generating plant would be additional equipment acquiring a location within the vessel design. Typically, this would be within the engine room or auxiliary machinery space. Within a Naval vessel this would likely be duplicated in two locations (a level of separation) to allow for redundancy. Each plant is to be sized to generate Nitrogen 125% of Methanol discharge rate, however the demand can vary significantly based on typical operating conditions (consuming Methanol) or the need to empty Methanol Storage tanks.

- *Assumed Discharge Rate of 625m3/hr from Methanol Tanks (most extreme scenario – Emptying tanks) = 125% N2Production Capacity =* ***782m3/hr*** *Production Rate for Nitrogen Generator.*

- *Typically Fuel Consumption ~ 4.3m3/hr @ 18knots. 125% N2Production Capacity =* ***5.4m3/hr*** *Production Rate for Nitrogen Generator.*

Due to spatial constraints in a naval vessel design, a consideration based on optimising the vessel design and accommodating two large plants or the potential to limit the discharge rate to accommodate smaller plants is advised, as will vary on each size/class/type of naval vessel.

3.1.6. Propulsion System

Integration of dual-fuel Engines or Generator Sets (depending on your P&P arrangement), have negligible impact on the ship design for the engine itself, it's the supporting systems to enable alternative fuel (methanol in this case) use on the engine that drive change in a vessel design (see all other sections noted within Section 3.1).

Commercial marine engines for dual-fuel are now readily available, with a greater range of engines expected over the next few years. Methanol as an alternative fuel for dual-fuel engine share the same common engine architecture, with the key changes made to the fuel injections system. This allows for in-service engines to be retrofitted at any point during its life, with upgrade packages, rather than entire engine replacements to accommodate an alternative fuel use.

The vessel would still need to install Selective Catalytic Reduction (SCR) System to remain compliant with IMO Tier III NOx emissions, as operation on either fuel (Diesel or Methanol) generate NOx.

3.1.7. Bunkering / Replenishment at Sea (RAS)

Dual-fuel vessels will require means of receiving both types of fuel, typically via a bunker station. Dedicated bunkering stations will be required, as guidance for Methanol states that Bunkering stations are not to be used for any other purpose than bunkering methyl/ethyl alcohol fuel.

The bunkering station should be located on open deck so that sufficient natural ventilation is provided. Bunkering stations that are not located on open deck are to be suitably ventilated to ensure that any vapour being released during bunkering operations will be removed outside.

Key capability for a warship is to be able to replenish at sea, and not require a visit to local port to taken on fuel and other supplies. Although, current Naval oilers lack the capability to store and transfer Methanol, future capability would be expected if Dual-fuel vessel become a common vessel design for warships. To allow RAS'ing, the typical arrangements to transfer Methanol across to the vessel (from Oiler), would required connections at the both bunkering station to be of dry-disconnect type equipped with additional safety dry break-away coupling/ self-sealing quick release. As detailed within Section 3.1.4, the fire-fighting requirements also extend to the bunker stations, to manage the store and transfer of Methanol.

3.1.8. General Arrangement changes

Given all the additional equipment with strict requirements for the safe storage, handling and use of Methanol onboard a vessel, the general arrangement of any vessel will change to accommodate these measures.

The following key changes for the vessel arrangement apply (in addition to the tank arrangement):-

- ***Dedicated Fuel Preparation Rooms***; Additional compartment to separate Methanol Fuel Pump Systems from other machinery. Typically located outside an engine room, an internal compartments within the engine room is allowable with an airlock arrangement to provide the necessary separation for safety. Redundancy measure for a naval vessel will require two sets Of Methanol Fuel Systems, locate in different areas (minimum of two WTB separation).
- ***Accommodation***; Accommodation spaces are not to be placed above Methanol tanks (applies under commercial guidance, this may be a challenge for a naval vessel given spatial constraints).
- ***Nitrogen Generation Plant***; Generation and storage of Nitrogen for purging pipework and tanks. Redundancy measure for a naval vessel will require two sets Of Nitrogen Generation, locate in different areas (minimum of two WTB separation).
- ***Bunker Station****:* The bunkering station should be separated by A-60 class divisions from machinery spaces of category A, accommodation spaces, control stations and high fire risk spaces, except for spaces such as tanks, voids, auxiliary machinery spaces of little or no fire risk, sanitary and similar spaces where the insulation standard may be reduced to class A-0.

Spatial constraints of Naval vessels (typically known for fully utilising all areas onboard and having little to no spare space) creates a technical challenge to integrate Methanol fuel onboard. Although guidance and standards are available for commercial vessels, implementation on a naval vessel may prove impossible. Whilst their full applicability may be open to interpretation/negotiation for defence standards/customers to achieve a suitable level of agreement within a Naval vessel.

4. Operational Implications

The availability of methanol was discussed in section 2.1.3. It was clear that currently methanol is not widely available compared to MGO. However, this is the benefit of a dual-fuel arrangement. There is a reduced risk of a stranded asset.

The use of methanol would have an impact on range, although this can be overcome by utilising just diesel when required.

The Replenishment-at-Sea (RAS) of Methanol fuel requires further investigation to determine the viability. However, it is not envisaged that oilers will be carrying both fuels.

Naval vessels are inherently well known for the levels of redundancy, this is similar to how commercial dual fuel vessels now operate. Although this adds greater complexity for a naval vessel as there may be a requirement for multiple methanol equipment.

Fire-fighting requires significant thought to overcome a methanol fire. Conventional methods are not suitable and as such further investigation into suitable foams is required.

5. Dual Fuel Operations

Previous sections have highlighted the considerations and implications required to accommodate Methanol fuel for use on a vessel. Within the commercial industry, typical shipping operations are pre-determined and provide the opportunity to ensure Methanol fuel availability. In defence, warships do not have this luxury of pre-determined routes and operations, especially when utilised for immediate aid support or conflict. Hence, the ability to operate on both fuels is key. Although warships predominately operate in a peace keeping scenario, their capability to deployed in conflict/warzone at short notice is fundamental to the purpose of the vessel. Compromising this capability through the use of Methanol fuel, needs to be minimised/resolved before Naval vessel may consider adopting its use.

Adopting a dual-fuel ready vessel, with supporting fuel systems and a tank arrangement that could accommodate any fuel (Methanol or Diesel) to be stored would allow the vessel to operate as environmentally friendly (green-Methanol) during peacetime, and revert to full Diesel when required without losing any original capability.

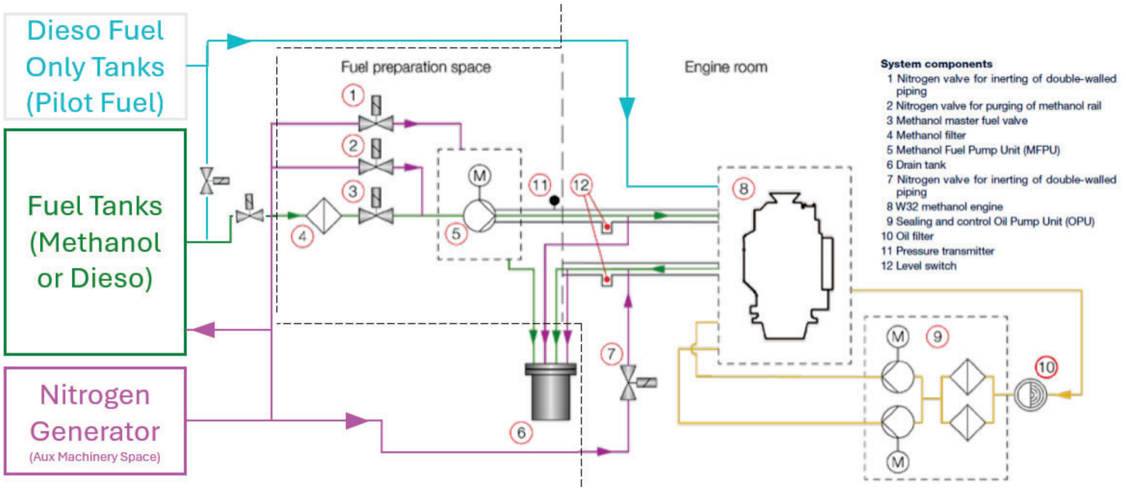

Figure 5 Concept fuel supply arrangement to allow dual use tanks (updated from Figure 4)

Guidelines from Class society state “Tanks need to be properly cleaned when changing fuel in the tanks”. This would restrict a naval vessel when required to change to either fuel rapidly and impact their operational capability. The following concerns regarding contamination of fuels have been raised from Engine Suppliers.:-

- **Diesel in MeOH engine mode;** is not consider an issue, as a pilot fuel (Diesel) is used, however the fuel supply system would need to be designed to account for removing contamination., At present, there is a fine filter before the Methanol high pressure pump to protect it from particles etc. so if Dieso entering that filter without pre-treatment then the filter will be clogged quite rapidly. The tolerances in the MeOH fuel supply system, incl. the Injector part for MeOH, are very small and may be very easily clogged if Dieso is entering.

- **MeOH in Diesel engine mode;** MeOH hasn't the same "lubricating " characteristics as diesel, meaning that when MeOH entering the Diesel supply system there is a lot more wear on components (pumps etc) and with a risk of seizure.

These restrictions and concerns pose a challenge to adopting a Methanol fuel within naval vessels, however, developments in fuel technology and fuel supply systems, may allow for acceptable contamination levels within the combustion process of a dual-fuel engine in the future, given the technology is still in it's infancy.

6. Conclusions

The use of a dual fuel arrangement would allow the use of 'green' fuels and thus a reduction in the net carbon emissions of a vessel. Whilst there is an impact on the operational capability, mainly a range reduction, this can be overcome by just reverting to F76 when required.

The use of dual fuel does come at a price, with increased complexity, especially if tanks are to be dual use.

However, it has been shown that it could be feasible for a vessel and as such is a consideration for the future fleet, whilst we await the energy source for the fleet after next.

There are still challenges to overcome, at least with RAS, fire-fighting and coatings, although these are challenges that should be embraced to solve the problem for the future.

Acknowledgements

The views expressed in this paper are that of the author and do not necessarily represent the views and opinions of BMT Ltd.

7. References

Department for Energy Security & Net Zero. (2023). *Net Zero Government Initiative.* UK Government.

DNV. (2023). *Transport in Transition.* DNV.

DNV. (2024, July). *DNV AFI Map*. Retrieved from DNV AFI: https://afi.dnv.com/map

IMO. (2022). *Rules & Regulations for the Classification of Ships using Gases or other Low-Flashpoint Fuels.* IMO.

International Maritime Organization. (n.d.). *2023 IMO Strategy on Reduction of GHG Emissions from Ships*. Retrieved from IMO.org: https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

Lloyd's Register. (n.d.). *Fuel for Thought – Methanol hub*. Retrieved from https://www.lr.org/en/knowledge/fuel-for-thought/methanol/

National Library of Medicine. (2023, June 12). *Methanol Toxicity*. Retrieved February 26, 2024, from https://www.ncbi.nlm.nih.gov/books/NBK482121/#article-25070.s9

Newman, S., & Beard, T. (2022). The Viability of Low-Carbon Fuels & Green Technologies for the Front-Line Naval Vessel. *RINA Warship.* Bristol.

Offshore Energy. (n.d.). *Clarksons: 45% of ships ordered in 2023 embrace alternative fuels*. Retrieved from https://www.offshore-energy.biz/clarksons-45-of-ships-ordered-in-2023-embrace-alternative-fuels-with-lng-still-in-the-lead/

Royal IHC. (2024, June). *Is methanol a realistic alternative fuel for work vessels?* Retrieved from Royal IHC Innovations: https://www.royalihc.com/innovations/methanol-realistic-alternative-fuel-work-vessels

SRC . (n.d.). *SRC Methanol Superstorage*. Retrieved from https://nova.src.ee/storage/media/479/SRC_Methanol-superstorage.pdf

Wartsila. (n.d.). *Wartsila Methanolpac*. Retrieved from https://www.wartsila.com/marine/products/gas-solutions/methanol-supply-systems/methanolpac

Through Life Carbon Emissions and Mitigation Opportunities

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Synopsis

The lifecycle of a ship is currently carbon intensive, with many mitigation methods focused primarily on a vessel's operational carbon emissions. However, there are significant emission reduction opportunities throughout the life cycle of a vessel. This paper investigates the through life emissions for an example hypothetical vessel; accounting for the various stages of the life cycle including build, operation, support, and disposal. Following review of the current emissions, mitigation strategies will be explored for the stages, predominantly focusing on emitted carbon but also on the ability to reduce embodied carbon throughout the life cycle.

Key words: Life-Cycle Analysis; Ship Design; Emission Mitigation

1. Introduction

The Greenhouse Gas Protocol Corporate Standard divides emissions into three categories, scope 1, 2 & 3 (The Greenhouse Gas Protocol, 2015). These all play a significant role in the emission calculations for everything, with companies choosing at what level they wish to publish. Although it should be noted that one entities scope 3 emissions may be a suppliers scope 1 emission. The different scope level definitions are defined as:

- Scope 1 – Direct emissions that are controlled or owned by a company;
  - Emissions from fuel combustion within company owned vessels.
- Scope 2 - Indirect Emissions;
  - Emissions caused by the generation of electricity within buildings or through the provision of shore power.
- Scope 3 – Indirect emissions;
  - Emissions created through the supply chain and external manufacture and provision of goods and services.

The maritime industry has previously focussed on operational emissions by using the tank-to-wake emissions of the vessel. However, this is changing. Just from the operational perspective the emissions are now well-to-wake, although it should be noted that well in this context is just the original power source (International Maritime Organization, 2019).

The life cycle of a ship is far more than just the operational aspect. The build of a conventional steel vessel has a significant emission impact due to the production of steel. Operationally the emissions are driven by the fuel, which is likely to be F76 (fossil fuel) for some time. The support of vessels is an interesting aspect as Defence are striving to be more self-reliant and reduce the logistics burden. Although this would also include upkeep and maintenance. The largest issue with the support aspect is that many vessels will undergo life extensions, these generally require significant upkeep to ensure it is possible for the vessel for continue operating for longer than designed for. Finally, the disposal of the vessel is the last area that should be accounted for. It is not ethically responsible to pass the burden onto somebody else by selling the vessel.

95% of a ships carbon emissions currently occur during the ships operational phase (The Sustainable Shipping Initiative, 2023), and this is through the combustion of non-renewable fuels, hence much of the legislation and drivers focusing on the operational phase of a ship’s lifecycle. The IMO state that the global introduction of alternative fuels and / or energy will be integral to achieve decarbonisation targets for shipping (International Maritime Organisation , 2024). With the introduction of alternative fuels, the 95% of emissions will shift towards the other lifecycle phases and drivers will have to re-focus to create more holistic long-term targets if the maritime industry is going to reach its decarbonisation goals.

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This paper explores the emissions at the various stages of the life cycle and then proposes some mitigations to support the naval sector in reducing emissions. This will be applying a Life Cycle Assessment (LCA) methodology to a 6,000-tonne naval steel hulled frigate. The paper will illustrate key activities where carbon emission controls and influences can be identified and mitigated.

2. Life Cycle Assessment

LCA is an evaluation method that considers a product's or system's entire life cycle, taking into account the successive and interlinked stages of a product or system from conception through to disposal. LCA encompasses the assessment of the benefits and burdens of all activities that generate carbon emissions, this includes consideration of scope 1, 2 and 3 emissions. Figure 1 highlights the key stages that require assessment through an LCA.

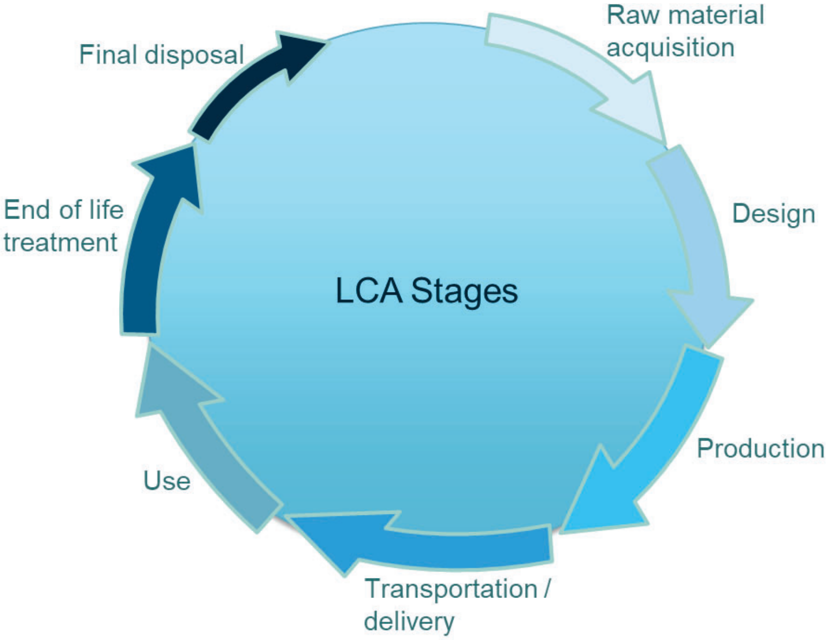


Figure 1: Stages of the Life Cycle Assessment

By considering all stages of the life cycle from raw material extraction to final disposal and or reuse, a holistic assessment of the environmental impacts can be performed.

A key part of LCA is that it does not favour one stage of a product or systems life cycle over another. As was previously stated, emphasis is often placed on the operational emissions from a ship. An LCA will give as much consideration to the emissions generated from the transportation of materials for a vessels maintenance as it does to the running of the vessel. This allows for a fair and balanced assessment and provides the opportunity to identify "environmental hotspots" that may be present in the life cycle. Emission reduction opportunities can then be identified through all lifecycle phases.

To produce a sustainable ship, there is a requirement to be a smart and responsible customer from the outset. A full analysis of the elements of the life cycle that can be controlled or influenced must be carried out and where identified this control or influence must be enacted. By assessing the supply chain and making sustainable choices in the products and services available a plethora of carbon reduction opportunities may become apparent, these could include the ability to choose different freight options (through build, maintenance and disposal activities), selection of recycled materials over new and the opportunity to use locally sourced equipment and materials. Key to this is a strong and trusted communications with the supply chain, stakeholders and service providers.

The LCA will help to ensure that environmental impacts from the whole life cycle are not ignored or transferred to another stage in the cycle. By identifying the sources of emissions, LCA enables the development of strategies to reduce greenhouse gas emissions, such as the adoption of cleaner energy sources and improved process efficiency.

3. Lifecycle phases

3.1. Design

Historically ship design has been driven by cost efficiencies in both building and operating phases, alongside compliance with minimum environmental standards. Through the onset of new regulations and growing awareness of climate change this is now changing. A fundamental part of this change is being applied through a change in thinking. This ensures designers are being regenerative by design, meaning that from the outset a positive impact on the overall environment has been considered. Regenerative design uses whole systems thinking to create resilient and equitable systems that integrate the needs of society with the integrity of nature.

Ships should now be designed with resource optimisation in mind from the outset, allowing for greater reuse of components, as well as choosing systems that promote repair and refurbishment over replacement.

To enable this there must be a shift of focus from one of reducing Capital Expenditure (CAPEX), which requires designers and ship owners to need to start looking at the bigger picture. An element of a design which can be disassembled easily and repurposed may initially carry a higher cost but these costs may be reduced when maintenance, mid service upgrades, end of life and environmental impacts are considered across the whole lifecycle of the vessel.

Key to a sustainable design is the ability to utilise and embrace new greener technologies. Design considerations to reduce carbon emissions through life for a large naval ship include:

- Green steel
- Wind assisted propulsion
- Air Lubrication System
- Absorption Chiller Plant
- Waste heat recovery
- Use of fuel cells for generating electricity and fresh water
- Alternative Fuels
- Carbon capture and storage
- Alternative energies (shoreside and shipyard facilities)
- Ship digitisation opportunities

This list is by no means exhaustive but provides an example of the potential carbon reduction technologies now available. Some technologies may not be appropriate for a naval vessel depending on operational requirements or technical readiness. However, by considering them from the outset designers can implement pathways to allow for future adaptations as technology evolves.

When considering the digitisation of systems, it should not be forgotten that automated systems also add an additional burden of data storage, how data is stored and managed must be considered. To put this into perspective the electricity required to store around 3,500 emails (of five MB each) produces around as much CO_2 as that from driving a compact car a kilometre and deleting 1,000 emails would give a carbon benefit of around five grams of CO_2 (Konica Minolta,, 2024).

The additional aspect to the design phase is the buildings and power that are used. Many companies are already investing in this aspect of the energy transition and as such this is deemed a negligible component.

3.1.1. Modular Design

Modularisation aims to increase the functionality of a vessel whilst also reducing repair and maintenance periods.

Modules are prefabricated which is a method of creating and producing components of a vessel off site and then delivering them to the project for them to be assembled. Within the construction industry this has proven to help accelerate construction projects and provide cost-saving opportunities, whilst also having implications for sustainability and embodied carbon, through waste reduction (University Collage of Estate Management, 2024) (V. Tavares, 2021).

The Maritime Modularity Concept is not new to navies, in a 2022 report carried out by the Royal Navy (Ministry of Defence, 2022) the benefits and risks of modularity were discussed. Whilst much of the report focusses on functionality and cost saving it does discuss the how modularity has the potential to increase the service length of a vessel (future proof), improve sustainability, improve time efficiencies (maintenance and service) and allow for increased adaptability. Whilst not mentioned in the report these benefits also have the potential to reduce carbon emissions through life.

Key to potential carbon reduction is adaptability, modular units can introduce modern technologies to a ship without the requirements of a full refit. Lessons can be learnt from this with regards to the implementation of the IMOs Ballast Water Convention (International Maritime Organisation, 2019) which states that all vessels built before 8 September 2017 will have to retrofit a ballast water treatment system that complies to the regulations standards. These standards have been mandatory for all applicable vessels on completion of their International Oil Pollution Prevention Certificate (IOPP) renewal, since 2019. For many vessels this will not be economically viable to retrofit and a surge in scrapping is being predicted (Drewery Maritime Research, 2019) (Hand, 2016).

3.1.2. Hull Form Design

The hull design can have a significant impact on a vessels overall efficiency, the more drag it creates the more fuel it will require similarly the heavier the hull the more fuel will be required. Through applying Computational Fluid Dynamics (CFD) modelling, opportunities can be identified through the design spiral to reduce the demand for materials and improve efficiency. With the onset of Artificial Intelligence further opportunities are now being identified to realise a real-time prediction of the total resistance of the ship-hull structure in its initial design process (Yu Ao, 2023). By implementing these kind of design initiatives early on in a vessel's lifecycle designers can help to ensure that all design options are considered towards producing a vessel that is environmentally sound to operate.

Whilst efficiency is a key driver for the reduction in emissions, the only true way to meet operational net zero is by using alternative power sources. However, these efficiency gains are still required as many of the options are far less energy dense.

3.2. Consideration of the use of Raw Materials

Raw materials must be considered from the iron ore extracted for the steel hull through to the precious metals used within circuit boards and batteries. Extraction of iron ore, bauxite, copper and other minerals used in steel and alloy production is a dirty and energy intensive process. In a 2020 study carried out by Nature Geoscience they estimated that greenhouse gas emissions associated with primary mineral and metal production was equivalent to approximately 10% of the total global energy-related greenhouse gas emissions in 2018 (Mehdi Azadi, 2020).

When assessing this impact, it is imperative to note how and if the steel production and mining companies are reporting their CO_2 to ensure no double accounting is taking place.

3.2.1. Alternative Materials

A potential solution is the use of alternative materials. The increase in 3D printing has the potential to support the use of alternative materials and more efficient component designs, for example printed propellers (3D Printing Industry, 2021). There is also the possibility for hulls built from sustainable composite materials, although the scale of a large warship may not make this viable. It should be noted that these technologies are still relatively new and a lot of further analysis is required to assess their environmental credentials, especially compared against the use of recycled steel.

3.3. Lifespan and Obsolescence

Hardware, software and support equipment are all items with a shelf life. Obsolescence as defined within JSP 886 (Ministry of Defence, 2012) by the International Standard IEC 62402:2077 is the "transition from availability from the original manufacturer to unavailability". Products must be designed to be repairable and more economically viable to fix than to throw away. This can be done by ensuring that elements within equipment can be reused, repaired or refurbished, the value of the raw materials and their embodied carbon should always be considered through to disposal.

3.3.1. Design for reuse

Ship design can no longer be linear. The shipping industry needs to rethink its approach to material use and design vessels which lower emissions and close the material loop. Consideration needs to be given to all materials used, from steel hulls to copper cabling and thermal insulation. Remanufacturing is a crucial part of reducing resource depletion and a vital strategy for cutting emissions, labour, and energy, and through extending the "end-of-life" of products and their components. Remanufacturing is becoming a recognised procedure within the automotive and aerospace industries (David Parker, 2015) with some predicting that the automative remanufacturing industry will be worth USD 126.42 billion by 2030 (Fortune Bussiness Insights, 2024). When designing a vessel how equipment can be remanufactured and the processes required should be considered i.e., how easy is it to retrieve precious metals or replace components.

3.4. Build

Some studies are now stating that the contribution of ship building will soon exceed that of the service phase, with some reaching more than 50% of a vessels carbon footprint (OSK Group, 2022), (Vakili Seyedvahid, 2023). Much of a vessels carbon emission through the build and manufacture phase will be scope 3 emissions. Sustainable manufacturing extends beyond the manufacturing process and the product, to include the supply chain, across multiple product life cycles as well as end-of-life considerations.

3.4.1. Steel Manufacturing

In 2020 UK steel estimated that for every tonne of steel produced, an average of 1.85 tonnes of CO_2 are emitted. This means that steel manufacturing produces nearly twice as much CO_2 emissions as it produces steel.

Global steel production is responsible for around 7% of the world's man-made greenhouse gas emissions (Holger, 2023). However, steel is one of the most recycled materials in the world, yet the demand for new steel is currently outweighing the supply of old steel, hence a race towards the production of green steel. Green Steel utilising hydrogen technology for production is now underway in Sweden, the company involved are planning to cut emissions by as much as 95%. It is currently estimating that will produce five million tonnes of green steel a year by 2030 (Savage, 2023). According to a recent Lloyds register study the maritime industry will demand circa 17.5 Mt of steel in 2030 (Lloyds Register, 2023).

How and when the steel industry decarbonise will have huge ramifications on a vessels overall carbon emissions. Steel makes up 75-85% of a vessel by weight (The Sustainable Shipping Initiative, 2021). Going by the UK steel estimate a vessel with a 16, 000 tonne steel hull and superstructure would produce 29,600 tonnes of CO_2 in its steel production alone, to put this into context the average UK citizen currently produces around 5 tonnes of CO_2 annually (Leberton, 2023).

The technology exists to produce a greener lower carbon steel, it is now down to industry across all sectors (construction, energy, transportation, maritime) to push and build the demand alongside the onset of global regulations that recognises and incentivises the role steel production will play in the world achieving decarbonisation targets within the maritime industry and beyond.

3.4.2. Build Energy Efficiency

The building of the vessel from the component parts can take considerable energy. This is not just the metal work but there also the lifting and logistics associated within the yard. By utilising renewable power sources this could have a significant reduction in the shipyard emissions. However progress can be made by the adoption of renewable power, which would mitigate many of the emissions produced. This can be further improved by utilising alternative powered handling equipment within the yard.

3.5. Support

The support function consists of a wide range of tasks; from supply chain, fuel, cold ironing and crew transfers. The current use of support is outdated and there has been a focus on minimal build costs as opposed to the lifetime costs, for example the QEC carrier decision to be powered by fossil fuel rather than nuclear.

Optimisation of supply chains may reduce the emissions, whilst additive manufacturing should reduce this further. The ability to create spares as required rather than transport them has significant advantages. If this is coupled with digitisation and predictive maintenance rather than reactive, there could be considerable operational increase, financial savings as well as emission reduction.

Predictive maintenance attempts to foresee unplanned machinery failure, a proactive rather than reactive approach, this can often extend the life of a piece of equipment resulting in reduced disposal of equipment and increased opportunities for regeneration and reuse.

The use of cold ironing would allow vessels to no longer operate engines whilst in ports which would have a considerable impact on the emission reduction and local air quality, especially for larger vessels.

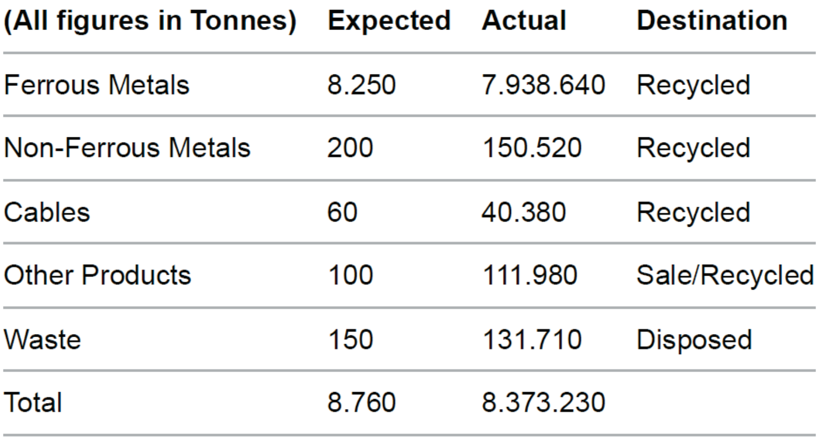
3.6. Disposal

A report commissioned by the Sustainable Shipping Initiative, exploring shipping's transition to a circular economy in June 2021 stated that global ship recycling volumes are expected to double by 2028 and near quadruple by 2033 to 28 million light displacement tonnes (The Sustainable Shipping Initiative, 2021). The World Steel Association (2023) estimates that every tonne of scrap steel used for steel production avoids 1.5 tonnes of CO_2 emissions, as well as considerable quantities of raw material (The Sustainable Shipping Initiative, 2023).

The disposal process for ships is currently carried out by the lowest bidder, how much they want to bid for the disposal contract is dictated by global steel prices and the yards processing procedures. 2021 prices varied from around \$560 per light displacement tonne in Bangladesh to \$300 per light displacement tonne in Turkey (Barlett, 2021). South Asia currently dominates the ship breaking industry and it is here that the ships are often beached and broken down in-situ, this regularly occurs under poor environmental and safety standards. Greater transparency and traceability of all materials is a necessity, not only to enable emission reductions through the circularity of resources, but to make ship recycling safer and more environmentally sound.

Within the UK ship recycling standards are becoming more stringent. Recycling rates by weight are high. The MOD reported that 98.4% of the material from the former Black & Gold Rover RFA was recovered and recycled with a final outturn of 8.373.230 tonnes (Minstry of Defence, 2020). A summary table from the report illustrating the waste breakdown is shown in Table 1.

Table 1 Summary of the Black and Gold Rover final waste outturn



(All figures in Tonnes)	Expected	Actual	Destination
Ferrous Metals	8.250	7.938.640	Recycled
Non-Ferrous Metals	200	150.520	Recycled
Cables	60	40.380	Recycled
Other Products	100	111.980	Sale/Recycled
Waste	150	131.710	Disposed
Total	8.760	8.373.230	

Ship dismantling and recycling is an energy intensive activity with a range of processes being applied across disposal yards. As ships become more digitised these waste streams will change creating further challenges for recycling. The American Environmental Protection Agency states that one metric ton of circuit boards can contain 40 to 800 times the amount of gold and 30 to 40 times the amount of copper that is mined from one metric ton of ore in the US (United States Environmental protection Agency, 2024). Recycling e-waste is a time-consuming process but can provide a route for economical and profitable extraction of valuable metals whilst also reducing biodiversity loss and carbon emissions.

Disposal through maintenance and obsolescence must also be considered, currently the focus is predominately on the final structure. Accountability needs to be made on equipment suppliers and designers that ensures clean disposal and reuse of products throughout a vessel's lifecycle.

More transparency is required across sectors, it should no longer be acceptable for a corporation to offload its carbon emissions through the gifting of a product. With design and manufacture should come some responsibility towards disposal.

4. Conclusions

For a shipbuilder / designer to account for their carbon each component industry must find a way to make standards quantifiable and measurable throughout a ships lifecycle. It will require collaboration and strong dialogue across all sectors. Transparency and sharing of data needs to become a positive offering from industry, the ability to share a products carbon data should be a recognised and celebrated commodity across industry from mining through to the repurposing and recycling at the end of life.

All sectors involved within the lifecycle need to take ownership of their carbon data and provide transparency to their customers in order to apply a fully holistic assessment of a ships carbon emissions. The marine industry has a stretched and complex supply chain that must be accounted for and made accountable for carbon emissions. Global regulations and multi stakeholder collaboration are essential, everyone must play their part towards shipping's decarbonisation from cabling through to hull construction and disposal.

Technology is changing fast and the ability to produce carbon neutral ships from cradle to grave is almost there. There is a wealth of carbon reduction technologies coming onto the market to support the marine industry throughout all lifecycle phases and these must be embraced and adapted where possible. It is imperative that these are considered from the outset of the ships design and that where current technology is not considered to be ready or economically viable for a design then consideration should be made to incorporate future technologies where possible. By accounting for this earlier in the phases then it can be determined where there is also an economical benefit as well.

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5. References

3D Printing Industry. (2021, January 14). *NAVAL GROUP HAS 3D PRINTED A ONE-TONNE SHIP PROPELLER FOR THE FRENCH NAVY*. Retrieved from https://3dprintingindustry.com/news/naval-group-has-3d-printed-a-one-tonne-ship-propeller-for-the-french-navy-182400/

Barlett, P. (2021, June 7). *Seatrade Maritime News*. (Informa Markets) Retrieved June 04, 2024, from https://www.seatrade-maritime.com/ship-operations/recycling-prices-stay-buoyant-despite-disruption

Drewery Maritime Research. (2019, August 08). *Hellenic Shipping News Worlwide*. (PG Software) Retrieved June 05, 2024, from https://www.hellenicshippingnews.com/imos-ballast-water-management-convention-to-rekindle-tonnage-scrapping-in-crude-tankers/

Hand, M. (2016, September 12). *Seatrade Maritime News*. Retrieved June 05, 2024, from https://www.seatrade-maritime.com/americas/ballast-water-convention-send-more-old-tankers-scrap-yard

Holger, S. a. (2023, August 29). *Why Steel can be an unexpected leader in decarbinization*. (World Economic Forum) Retrieved June 3, 2024, from https://www.weforum.org/agenda/2023/08/why-steel-can-be-an-unexpected-leader-in-decarbonization/

International Maritime Organisation . (2024, June 04). *2023 IMO Stratergy on Redction of GHG Emissions from Ships*. Retrieved from International Maritime Organisation : https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

International Maritime Organisation. (2019). *BWM Convention and Guidelines.* Retrieved June 05, 2024, from https://www.imo.org/en/OurWork/Environment/Pages/BWMConventionandGuidelines.aspx

International Maritime Organization. (2019). *Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines)*. Retrieved from https://www.imo.org/en/OurWork/Environment/Pages/Lifecycle-GHG---carbon-intensity-guidelines.aspx

Konica Minolta,. (2024, January 1st). *ethink Work with Konica Minolta*. (Konica Minolta Business Solutions Europe GmbH) Retrieved May 30th, 2024, from https://www.konicaminolta.eu/eu-en/rethink-work/sustainability/five-ways-to-clean-up-your-data-%E2%80%98junk-and-save-energy#:~:text=This%20is%20important%20as%20digital,0.28kg%20of%20CO%E2%82%82%20emissions.

Leberton, T. (2023, December 5). *What's The Averag Carbon Footprint in teh UK?* (Th Ecoexperts) Retrieved May 06, 2024, from https://www.theecoexperts.co.uk/blog/average-carbon-footprint-uk#:~:text=The%20average%20carbon%20footprint%20in%20the%20UK%20is,are%20around%20five%20tonnes%20per%20person%20per%20year.

Lloyds Register. (2023). *Steel Demand and Emissions in Shipping 2024-2050.* Lloyds Register UMAS.

Mehdi Azadi, S. A. (2020). Transparency on greenhouse gas emissions from mining to enable climate change mitigation. *Nature Geoscience, 13*, 100-104.

Ministry of Defence. (2022). *Maritime Modularity Concept.* London: Crown.

Minstry of Defence. (2020). *Recycling of the former RFA Black Rover and Gold Rover.* London: Crown.

OSK Group. (2022, May 04). *There is no such thing as a zero-emission ferry! Retrieved*. Retrieved from Vessel Finder: https://www.vesselfinder.com/news/23391-OSK-ShipTech-There-is-no-such-thing-as-a-zero-emission-ferry

Savage, M. (2023, Febuary 17). *The Race Across Europe to build green steel plants*. (BBC News) Retrieved 28 May, 2024, from https://www.bbc.co.uk/news/business-64538296

The Greenhouse Gas Protocol. (2015). *A Corporate Accounting and Reporting Standard.*

The Sustainable Shipping Initiative. (2021). *Exploring shipping'stransition to a circular industry.* London: SSI.

The Sustainable Shipping Initiative. (2023). *Green Steel and Shipping - Exploring the material flow of steel and potential for green steel in the shipping sector.* SSI.

United States Environmental protection Agency. (2024, February 15). *Sustainable Management of Electronics*. (EPA) Retrieved June 04, 2024, from https://www.epa.gov/smm-electronics/frequent-questions-about-sustainable-materials-management-smm-electronics-challenge

University Collage of Estate Management. (2024, June 03). *UCEM* . Retrieved June 6, 2024, from https://www.ucem.ac.uk/whats-happening/articles/what-is-embodied-carbon/#:~:text=Consider%20prefabricated%20or%20modular%20construction&text=This%20can%20help%20accelerate%20building,waste%20from%20a%20building%20site.

V. Tavares, J. G. (2021). What is the potential for prefabricated buildings to decrease costs and contribute to meeting EU environmental targets? *Building and the Environment, 206*.

Vakili Seyedvahid, S. A. (2023). The road to zero emission shipbuilding Industry: A systematic and transdisciplinary approach to modern multi-energy shipyards. *Energy Conservation and Management, x*(100365).

Yu Ao, Y. L. (2023). An artificial intelligence -aided design (AIAD) of ship hull structures. *Journal of Ocean Engineering and Science , 8*(1), 15-32.

A Suggested Energy Efficiency Index for Warships

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Synopsis

The International Maritime Organization (IMO) now has in place a set of metrics which allow the Transport Energy Efficiency (TEE) of the design and operation of a wide range of commercial ships to be assessed. These are the Energy Efficiency Design Index (EEDI) and the Carbon Intensity Indicator (CII).

The EEDI is the TEE at the nominal design point as prescribed by IMO at 75% loading of the ship's main engine with an electrical load which is a function of the ship's main engine rating. It is usually quantified in terms of mass of carbon dioxide (CO_2) equivalent emitted per "useful work done." The CO_2 emitted is based on the fuel consumption rate at the design point and its carbon factor. The useful work done is measured by the ship's deadweight capacity times the design speed.

These metrics are categorised by ship types using historical ships' TEE data from the large vessel population. The required IMO-regulated performance is to show a progressive year-on-year improvement compared to the average performance of the whole fleet of international ships.

Naval ships are leading diplomatic and functional representatives of their government and as such, the navies of the world are arguably morally bound to adopt best practice and present the best possible image of their country. However, each aval vessel is different: they have a wide range of sizes and a rage of service and top speeds, and so to create a single metric to allow a comparison and regulation is challenging.

Using information from the public domain, a means of setting a valid TEE target values for warships has been developed which makes use of their given hullform displacement and their declared cruise speed as stated for the associated range calculation.

A method for derivation of the warship TEE is proposed which uses fundamental principles to derive the (CO_2) emitted at the stated cruise speed. The approach includes the Ships Electrical Load (SEL) which is estimated using the IMO equation in this instance. This approach is independent of propulsion configuration and incentivises the design to reduce the SEL as well as to increase the overall propulsion energy efficiency.

To prescribe the required target TEE values, using values derived from existing vessels, 3D contour plots of the Naval Energy Efficiency Measure (NEEM) are presented for warships and for naval auxiliaries on diesel engines at their cruise speed. A spatial, contoured distribution plot of TEE versus the vessels' displacement and cruise speeds, allows targets to be set for vessels with intermediate displacements and speeds. The target TEE value is based on the declared cruise speed and the ship's displacement, the IMO Capacity term for the EEDI.

Key words: Transport energy efficiency, warships

1 Introduction

This study seeks to identify a means by which naval vessels can be assessed for their energy efficiency. The International Maritime Organization (IMO) has already developed a set of Energy Efficiency Metrics (EEM) which allow the efficiency of the design of ships and the operation of ships to be assessed. These metrics are categorised by ship types: e.g. bulkers, tankers and container ships and the required performance is identified through a progressive time-based improvement compared to the average performance of the whole fleet of international ships.

The objective was to identify a means of setting a valid Naval EEM (NEEM) target value for warships, having assessed a set of relevant conference papers that have sought to address this problem in the past.

The study is therefore to identify how can such a metric can be set for warships and other naval vessels, and more importantly, how this value can then be assessed against other ships that may be similar but which are of different displacements and may have different declared cruise speeds.

Author's Biography

John Buckingham is the Chief Mechanical Engineer at BMT. A Fellow of the IMechE, he has over 40 years' experience in marine engineering systems design. He has designed and analysed hybrid power and propulsion systems for naval and commercial vessels and is currently involved with the modelling and analysis of energy saving technologies. He has been the technical lead for a wide range of technology studies and concept development work, specifically on studies relating to hydraulic fluid power and heat management systems.

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The study reviewed the IMO energy efficiency metrics for ship design, Energy Efficiency Design Index (EEDI), and identified where it can be adopted for warship applications. Three leading technical papers were reviewed to identify their ideas that can be developed further.

A calculation for a NEEM is developed which uses first principles to derive the carbon dioxide (CO_2) emitted at a given cruise speed. The approach includes the Ship's Electrical Load (SEL) which has been estimated using the IMO equation in this instance, though the actual value would be included in the design dossier.

This approach is independent of propulsion configuration and incentivises the designer to reduce the SEL at normal cruise conditions, as well as to increase the overall propulsion efficiency.

2 Background

2.1 Commercial Ships

Over twenty years ago, the IMO and other agencies recognised that there is a pressing need for international commercial vessels of all types and sizes to show an appropriate regard to the need to reduce their greenhouse gas (GHG) emissions, by conserving energy and by using the fuel they consume in the most efficient manner.

The commercial maritime sector is advancing towards both improved energy efficiency and reduced emissions of GHG. This has been led by goals set at a multinational level through the IMO and the EU which embody targets to cut emissions by 50% by 2050 compared to a 2008 baseline, and at a national level through targets such as the UK Net Zero by 2050 presented in the Clean Maritime Plan (DfT, 2019).

2.2 Naval Ships

As naval ships are leading diplomatic and functional representatives of their governments', arguably the navies of the world are duty bound to adopt best practice and present the best possible image of their home country.

The UK Secretary of State for Defence, through the Defence Maritime Regulator (DMR), requires that adverse effects on the environment are minimised, and all safety risks are reduced to As Low As Reasonably Practicable (ALARP). There is currently a lack of guidance for naval ship designers and requirement writers in the areas of ship energy efficiency and GHG emissions reduction.

Vessels on Government Service are excluded from the scope of IMO conventions including Marine Pollution (MARPOL) Annex VI (IMO, n.d.), meaning the energy efficiency improvement and emissions reductions metrics proposed by the IMO are not directly applicable to warships. There is however potential that some of the monitoring, verification, and reporting methodologies developed by the IMO to track energy efficiency in the commercial shipping sector could be adapted for warships.

This paper describes a proposed means by which a suitable NEEM may be determined.

2.3 Current IMO EEM

The IMO has a set of regulations under its MARPOL regulations for the prevention and control of pollution from ships, (IMO, Prevention of Air Pollution from Ships: https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx). The world's international commercial shipping fleet is subject to the laws and regulations imposed by the IMO. They are currently subject to three principal efficiency-based criteria:

1. Energy Efficiency Design Index (EEDI);
2. Energy Efficiency Operating Indicator (EEOI);
3. Carbon Intensity Indicator (CII).

This paper will focus on the EEDI only.

2.4 EEDI

The EEDI is a design-based simplistic measure of the energy efficiency of a ship design, stated in the emission rate of equivalent CO_2 emitted to atmosphere per tonne of cargo deadweight, per knot of speed. During the ship design phase, there might be assessments of the EEDI which would be compared to the specific IMO requirement for that vessel. If the EEDI value as designed exceeded the IMO requirement, extra measures are required to allow it to pass below that score.

The EEDI is also a measure of the damage inflicted to the world's environment in term of mass of CO_2 per unit work done (i.e., mass times distance).

The EEDI equation is shown here in simplified format:

EEDI = [Damage/impact to environment]/[Useful work done]

The fuel consumption at a main engine load of 75% is combined with the estimated fuel consumption for electrical power generation relating to a fraction of the main engine rating, not the actual SEL. The fuel rate is multiplied by the carbon factor to yield the emission of CO_2 per hour.

The IMO's EEDI regulation was originally defined in Resolution MEPC.203(62) within the document MEPC 62/24/Add.1 dated 15th July 2011, (IMO, regulations on energy efficiency for ships in MARPOL Annex VI., 2011).

The denominator is the product of the ship's service speed (expected to be when the main engine is at 75% load) and its cargo payload, i.e. its deadweight. The so-called "work done" term therefore does not factor in the weight of the ship transported, and for EEDI, it is also assumed that the ship is operating at 100% full capacity.

The "work done" term also assumes the ship to always be at its declared service speed for a given power, even though it is recognised that actual speeds will vary with the environmental factors stated above for a given shaft power.

At the design stage, the distances travelled and the ship speeds for the ranges of heavy weather, draught and fouling conditions are not known. Therefore, the EEDI uses the rated power of the main engine and its specific fuel consumption at a given design point, and load to determine the fuel consumption.

These short-comings are inevitable for the whole range of ship operating conditions which cannot be adequately captured in one number, but that number, using the same common assumptions, can be used for ship-to-ship comparisons as is now widely the case.

The EEDI for commercial ships are compared based on designated "ship types" i.e. bulker, tanker, containership, etc and their deadweight. Within a specific ship type category, the deadweight is used in an equation to determine the required EEDI performance. The equation has been determined from a set of IMO greenhouse gas (GHG) studies which have analysed the world's fleet to identify average EEDI values, which have been used as a baseline from which the target EEDI is progressively reduced so that there is less and less CO_2 emitted for every tonne-nm of useful work undertaken.

The EEDI is used at the ship design phase to encourage designers to provide future ship designs which are progressively better every four years. The targets encourage:

- progressive ship hullform designs which seek to match the ship's operating profile,
- the uptake of EST to reduce energy consumption and to recover lost energy;
- the uptake of alternative green fuels with have a lower overall Life Cycle Assessment (LCA) impact.

By having a common method for comparing designs, the efficiency of new-build commercial ships has progressively improved as better hullforms, propellers and main engines are developed together with the introduction of Energy Saving Technologies (EST) such as wind propulsion, hull air lubrication and Organic Rankine Cycles (ORC).

2.5 Application of EEDI to Naval Vessels

The application of the IMO's EEDI equations and methodology for warships and other naval auxiliaries is not straight forward. Naval vessels today often have all-electric and hybrid propulsion designs which are more complicated than the two-stoke main engines with fixed pitch propeller designs of most containerships, tankers, and bulkers.

Warships will often have booster engines for a top speed of between 25 to 35 knots. These may be additional main diesel engines or gas turbines. Simply considering the fuel demand when all these engines are operating at

75% is not a suitable representation of the likely power and propulsion (P&P) set up for the cruise speed at which the ship is operating for most of its service duties.

The Capacity term in the EEDI and CII equations is also a value that cannot be easily derived for a warship. The review of warship displacement data shows many with a common average displacement with a very low standard deviation of 1%. The data is based on draught readings by ships staff at the time of monthly trials and so the accuracy may not be as good as indicated. The data shows that the whole warship displacement does not vary significantly, and its variation has a negligible effect on NEEM calculations.

One method of identifying a standard duty speed is to take the given speed often declared for the total amount of carry-on fuel. This is often stated as the range requirement to sail a distance in nautical miles at a given naval service speed in knots. For the purposes of the naval EEDI, only the fuel consumed by those engines normally operating at this naval service speed would be considered. This would be for a common set of environmental operating conditions suggested as:

4. Sea state 1 (i.e. calm with very little wind);
5. A clean hull;
6. Standard displacement, i.e. start of life at standard draught;
7. Trim near as can be to original design intent.

The required resistance, and thus fuel demand, for this condition is straight forward to calculate as there is no requirement for added resistance in waves to be assessed. This can be something which is very difficult to determine with confidence at higher sea states even with first principles or empirical methods.

2.6 EEDI Target Values

If it can be established/agreed that the use of standard displacement for Capacity and the declared range speed to be the servcie speed then the determination of warship EEDI is straight forward, but to what target value is the design to be fashioned?

A warship is not directly comparable to any of the standard IMO ship type classes. A RoRo vessel was considered the closest in terms of operating speed and the use of four-stroke engines. The EEDI for a RoRo passenger vessel with the Type 23 displacement used as the deadweight has an EEDI target score of 30.66 g.CO_2/tonne.nm. This is from the IMO EEDI equation for RoRo vessels:

$$EEDI = 752.16 \times {D_{wt}}^{-0.381} \qquad \text{Equation 1.}$$

However, the RoRo’s deadweight is a small part of its displacement, and the Type 23 has low average speed of around 10 knots compared to a RoRo’s 18 knots, so a comparison with a RoRo is thus invalid.

The EEDI values are much lower than CII as the CII value includes the fuel consumed by DG sets when the ship is alongside or at anchor.

Typical EEDI values are likely to be much lower than the calculated EEDI for the given cruise speed because the average speed of warship vessels is now closer to 10 knots, below the declared service speed of many. The study of speed-time operating profile for a number of warships shows most of the speeds to be below the servcie speed declared at build.

2.7 EEXI

The Energy Efficiency EXisting Ship Index (EEXI) has been applied as a one-off assessment to those commercial ships that were not designed to meet the original EEDI regulations, (IMO, GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY EXISTING SHIP INDEX (EEXI), 10-Jun-2022). It uses the same equation as the EEDI but allows some adaptation where the ship has been operating at a load point away from the 75% main engine loading condition.

For warships, the IMO EEXI method therefore has the same drawbacks as the commercial ship EEDI.

3. Review of past papers

3.1 Introduction

The limited set of papers and articles on the issue of how to define the energy efficiency of a warship so that it can be compared to other warships and other vessels to identify best practice are shown in Table 1.

Table 1. Warship Energy Efficiency Metrics Papers

Title	**Authors, Year**
Controlling greenhouse gas emissions from ships and the implications for Military Ships,	A R Greig, UCL, 2009
Low Carbon Shipping: Consideration of the applicability of IMO Greenhouse gas regulations to warships,	Dr R.W Bucknell, Lt Cdr T.H.H Wyand & Dr A Greig, UCL, 2012
CO_2 reduction design strategies for naval ships	Lt Cdr B Michalchuck & Prof R Bucknell, UCL, 2014

These papers have been reviewed to identify the ideas they propose and to allow those ideas to be reviewed in the content of this study.

3.2 Greig, 2009

In his paper, “Controlling greenhouse gas emissions from ships and the implications for Military Ships,” Dr Alistair Greig of UCL gives a summary of the development of the EEDI and points out that it could be difficult to navies to adapt to meet market-based measures (MBM) because of the work they operate.

Greig recognises that EEOI has a role to play so that a given ship can be operated progressively more efficiently. Clearly, if this were developed further, the MoD’s fuel and lubricants consumption (FlubCon) data reporting system could offer feedback on the ship given a suitable algorithm, and/or sufficient additional information.

Greig also identifies that an incentive-based measure may be useful but for the UK, it is known that the FlubCon system, in part, is a means by which Commanding Officers (CO) are incentivised to reduce fuel usage. The ships’ COs are given average monthly fuel consumption targets to which they must justify any significant deviation in a text box in their monthly FlubCon submission. Hence, they are obliged to behave within limits but arguably, they are not incentivised to push below them.

3.3 Capacity Term

Greig states that the total ship displacement could be used instead of the IMO deadweight value for the Capacity term as the payload/cargo value is not applicable to warships. The use of the ship’s standard displacement can be justified by observing that when bulkers and tankers trade, they unload their cargo to take on new cargo. A warship takes its “cargo,” or capability, with it at all times and arguably, the whole ship is one integrated capacity, thus supporting the argument for the whole ship standard displacement to represent the “Capacity” term.

3.4 EEDI Comparisons

For warships, there is no easy set of ship-based EEM for the world’s fleet by which to compare the EEDI for a given vessel. Whatever is developed as a NEEM will need to be easy to define whilst still being valid so that there is a general buy-in from other NATO and associated navies. If such navies can agree to pool and share their basic ship P&P system data, there would be a growing basis for performance benchmarking so that informed decisions about setting NEEM limits, and how to design to meet them could be developed further.

3.5 Electrical Demand

Greig states that the electrical power term for warships need not include ship systems such as Replenishment At Sea (RAS), weapons, and sensors. This is compared to liners and ferries where the payload consumption of the passengers is not included as they are part of the payload. However, as outlined above, on ferries the cargo gets off whilst on a warship the crew and overall capability remain, so it is suggested that the SEL is used. This could

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still use the equation stated in the IMO regulations as a first estimate, whilst those who wish to submit the value of the NEEM to a central assessment centre would have the scope to submit a technical dossier which explained why their SEL was lower than the IMO equation.

As the electrical demand of a warship will be a complex interaction of different loads, all of which are essential for the ship to function at all times, it is to be assumed that the SEL when cruising is used, unless a dossier is submitted. As the EEDI is all about economy, i.e. the time-averaged demand, this is considered a valid basis as active use of the weapons and sensors in their high-power states for any period of time will not occur when cruising.

3.6 Electrical Propulsion

Greig notes that the EEDI prevailing in 2009 did not adequately address the need to capture the use of electric propulsion in hybrid and full electrical forms. The Power Take-In (PTI) arrangement is now in the IMO equation set and this allows for this to be treated as in the Type 23 where the electric propulsion motors (EPM) are used for almost all the time.

Given the issues raised by Greig, it is considered that the loading of the electrical propulsion machinery set be determined from the declared cruising speed. If one deconstructs the EEDI approach, they have assumed that main engines operate at 75% load because the engine's best specific fuel consumption (Sfc) is at this point. This was set before the Global Financial Crisis in 2008, after which slow steaming was introduced to save money and was accommodated by much lower trade volumes. Engine suppliers were then able to tweak the engine's set-up to achieve an Sfc sweet spot at lower loadings.

If the ship is declared to operate at a given speed when in cruise mode, and this is on electric or mechanical propulsion, the propulsion fuel demand at this condition and the CO_2 emissions that go with it could be used.

3.7 Summary

Greig's paper covers a large number of issues associated with the issue of a warship EEM but does not readily present a proposed way forward. He makes a case for the ship's displacement being the Capacity value in the EEDI equation.

3.8 Bucknall, 2012

Prof Richard Bucknall's paper "Low Carbon Shipping: Consideration of the applicability of IMO Greenhouse gas regulations to warships", follows on from Dr Greig's 2009 paper by supporting the use of ship displacement for the Capacity term instead of payload/deadweight, by showing that the so-called deadweight of a warship never leaves it as it would then be lightship and not in service. He makes the case for the use of the deep departure displacement condition, which may also be considered as the standard displacement.

The variable load due to weapons in terms of weight and power demand is a small change to the ships weight and SEL, respectively and so can be ignored. Bucknall outlines why the gross tonnage should not be used for Capacity as the warship's superstructure is generally quite small, but more importantly it is not a term used to define warships.

Bucknall proposes a warship EEDI, (wEEDI) using cruise speed conditions for power and fuel consumption purposes. He does not address specifically the SEL demand requirements, or how these can be assumed.

He assumes that only those propulsion engines to be used at cruise speed are assessed and the Sfc comes from their loading at that condition.

Bucknall discusses how ship designers might be tempted to design ships bigger to achieve lower wEEDI. The point is made that the whole set of complex design challenges and the cost of a vessel tend to make the vessel the "right-size" to achieve the right blend of the requirement set of operating performances.

As larger ships are more efficient and have a lower EEDI, the trend to larger warships may enhance the efficiency measure but of course they will still burn more fuel because they still need more energy to achieve the same speed as a small vessel. Warships are not bulkers, so a larger more efficient warship may still carry the same mission systems whereas a larger bulker carries more cargo.

To address the issue with the need to compare a calculated wEEDI against a peer-set of values, Bucknall analysed a set of 12 western warships of various ages to show how their wEEDI varies with displacement.

He observed that warship EEDI values:

- Have fallen with time;
- Fall with lower cruise speeds;
- Fall with dedicated cruise engines;
- Increase with decreasing displacement, a trend common to commercial ships.

In Figure 1, Bucknall presents a plot of wEEDI vs displacement for the 12 data points and added a regression curve using the logarithmic trend as used by the IMO to determine maximum allowable EEDI values.

Although there is a fair degree of scatter due to the spread of warship ages, the trend of the regression line has the same shape as commercial ships.

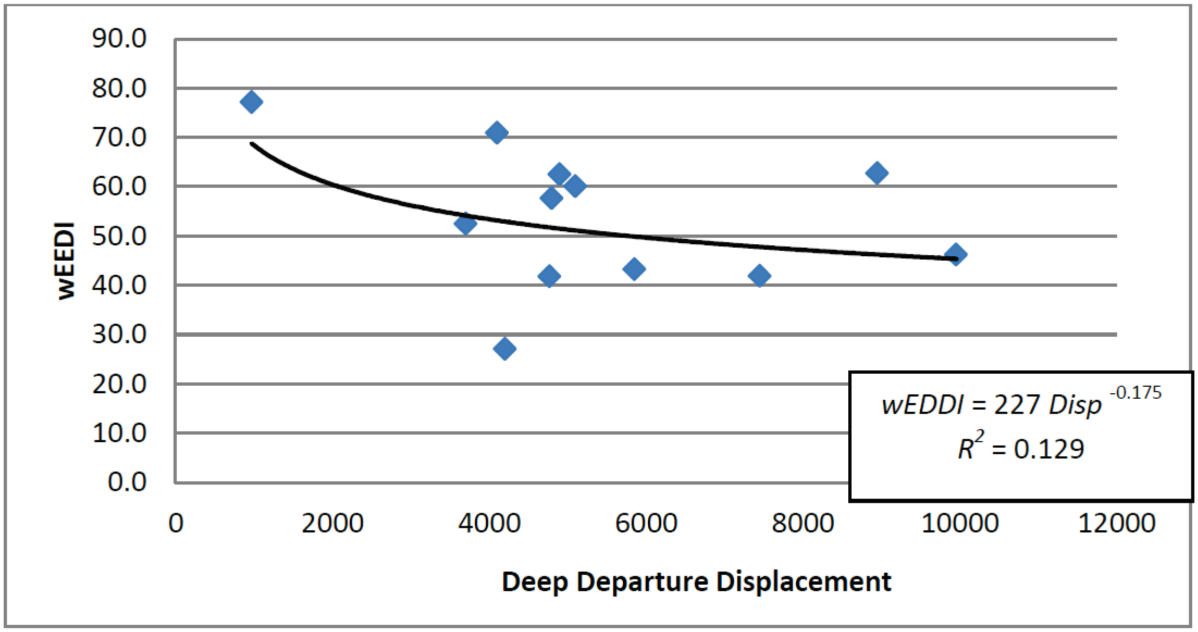

Figure 1. wEEDI versus Deep Departure Displacement

In addition to the observations by Bucknall, the scatter is probably due to a number of factors, chiefly:

- The varying cruise speeds for each vessel ranging from 12 to 20 knots;
- The range of engines used at the cruise speed (diesel or Gas Turbine (GT) engines);
- The different propulsion configurations (electric or mechanical).

The key factor is the variation in cruise speed as the power demand at 20 knots is over four times that at 12 knots. The use of the EEDI trend line as shown in Figure 1 is therefore inadequate for warships if the use of their stated cruise speed is to be adopted in the assessment .

Bucknall's work shows that there is a basis for adapting the IMO EEDI to develop a naval-based measure of efficiency. However, the obvious observation from his work is that those vessels with similar displacement but slower cruise speeds have a better, lower EEDI. When setting ship's requirements, the speed is chosen to meet necessary duties associated with accompanying convoys and the company of other ships as well as requirements associated with the time to achieve specific transit distances for operational purposes. It is therefore considered that a means of comparing warships using both speed and displacement as measures is required.

Bucknall clearly shows that there is a basis for developing a wEEDI or more generically a NEEM, to allow warship energy efficiency performance to be assessed.

The paper does not address SEL or how the cruise speed selection can be accommodated to allow ships of the same displacement but different cruise speeds to be compared to each other for example.

The paper suggests that the wEEDI could accommodate a set of different speeds and it is known that this has been adopted for a recent ship contract competition.

The paper does not observe that the removal of the fixed 75% power load and its alignment with the cruise speed, now makes it much easier to accommodate electric propulsion. By orienting the whole equation around the selected cruise speed, its propulsion load and the standard SEL at cruise speed, the equations are not driven by the individual term for the specific actual architecture of the P&P system, but by the actual total fuel consumed and the associated (CO_2) emissions.

3.9 Michalchuk, 2014

Michalchuk re-iterates the concept of a Warship EEDI as presented in Bucknall's paper. He states that the long lifetimes of warships means that a Fleet EEDI may be better so that the change of the total fleet energy efficiency can be plotted as new ships enter and old ones leave the fleet. He plots the fleet EEDI for 14 navies and shows that the line of EEDI versus average displacement comes out close to the size and shape of the warship EEDI.

However, the fleet EEDI idea has limited usage as it does not allow the ship owner to specify a target EEDI for a new ship design. Michalchuk states that to become more efficient, the ships will get bigger but then this has a natural restraint that such ships would be overly costly. Arguably this situation leads to good place where ship designers will seek an efficient but affordable ship design.

From the work of Michalchuk, Bucknall, and colleagues, it would appear that one way forward for the EEDI criterion to be met is to be driven by not only displacement but also by the cruise speed.

However how does one set the target EEDI for a given speed and displacement? The required target EEDI could take the more developed form of the equation below.

$$EEI_{reqd} = A \times V_{cruise}{}^{b\ X\ Disp^{c}} \qquad \text{Equation 2.}$$

Where A, b and c are coefficients derived from a regression analysis of a set of modern warships. In this way the highly influential factor of ship speed would be accommodated so that the wide range of calculated EEDI values in the figures of Bucknall and Michalchuk are brought closer once cruise speed is factored in.

But curve fitting to one overall equation by complex regression means that there will be significant deviations on some part of the speed-capacity plot.

4 Discussion

4.1 Commercial Vessels

The current measures utilised by the IMO are designed for international shipping which has a large baseline population with a coherent set of estimated efficiencies which have been developed from the four IMO sponsored GHG studies. This set of ship operating efficiency data allows the developed IMO metrics to be compared to the data average, thus showing whether a specific ship is above or below the average value for comparable ships of the same ship type and displacement.

The IMO's EEDI and CII approach both assume that ships of the same deadweight and type will have comparable installed propulsion power and therefore a comparable speed. IMO also assumes, for the most-part, that ships will operate at a full deadweight capacity, when often the ships are in ballast for return trip (e.g. an ore carrier), or part loaded due to commercial reasons.

In the IMO EEDI calculation, the rated power of the electrical power generation demand is based on an equation which uses the rated propulsion power. This is recognised as a generalisation but as the electrical load is usually a small proportion of the propulsion load this is considered so far to be an acceptable approach for simple cargo vessels (i.e. not cruise liners).

4.2 Naval Vessels

As with commercial vessels, the CO_2 emitted per unit of useful work done is a good basis for assessing the vessel's energy efficiency. For naval vessels, especially warships, there is no deadweight which is carried and then disembarked at the destination port. Arguably the whole vessel is the valuable cargo which stays "onboard" and the weight which is considered as the Capacity when assessing the useful work done.

The study has found that the naval vessel's declared operating speed in its range statement is a good basis for assessing the NEEM as the operational range speed is required for long periods and is also the speed at which the vessel has been designed for its best efficiency at the start of life.

5. NEEM Target Setting

Although Equation 2 indicated that the required EEDI could be prescribed by an equation including a cruise speed term, the ability to have a more flexible 3D NEEM contour plot approach based on the EEDI values of specific existing warships and their service speeds was explored.

The machinery set-up for the declared cruise speed is usually that for an efficient operating condition and so gives the best EEM for the vessel at the speed it is designed to operate at, therefore, this all looks like a sound basis for assessing the NEEM.

However, once a value of NEEM is determined there is no standard set of values against which it can be compared. Unlike commercial ships with standard and therefore comparable speeds, warships can have cruise speeds which are typically between 12 and 20 knots as shown in Figure 2. This large speed range has a correspondingly larger range of power and NEEM.

To allow the NEEM values to be compared, it was considered that a 3D contour plot based on a set of modern, in-service warships could be used to set the baseline targets. To add extra data points, a vessel with an 18 knot cruise speed is also considered at slower speeds to identify the NEEM scores at those points.

Figure 2 shows an example 3D contour plot with target NEEM contours in g.CO_2/tonne.nm on the z-axis, ship cruise speed on the y-axis and the ship's displacement (i.e. Capacity) in tonnes on the x-axis. This plot is for diesel powered ships only, i.e. for ships that are operating on diesel engines at the cruise speed. This includes warships such as Type 26 up to a specific speed even though they use GT boost engines above this speed. The plot is based on calculated NEEM at a range of speeds for Type 23, Type 31, Type 45, and the Type 26 as well as models of other vessels.

The models to define the performance have been developed using publically available data which was then fed into the BMT marine P&P modelling capability to determine the fuel consumption at the declared service speed, and at other speeds to help populate the plot.

The current example version shown is based on relatively few data points and so the contours are not as regular as they would be with more data points. However, it may also indicate step points in ship hullform design for the top design speed will vary between ships and this will affect their slenderness (block coefficient).

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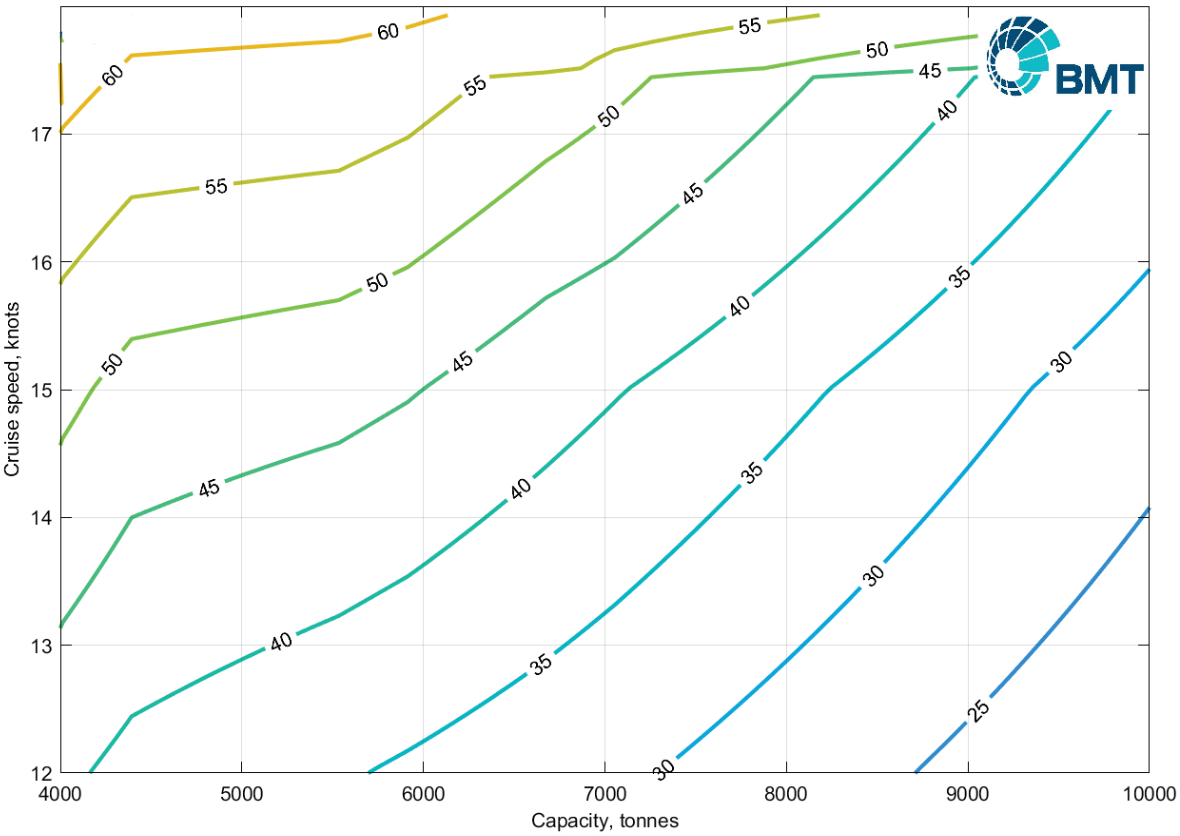

Figure 2. 3D contour plot of NEEM on warship speed v displacement

Figure 2 therefore, may serve as the basis of a reference plot from which the current NEEM for a given speed and displacement for a new build might be expected to occur. The Ship Authority may then choose to set a target NEEM for the design competition which is less than the derived current stand from the plot.

As an example, a 6,000 tonne ship with a 15 knot cruise speed is indicated to have a current NEEM of 45g.CO_2/tonne.nm. The Authority may choose to set a design target which is below this value so as to encourage a positive approach to designing the ship for efficiency at this speed. The offered EEDI performance with its supporting technical dossier will then provide a basis for scoring the offered designs for this criterion.

The reference plot may also allow the benefits of changes to ships, such as the addition of an EST, to be compared.

There is a clear change of EEDI between warships that are designed for a high top speed on GT engines, and naval auxiliaries which operate at much lower top speeds and who use diesel for all P&P duties. Consequently, Figure 3 shows the contour plot of NEEM values on ship cruise speed (y-axis) versus ship displacement (x-axis) for non-warships, i.e. naval auxiliaries.

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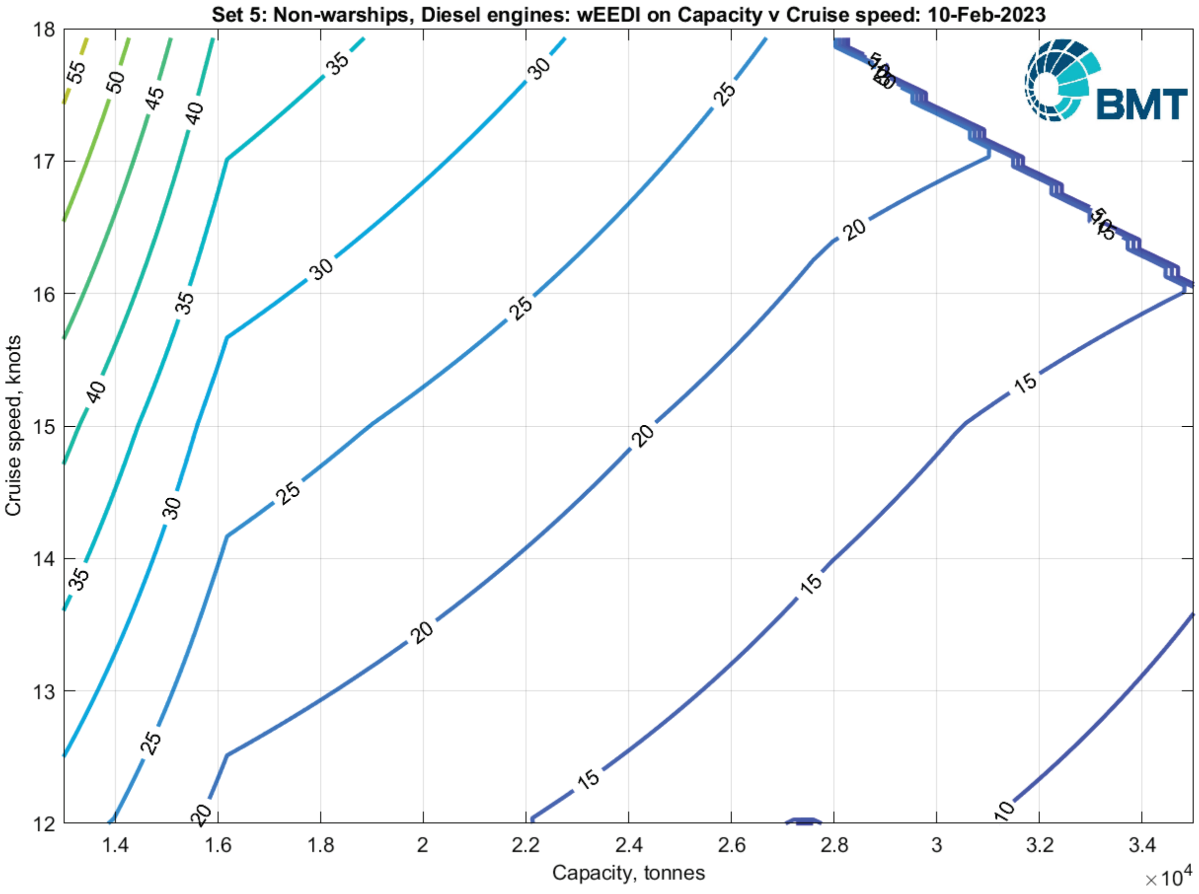

Figure 3. 3D contour plot of NEEM on naval auxiliary speed v displacement

As naval auxiliaries are closer to commercial bulkers and tankers, future work may consider how similar the plot compares with the IMO EEDI equation settings.

6 Conclusions

The study has reviewed the IMO energy efficiency metrics and has identified where they can be adopted for warship applications. Three leading technical papers on the subject have also been reviewed to identify their ideas that can be developed further.

The NEEM plot has been based on the basic P&P information for a set of existing modern warship designs. The EEDI value is based on the vessel's cruise speed and its capacity term is based on its displacement. There would be separate contour plots for vessels which rely on GT engines at the nominated cruise speed.

A calculation for the ship's NEEM score is developed which uses first principles to derive the CO_2 emitted at a given cruise speed. The approach includes the ship's SEL which in this study has been estimated using the IMO equation. This approach is independent of propulsion configuration and incentivises the design to reduce the SEL as well as to increase the overall propulsion efficiency.

To prescribe the required NEEM target values, using values derived from existing vessels, target NEEM contour plots are presented for warships on diesel engines and for naval auxiliaries. The NEEM score is based on the vessel's cruise speed and its capacity term is set to its displacement.

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References

DfT. (2019). Retrieved from Clean Maritime Plan: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf

Fuels, I. (2019). *Buying fuel on calorific value as means to achieve savings.*

IMO. (n.d.). Retrieved from Marpol Annex VI: https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx

IMO. (10-Jun-2022). GUIDELINES ON OPERATIONAL CARBON INTENSITY INDICATORS AND THE CALCULATION METHODS (CII GUIDELINES, G1). *MEPC 78/17/Add.1, RESOLUTION MEPC.352(78).*

IMO. (10-Jun-2022). GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY EXISTING SHIP INDEX (EEXI). *MEPC 78/17/Add.1, RESOLUTION MEPC.350(78).*

IMO. (2011). regulations on energy efficiency for ships in MARPOL Annex VI.

IMO. (n.d.). Prevention of Air Pollution from Ships: https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx.

ISO. (n.d.). *ISO 8217, Quality specifications for marine bunker fuels.*

MoD. (2013). *Def STan 91-004, Fuel, Naval, Distillate NATO Code: F-76 Joint Service Designation DIESO F-76, Issue 9 .*

OLMER, N. (2017). GREENHOUSE GAS EMISSIONS FROM GLOBAL SHIPPING, 2013–2015.

The Truth Behind Green Alternatives For Future Ship Design

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Synopsis

The most recent IPCC (Intergovernmental Panel on Climate Change) report has outlined the risks and potential impacts across the globe, highlighting that changes we will face under climate change will be both difficult to predict and costly to adapt. As global resource scarcity and the energy crisis collide under a warming climate, it is crucial that we look at solutions for our Defence assets to be future ready, one of the most important being how we generate and store energy for our surface fleets. With current designs, new and improved materials used to power and source energy are being highlighted as successful 'green' alternatives to oil and gas.

This paper examines the production of nuclear, green hydrogen and lithium as alternative energy stores. Discussion is centred around the environmental impacts associated with the mining of the minerals required alongside the present socio-economic challenges faced that, if not addressed, will prevent these emerging systems having a truly sustainable credential. A reduction in carbon emissions is just one aspect of a truly ‘green’ alternative and both the short and long-term impact of these fuels on the environment, economy, and society cannot be ignored.

Keywords: Green fuels; Climate change; Marine systems;

1. Introduction: Background and the issue

It is now widely accepted by researchers that our climate is rapidly changing, both in terms of anthropogenic carbon in our atmosphere and oceans, to resource scarcity and an increase in extreme weather. The natural environment is under threat from a variety of challenges, with climate change being the most uncertain and complex issue (Rising, Tedesco, Piontek and Stainforth, 2022). The IPCC’s 2022 (Portner et al, 2022) report evidences the observed and projected impacts of climate change, with increased weather events resulting in irreversible impacts on some human and natural systems. These impacts have already effected some natural systems and human societies, with increases in disease, loss of species, and extreme weather events causing economic loss, human migration, and subsequent conflict. Climate change will inevitably impact how the Royal Navy (RN) protect, operate, and fight, from melting icecaps causing sea levels to rise and reducing the number of ports available for Navy Ships, new transit routes creating new security risks, and an increased requirement for humanitarian and disaster relief.

It is not only RN ships that will be impacted by these changes, but also commercial shipping. International shipping emissions rose to approximately 700 million metric tons of carbon dioxide ($MtCO_2$) in 2021, accounting for 11% of that year’s total global transportation CO_2 emissions. International shipping emissions have increased by 90% since 1990, due to increasing seaborne trade coupled with an increasing number of ships (Tiseo, 2023). Efforts to decarbonise shipping has increased since 2018 when the adoption of the International Maritime Organisation’s (IMO) Initial Strategy on GHG Reduction took place (IMO 2018), now replaced by the 2023 IMO Strategy on Reduction of GHG Emissions from Ships (IMO 2023). The strategy states indicative checkpoints to reach net-zero GHG emissions, including to strive for a 30% reduction in GHG emissions from international shipping by 2030.

The RN has a heavy reliance on fossil fuels to power its fleet and naval bases and contributes to Defence accounting for 50% of the UK central government’s emissions (Ministry of Defence, 2021). The RN has taken responsibility to drive towards decarbonisation, with a focus on the main issues of powering the fleet and naval bases. The pressure for an efficient transition to green alternatives is also fuelled by fossil fuels rapidly depleting, with oil, natural gas, and coal, being limited in quantity and the scarcity increasing exponentially (Wang and Azam, 2024). This has been furthered by energy market volatailities and geopolitical events, such as COVID-19 and the war in Ukraine, whereby energy prices have been at a record-high. This has taken nations by surprise and identified their severe reliance on imported fossil fuels and the strong interdependence of their domestic electricity process with global gas markets (World Economic Forum, 2022).

The use of alternative fuels is the only route for decarbonising the maritime industry, as well as providing the RN assured security and operability in the future, given that necessary ports will bunker the required alternative fuels.

Author’s Biography

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One of the greatest challenges to the RN is resourcing a sustainable source of propulsion. As new power alternatives have been derived, the question remains about how ‘sustainable’ they truly are compared with traditional oil and gas. To be classed as sustainable, alternative power systems must “meet the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987). The alternative source should also present no (or minimal) harm to the environment, be cost-effective, and present no societal challenges. With current designs, new and improved materials used to power and source energy are being highlighted as successful 'green' alternatives to oil and gas, including nuclear, green hydrogen and lithium-ion batteries. With these options evolving, and greenwashing becoming increasingly used by companies, here we will explore the true environmental, economic, and societal impacts associated with the production of these alternatives to seek where improvement is needed for them to become truly sustainable.

2. Introduction to alternative systems

Various systems have been proposed around the world that provide what is quoted to be ‘environmentally friendly’ and ‘sustainable’ sources of power. Here we introduce nuclear, green hydrogen and lithium-ion as contenders for marine propulsion, alongside their general advantages and limitations.

2.1. Nuclear power

The Nimitz Class, of the US Navy, are a class of ten nuclear-powered aircraft carriers, which use two A4W pressurised water reactors. These reactors conduct nuclear fissions that heat the water to produce steam which is then passed through four turbines shared by the two reactors. Power is then transmitted through a gearbox which produces power to four propeller shafts and can produce a maximum power of 190 megawatts (MW) (Gibbons, 2001). Choosing nuclear power, over coal or oil, has many operational advantages, such as allowing ships to operate for over 20 years without refuelling. Nuclear power has been present in UK submarines since 1954 allowing increased speed and operational radius as a submarine can remain submerged on patrol for months (Friedman 2024). All fuel is contained within the nuclear reactor, meaning no supply space is sacrificed for fuel, exhaust stacks or combustion air intakes. The many benefits of nuclear marine propulsion are to be admired, however, the high operating costs and wariness of insurers providing cover for ships sailing into commercial ports without more understanding of the risks, limit the use of it in civil ships, hence why nearly all nuclear-powered vessels are military (Trakimavicius, 2021).

Research into the feasibility of nuclear-powered container ships has identified risks that need to be overcome for it to be viable. The risks include how a reactor will be fitted onboard and the potential for radiation exposure to installers. Questions have also arisen over the safeguards required when the vessel is in motion, the ownership of the vessel, and if tighter security is required when at sea (Saul, 2021).

2.2. Hydrogen Fuel

Hydrogen (H_2) is widely accepted as critical to the decarbonisation of transport and industry, with ~100 million tonnes per annum (Mtpa) being produced globally (IEA, 2023). However, the majority of H_2 is currently produced from fossil-based feedstocks. Therefore, the development of low-emission production methods whilst also increasing the volume of H_2 produced is required to achieve significant CO_2 abatement via emerging H_2-related applications.

Blue H_2 refers to production methods whereby the carbon generated from steam reforming is captured and stored underground through industrial carbon capture and storage (CSS) and is commonly referred to as carbon neutral (World Economic Forum, 2021). This paper will focus on green H_2 which is most commonly formed through water electrolysis, powered by renewable electricity. The water electrolysis method has been associated with higher costs (Yu, Wang and Vredenburg 2021), however, it is recognised as the most viable option for producing H_2 in a low-emissions manner to reach net-zero targets by 2050 (IRENA, 2022).

With increasing interest in H_2 as a replacement to fossil fuels, more research has been conducted into the environmental impact of H_2 leakages into the atmosphere. Sand et al (2023) conducted a multi-model assessment of the 100-year time-horizon Global Warming Potential (GWP100) of H_2. The results estimated a H_2 GWP100 of 11.6, which is significantly higher than CO_2 which has a GWP of 1. Although H_2 is not directly a GHG, it reacts with and increases the abundance of GHGs such as methane, stratospheric water vapour, ozone, and aerosols.

H_2 propulsion systems can be implemented via a fuel cell plant that creates electricity to power a propulsion electric motor or an Internal Combustion Engine (ICE), this can be used as either an electrical generator or as a main engine (Beard et al, 2023). Utilising fuel cells and combining them with batteries can remove the need for generators as the power plant can be altered to include both hotel load and propulsion requirements. If all H_2 and electrical power is produced via renewable electricity, then a fuel cell-based system has the potential to operate

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emission-free. However, H_2 is categorised as a low flashpoint fuel, with a flashpoint of -253^{O}C, meaning vapours that can ignite are formed in almost any condition and has a flammable range of 4-75 vol% in air (Lewis and Elbe, 1987).

With H_2 having a lower volumetric energy density compared to diesel, ships would need to store larger quantities of hydrogen to obtain the same level of endurance as diesel-powered ships. This results in larger or multiple storage tanks being required onboard which may increase the overall size of a ship, or eat into valuable space on curent designs (H2 IQ, 2024). Moreover, the requirement for larger storage facilities and specialised equipment for the handling of H_2 will lead to the construction of new infrastructure at ports, such as safety systems, bunkering facilities and fueling stations.

Precious metals such as platinum and iridium are typically required as catalysts in fuel cells and some types of water electrolyser, which means that the initial cost of these technologies can be high, it is currently twice as expensive as blue H_2 (Beard et al, 2023). This high cost has deterred some from investing in H_2 fuel cell technology. Such costs need to be reduced to make H_2 fuel cells a feasible fuel source for all.

Moreover, an environmental aspect to consider is that the use of H_2 in a marine ICE can lead to the thermal formation of nitrogen oxides (NOx). Careful control of combustion conditions can reduce emissions; however, this may lead to reduced power performance and output. Aftertreatment for the removal of NOx is a possibility for ships, but it will increase the complexity and cost of appliances (Laursen et al, 2023).

2.3. Lithium-Ion

Battery power has become a popular option for the transportation sector, with the maritime industry incorporating batteries onboard ships to reduce GHG emissions. lithium-ion batteries can be used as backup power to support the operating profile of a ship, such as maintaining Dynamic Positioning (DP) systems. Ships can run in zero emissions mode when batteries are used as the only source of electricity and can be used for “peak shaving” when taking over from onboard generators to deliver the peak load of electricity (Bureau Veritas, 2021).

A key challenge however is the safety issue known as “thermal runaway”, when a battery is either damaged or subject to high temperatures it can emit heat, flames, and gas, which can harm crew members and damage vessels (Bureau Veritas, 2021). Specific rules and standards are complied with when testing batteries for damage, and safety measures, such as a Battery Management System (BMS) can be applied, to ensure a battery is in an optimal working condition.

A major disadvantage is that lithium-ion batteries suffer from ageing, which is dependent on the number of charge-discharge cycles that the battery has undertaken. Furthermore, the viability of a fully battery-powered vessel depends on its operating profile and the reliability of shoreside charging infrastructure from fossil-free sources (Ship & Boat International, 2023).

3. Production activities and impacts of alternative systems

Here we will investigate the impacts involved in the production of these energy sources, namely the extraction and manufacture of the materials used to assess whether they are the final and sustainable solution they are advertised to be or whether they are just a temporary fix.

*Note due to the different country specifications and uncertainty around it, deep sea mining has not been included within this review.

3.1. Nuclear

The lifecycle resource use of nuclear power generation is commonly assessed using the concept of total material requirement (TMR), which expresses the total mass of primary materials extracted (European Environment Agency, 2016). The first stage of nuclear power production is the mining of the primary nuclear fuel, uranium, which is distributed in the earth’s crust as uranium ore. The three major techniques for uranium mining are underground mining, open-pit mining and in-situ leaching (ISL).

The open-pit method involves drilling the earth’s surface, which is then blasted and excavated. To extract the uranium ore, a large quantity of overburden, including mine waste, is extracted. The underground method involves drilling the earth’s surface to develop vertical tunnels to access the uranium deposit (Doka, 2011).

The in-situ leaching method involves injecting a lixiviant, usually sulfuric acid, into the boreholes. The acid interacts with the ores and leaches out a mixture of uranium that is then collected, the uranium is extracted and then purified. This process can result in water contamination when the lixiviant mixes with underground water, which can lead to the sulfuric acid being present in downstream ecosystems (Srivastava, Pathak and Perween 2020).

Milling is then conducted to convert the uranium into a usable form, which consists of crushing the uranium into a fine sand and the use of a lixiviant to separate and purify the uranium into a form known as "yellow cake". Tailings is the term given to the radioactive rock and sand byproducts of this process, with finer dust residue being mixed with water and the slurry placed into tailing ponds.

Tailings are the primary environmental challenge associated with uranium extraction. Uranium tailings contain miniscule particles that are transported by the wind and can contaminate soil and water (Dewar, Harvey and Vakil, 2013). Leaks from tailing ponds result in contamination of underground water with heavy metals, which can lead to the pollution of rivers and lakes. Rain added to tailings can introduce sulfuric acid to aquatic ecosystems and direct wildlife exposure to tailings can be fatal. In 2008, 1600 ducks died in Canada after flying into a tailing pond (Sutton, 2017).

Nakagawa, Kosai and Yamasue (2022), conducted research into the environmental impact of nuclear power generation via a lesser-known measure; the volume of resources extracted from the lithosphere during the lifecycle of this process. This research had a focus on the mining methods used, the nuclear reactor types, and the type of uranium fuel cycle system used. Furthermore, the different grades of uranium ore mined and their effect on the TMR was assessed. The research found that there is a 26% reduction in resource use when a closed cycle that reprocesses uranium fuel is used, compared to an open cycle that does not reuse its by-products.

As well as the adverse environmental impacts associated with uranium mining activities, some human health and societal issues are also presented. Tailing deposits, coupled with piles of mining debris can become unstable and create landslides which can cause fatalities. Moreover, radioactive particles can be transported through the air via wind, causing kidney disease and lung cancer if inhaled (Dewar et al, 2013). Unfortunately, certain populations are at greater risk of exposure to these health hazards, with black individuals and low-income communities being disproportionately subjected to the hazards of mining. For example, the Native American reservation of Navajoland, is littered with tailing piles, with the United States Environmental Protection Agency mapping 521 abandoned uranium mines on the reservation (Arnold, 2014). Regarding this, uranium mining serves as an avenue for continued environmental racism, with the issue demanding public awareness and close examination. The conditions in which uranium is produced and the social impacts this can cause must be reviewed and corrected in order for nuclear to be classed as sustainable.

3.2. Hydrogen

Greenwald, Zhao and Wicks (2024) assessed the critical mineral and energy demands associated with the production of green H_2 under varying demand scenarios; 100 million tonnes per annum (Mtpa) for a "business as usual" case if green H_2 were to replace current fossil-based production, 500 Mtpa for a "net-zero" case with increased demand (based on the IEA's Net Zero Roadmaps) (IEA, 2023), and 1,000 Mtpa for a "high growth" scenario where green H_2 would be widely used as a fuel and replace natural gas (Energy Transitions Commission, 2020). For each scenario, they calculated the critical mineral demands required to build water electrolysers and renewable electricity sources to power the electrolysers.

Alkaline water electrolysis (AE) uses Nickel (Ni) catalysts, however, the corrosion of the Ni-based electrodes resulted in the development of membrane-based method, such as proton exchange membrane (PEM) electrolysis. PEM electrolysis involves a solid polymer electrolyte, composed of perfluorosulfonic acids (PFSAs). PEM uses platinum group metals (PGMs) (platinum, Pt; palladium, Pd; and iridium, Ir) as electrode catalysts**,** these raw materials are more expensive than those required for AE. Solid oxide electrolysis cells (SOEC) have the potential to enable higher efficiency H_2 production than AE and PEM (Ni and Leung, 2008), but require transition metals and rare earth elements (REEs), such as, Ni with yttrium (Y)-stabilised-zirconia and strontium (Sr)-doped lanthanum (La)-based manganese (Mn) or iron (Fe) oxides as separator materials.

Greenwald et al (2024) estimated the total mineral quantities required for each H_2 demand scenario described above and found that PEM electrolysers require the least amount of raw material, however, as PEM methods rely on PGMs, it is also the most resource constrained method. Even under the "business as usual" scenario, half of all annual global Ir production is required for sufficient PEM capacity. Restrictions on the production of fluorinate compounds, such as PFSAs (Lim, 2023) only increase the unreliability of PEM as a sustainable method for water electrolysis.

The limited distribution of REE reserves, specifically for La and Y, alongside increasing demand for these elements from other clean energy technologies, challenges the feasibility of scaling up SOECs to meet future demands. AE is the most resource intensive in terms of the total tonnage of materials required, leading to a higher CO_2 footprint associated with its material production (Azadi, 2020).

The environmental and socio-economic impacts of mining these minerals are rarely acknowledged when evaluating energy transition methods and scenarios, but their understanding is crucial as they pose a risk to future supply. Research suggests that PGMs pose the highest level of risk of all minerals required for the energy transition in the mining industry (Lebre et al, 2020). The Bushveld Igneous Complex (BIC) in South Africa is where 91% of global PGM resources are found, accounting for 74% of global platinum production (Schulte, 2023), however, this mining area faces multiple risks, such as energy and water supply, local governance and community relations.

Figure 1 Mogalakwena Mine in South Africa is one of the largest PGM producers in the world.
Mine profile: Mogalakwena | Anglo American

Mogalakwena mine as pictured above, located on the Northern Limb of the BIC, is one of the world's largest PGM producers (MDO, 2024). The site has low annual rainfall (620 mm) and has a hot semi-arid climate (SRK Consulting, 2019). However, the mine consumes 66 megalitres (ML) of water per day, whilst only 26% of residents have piped water access to their dwellings which has led to social unrest, vandalism and disruption of mining activities.

Mines within the BIC area are 90% dependent on national utility coal-fired power stations, producing high GHG emissions (IPA, 2024). There is a national energy crisis in South Africa due to the poor performance of the coal-fired power stations and the lack of roll-out of renewables due to political factors (Kruger and Alao, 2022).

Waste is another significant environmental challenge faced, in 2022 Mogalakwena mine extracted 84.7 million tonnes (Mt) of rock but only utilised 13.9 Mt. Subsequently, the mine has eight waste rock dumps covering a total area of 2,182 hectares (ha). Tailings are stored in three onsite tailing storage facilities, failure of which is one of the key risks to the mine. If a landslide were to occur, there would be a significant impact on the twelve villages that are within a 1 kilometre (km) radius (GRID-Arendal, 2023).

Ultimately, these risks could increase operating costs and limit PGM production, having a significant impact on the global supply of PGMs and subsequently the supply of H_2 (Cole, 2023).

3.3. Lithium-Ion

Lithium is an increasingly popular material onboard ships to limit GHG emissions. However, the adverse environmental and socio-economic impacts that arise during the production of lithium could outweigh the positive reduction in emissions during operations.

Lithium exists as salts or compounds within underground deposits, clay, brine, mineral ore and seawater. It is traditionally extracted via evaporative brine processing, whereby lithium-rich brine is pumped into substantial surface ponds for solar evaporation (Lithium Harvest, 2024).

Water consumption is a significant environmental impact associated with lithium extraction, consuming approximately 500,000 gallons of water per metric ton. South America's 'Lithium Triangle' contains over half the world's supply of lithium under its salt flats; however, it is one of the driest places on Earth. This leads to excessive water use, in proportion to the regions supply, during mining activities. For example, in Chile's Salar de Atacama, lithium mining consumed 65% of the region's water (Institute for Energy Research, 2020).

Figure 2 An aerial view of the brine pools and processing areas of the lihtium mine on the Atacama salt flat, in the Atacama desert of northern Chile. South America's 'lithium triangle' communities are being 'sacrificed' to save the planet | Euronews

Mining has brought the benefits of revenues to the State funds and profits for local businesses, however, the excessive water use has led to ecosystem degradation and forced residents to migrate and abandon ancestral settlements due to water scarcity effecting their livelihoods (Romero, Smith and Vasquez, 2009).

Furthermore, the use of evaporation ponds exposes toxins to the environment (Figueroa et al 2013). Tibetan mines have experienced the leak of toxic chemicals, such as hydrochloric acid, from the evaporation pools into the water supply and in Nevada, scientists found lithium mine toxins in fish 150 miles downstream from the lithium production site (Institute for Energy Research, 2020).

Hard rock mining is another traditional lithium extraction method, whereby it is extracted from clusters of crystals or rocks. Once the ore is mined, it undergoes crushing, concentration, and chemical treatments, such as leaching and roasting, to receive the lithium concentrate. This method creates chemical waste and contaminates groundwater, rivers and soil. Furthermore, the carbon footprint is increased through transportation of the crushed rock to China for processing.

Moreover, open-pit mining alters and disrupts the natural environment which significantly impacts the visual aesthetics of an area. Subsequently, this can impact tourism rates and the livelihoods of residents through reduced income, recreational space and cultural ties to the land.

4. Strategic Implications on Naval Shipping

Applying these green alternatives to the maritime industry is a technical challenge due to the IMO's regulatory framework and availability of ports. The need to adopt alternative fuels within the RN stems from the requirement to diversify its energy source, to maintain an omnipresent and effective combat capability. Sourcing the most cost-effective solutions to obtain energy availability and accessibility require robust policies and strategies, and management of the strategic tension between investing in the infrastructure for alternative fuels and funding survivability and combat capability improvements (DNV, 2022).

Nuclear propulsion offers many strategic benefits to a naval vessel, such as travelling long distances at high speeds without refuelling which allows quicker response to distant contingenices. The lack of exhaust gases mitigates the challenge of infared detectablility that occurs with fossil-fuelled ships. However, strict regulations on maintenance and operator training have led to nuclear being a burden for sustenance. This, coupled with the great risks of radioactive waste, will create extra cost and logistical pressures for the navy, which may not be practiceable.

Hydrogen fuel cell technology has the potential to become more widely adopted on naval ships in the coming years. With H_2 having a lower volumetric energy density compared to diesel, ships would need to store larger quantities of hydrogen to obtain the same level of endurance as diesel-powered ships. This results in larger or multiple storage tanks being required onboard which will take up valuable provisions space (H2 IQ, 2024).

Moreover, naval ships will only be able to refuel at specific ports that have the appropriate infrastructure in place, which may not always be practiceable and could disrupt operations.

Furthermore, a primary challenge for better-powered vessels is thermal runway. This occurs when a battery is subject to high temperatures, which can occur from a high current discharge rate or being exposed to external heat sources (Bureau Veritas, 2021). The inherent risks of lithium batteries, such as fire and explosion, means that it is crucial that containment strategies are in place for successful deployment. A safe strategy to transport, store and charge lithium batteries is key in preventing battery failure and to enhance operational readiness (NAVSEA, 2023). A Battery Management System (BMS) is a safety measure that monitors the voltage, temperature and current of batteries. A BMS is ideal for navy ships as it also enables operators to optimise energy use and availailability whilst also increasing battery lifetime.

5. Conclusion and Comparison to Oil and Gas

The alternative fuels discussed in this paper are relied upon to decarbonise the shipping industry and reach net zero targets by 2050. Whilst these alternatives mitigate the impact of in-service carbon emissions, the environmental and socio-economic impacts associated with their production must not be overlooked if they are to be categorised as sustainable.

Here we discuss some of the main challenges of these alternative systems against oil and gas to give a broad understanding and implication of their environmental impact and evaluate whether these alternatives are a sustainable solution for the shipping industry.

Oil and gas are the largest sectors in the world, employing millions of people and with products used in most major industry sectors. The environmental impacts are well known from oil spills to GHG emissions, hence the demand to source an alternative.

Nuclear power, green hydrogen, and lithium have become increasingly advertised as the solution to decarbonising the shipping industry and reaching the net zero targets by 2050. However, to become completely reliant on these as fuels we must be conscious of the environmental impacts associated with their production, as we are with oil and gas, and identify mitigation methods so that we are not just replacing one problem with another.

An environmental challenge that is shared among the production of all the discussed alternatives and oil and gas is water usage, waste and contamination. Excessive water usage in areas where it is already scarce, such as for lithium mining in Chile and PGM mines in South Africa, alongside wastewater as a by-product of mining activities and subsequent contamination to soil are detrimental to the local environment and wildlife. This, partnered with the impact on residents who depend on these assets for their livelihood being forced to migrate, results in adverse socio-economic challenges. As with the human health impacts of uranium mining, certain populations are at greater risk of exposure, with low-income individuals being disproportionately subjected to the hazards of mining.

In 2022, the production, transport and processing of oil and gas resulted in 5.1 billion tonnes (Gt) CO_2 -eq, which accounted for 15% of total energy-related GHG emissions (IEA, 2023). Advocates of alternative fuels, such as green hydrogen, misguide consumers by promoting the low carbon properties. Whilst this may be the case, it masks the fact that hydrogen has a significantly higher GWP than CO_2 as it increases the quantity of other GHGs.

In conclusion, the Royal Navy strive to create one of Earth's greenest fleets, having already used existing technological innovations to reduce its impact on the environment. However, the long-term challenge of resourcing a sustainable method of propulsion remains key. With many alternative fuels and power systems emerging on the market, it is crucial that the integrity of each is examined prior to agreement. A system promoted as being the 'green' option may be masking unsustainable production practices that outweigh the benefits in the long-term.

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References

Arnold, C "Once Upon a Mine: The Legacy of Uranium on the Navajo Nation," Environ. Health Perspect. 122, A44 (2014).

Ashbridge, S and Beard, A. Greening Defence: Transforming the Royal Navy for a Climate-Affected World. *RUSI*. May 2022.

Azadi, m; Northey, S; Ali, A and Edraki, M. Transparency on greenhouse gas emissions from mining to enable climate change mitigation. *Nat. Geosci.* 13, 100-104.

Beard, T; Rident, C; Priftis, A; Lobo, F; Davis, M and Burrows, A. Feasibility of retrofitting medium sized Ro-Pax ferries to utilise hydrogen propulsion and storage technology. *BMT Ltd. & PA Consulting Ltd.* November 2023.

Bureau Veritas. Entering a New Era for Battery-Powered Ships. June 2021.

Cole, M. ESG risks to global platinum supply: A case study of Mogalakwena Mine, South Africa. Science Direct. Vol 85, Part B, 2023, 104054.

Dewar, D; Harvey, L and Vakil, C. "Uranium Mining and Health," Can. Fam. Physician 59, 469 (2013).

DNV. Alternative Fuels for Naval Vessels. Pg. 21-24. 2024

Doka, G. Life Cycle Inventory of generic uranium in-situ leaching. *PSI.* November 2011

Energy Transitions Commission. Making mission possible: delivering a net-zero economy. London (2020)

European Environment Agency. Developments in indicators: Total Material Requirements (TMR). April 2016.

Figueroa, L; Razmillic, B; Zumeata, O; Aranda, N; Barton, S; Schull, W; Young, A; Kamiya, Y; Hoskins, J and Ilgren, E. Environmental Lithium Exposure in the North of Chile—II. Natural Food Sources. *Biol Trace Elem Res* 151, 122–131 (2013)

Friedman, N. Nuclear Submarine. *Encyclopaedia Britannica.* May 2024.

Gibbons, T. The Encyclopaedia of Ships, 2001. London, United Kingdom: Amber Books. p, 444. ISBN 978-1-905704-43-9.

Greenwald, J; Zhao, M and D, Wicks. Critical mineral demands may limit scaling of green hydrogen production. *Frontiers in Geochemistry.* January 2024.

GRID-Arendal. Global tailings portal. 2023

H2 IQ. Hydrogen Energy Density: Practical Solutions for Efficient Storage and Transport. 2024.

IEA. The Future of Hydrogen, Seizing today's opportunities. Report prepared by the IEA for the G20, Japan. 2019.

International Energy Agency. Emissions from Oil and Gas Operations in Net Zero Transitions. Revised version, June 2023.

IEA. Global hydrogen review 2023. Paris: International Energy Agency.

IEA. Net zero roadmap: a global pathway to keep 1.5°C goal in reach. Paris: *International Energy Agency.* 2023

IMO, “Rules & Regulations for the Classification of Ships using Gases or other Low-Flashpoint Fuels,” IMO, 2022.

INSA: Alternative Fuels Working Group, “Brief on the viability of alternative fuels for naval applications,” 2022.

Institute for Energy Research. The Environmental Impact of Lithium Batteries. November 2020.

International Maritime Organisation. IMO Strategy on Reduction of GHG Emissions from Ships. Adopted 7th July 2023.

International Maritime Organisation. Initial IMO Strategy on Reduction of GHG Emissions from Ships. Adopted 13th April 2018.

International Maritime Organisation. Methanol as a Marine Fuel: Environmental Benefits, Technology Readiness, and Economic Feasibility. 2016

IPA. The Primary Production of Platinum Group Metals (PGMs). *International Platinum Group Metals Association.*

IRENA. Global hydrogen trade to meet the 1.5°C climate goal: Part III – green hydrogen cost and potential. Abu Dhabi: International Renewable Energy Agency. April 2022.

Kruger, W and Alao O. The status of South Africa’s renewable energy independent power projects procurement programme. In: Power Futures Lab Working Paper 2022 (Cape Town).

Laursen, R.; Patel, H.; Dowling, M.; Sofiadi, D; Ji, C.; Nelissen, D.; Király, J.; van der Veen, R.; Pang, E., (2023). Potential of Hydrogen as Fuel for Shipping, American Bureau of Shipping, CE Delft and Arcsilea

Lebre, E; Stringer, M; Svobodova, K; Owen, J; Kemp, D; Cote, C; Arratia-Solar, A and Valenta, R. The social and environmental complexities of extracting energy transition metals. *Nat. Commun*. 11, 1-8. 2020.

Lewis, B and Elbe, G. Combustion, Flames and Explosions of Gases, Academic Press Inc, 1987.

Lim, X. Nature 620, 24-27 (2023)

Lithium Harvest. Lithium Extraction Methods, January 2024.

MariGreen. Perspectives for the Use of Hydrogen as Fuel in Inland Shipping: A Feasibility Study. 2018.

McKinlay, C; Turnock, S; Hudson, D; Manias, P. Hydrogen as a deep-sea shipping fuel; Modelling the volume requirements. *International Journal of Hydrogen Energy.* Volume 69, May 2024.

McKinsey and Company. Land: A crucial resource for the energy transition. 2023

MDO. Mogalakwena Mine. *Mining Intelligence and News.* 2024

Ministry of Defence Climate Change and Sustainability Strategic Approach. GOV.UK, 30 March 2021.

Nakagawa, N; Kosai, S; Yamasue, E. Life cycle resource use of nuclear power generation considering total material requirement. *Journal of Cleaner Production*, 2022; 363: 132530

National Treasury. Municipal Money Data. 2022

Naval Sea Systems Command (NAVSEA). Let’s Get Smart About Lithium-Ion Batteries. 2023

Ni, M., Leung, M.K.H, and Leung, D.Y.C. Technological development of hydrogen production by solid oxide electrolyser cell (SOEC). Int. J. Hydrogen Energy 33, 2337-2354. 2008

Palmer, J. Renewable energy: ways to value green hydrogen projects. *Grant Thornton.* May 2024

PARI. The Mogalakwena Local Municipality in South Africa: an Institutional Case Study Conducted by the Public Affairs Research Institute (PARI) (Johannesburg) 2017

Portner, H.-O.; Roberts, D.C.; Adams, H.; Adler, C.; Aldunce, P.; Ali, E.; Begum, R.A.; Betts, R.; Kerr, R.B.; Biesbroek, R.; et al. Climate Change 2022: Impacts, Adaptation and Vulnerability; IPCC Sixth Assessment Report; IPCC: Geneva, Switzerland, 2022.

Rising, J; Tedesco, M; Piontek, F and Stainforth, D.A. The missing risks of climate change. Nature 2022, 610, 643–651.

Romero, H; Smith, P and Vasquez, A. lobal changes and economic globalization in the Andes. challenges for *developing nations Alpine Space - Man & Environment 7: Global Change and Sustainable Development in Mountain Regions* ed R Psenner *et al.* (Innsbruck: Innsbruck University Press) pp 71–95, 2009

Safari, F and Dincer, I. A review and comparative evaluation of thermochemical water splitting cycles for hydrogen production. *Energy Conversion and Management.* Vol. 205, February 2020, 112182.

Sand, M; Bieltvedt Skeie, R; Myhre, G; Krishnan, S; Sandstad, M. A multi-model assessment of the Global Warming Potential of hydrogen. *Commun Earth Environ* 4, 203 (2023).

Saul, J. Maritime industry explores nuclear power for ships as technology opens up. *Reuters.* September 2023.

Schulte, R. Platinum-Group Metals Mineral Commodity Summary. United States Geological Survey. 2023

Ship & Boat International. Future Fuels: Multiple Paths To A Common Goal. *In-Depth.* 2023

Srivastava, R; Pathak, P; and Perween M. Environmental and Health Impact Due to Uranium Mining. *Uranium in Plants and the Environment.* Springer, 2020.

SRK Consulting. Draft Environmental Impact Assessment Report and Environmental Management Programme Report – Mogalakwena Mine Expansion Project EMPrs Amendment. *Department of Mineral Resources, Government of South Africa*. 2019

Sutton, M. Discourses of the Alberta Oil Sands: What Key Stakeholders Really Think About Sustainability. Consilience 18, 175 (2017).

Tiseo, I. Shipping emissions worldwide – statistics and facts. *Statista.* 2023

Trakimavicius, L. The Future Role of Nuclear Propulsion in the Military. *NATO Energy Security Centre of Excellence*. Retrieved 2021-10-15.

United Nations. Report of the World Commission on Environment and Development. August 1987

Wang, J and Azam, W. Natural Resource Scarcity, Fossil Fuel Energy Consumption, and Total Greenhouse Gas Emissions in Top Emitting Countries. Volume 15, Issue 2, March 2024, 101757.

World Economic Forum. Grey, blue, green – why are there so many colours of hydrogen? Energy Transition, July 2021

World Economic Forum. Fostering Effective Energy Transition. Pg 12, May 2022

Yu, M; Wang, K and Vredenburg, H. Insights into low-carbon hydrogen production methods: green, blue and aqua hydrogen. Int. J. Hydrogen Energy 46, 21261-21273. 2021

The application of physics-based 3D modelling software in ship design and manoeuvrability trials

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Synopsis

Design of naval vessels goes through rigorous preliminary design, critical design, and detailed design phases. Although experience is essential for designers and engineers during ship upgrade, the use of block diagrams and charts to represent the design challenges in maritime application often results in misconceptions, with the required outcome not fully realised. The integration of 3D modelling and visualisation in ship design and operation is favourable when presenting complex design and procedures. These methods aid in observing technical limitations that might otherwise be obscure. The use of physics-based 3D modelling is a continuously growing hybrid modelling technique that blends particle effects with ship design. These procedures allow for a holistic representation of the asset in its natural environment and under predictable sets of conditions. The research presented in this paper illustrates how 3D modelling can accurately be used to represent and evaluate a surface ship under simulated working conditions. Selective serials and protocols were recreated based on mock-up vessel in a marine environment in adherence to classification rules. The use of particle physics extension related to water and weather effects were added to simulate real-life fog formation during channel transit. The use of 3D configuration was applied to a patrol boat to demonstrate the changes implemented instantly without the need for reengineering, particularly at earlier stages of the contract.

Keywords: 3D Design, Blender 4.1, manoeuvrability test, random seed, wake generation, classification rules,

1. Introduction

Naval architects leverage advanced three-dimensional (3D) modelling software to create intricate digital representations of ship hull and complex geometries. By simulating various design configurations and operating conditions, designers can iteratively refine vessel designs, optimising hydrodynamic and other performance metrics such as speed, stability, and fuel efficiency while ensuring compliance with regulatory standards and safety requirements.

Moreover, the integration of 3D design technologies allows for interdisciplinary collaboration of specialised project teams. DNV has founded the Open Class 3D Model Exchange (OCX) which allows 2D drawings to be replaced with 3D model in the ship publication . This standard has already planted its roots with major marine and offshore players such as NAPA, Lloyds Register, Bureau Veritas, and DAMEN and further endorsed by classification rules (IMO, 2002) (ABS, 2017).

The designing of a ship goes through a design spiral (Wang & Pegg, 2022) (Paik & Thayamballi, 2006) which lays down a sequential set of requirements. A digital twin becomes a more relevant approach, (Wang & Pegg, 2022). In a study (Uzcategui, et al., 2018) focusing on pipe fitting and assembly during different stages of assembly, the complexity of the measurement process resulted in uncertainties. A 3D scanning gave accurate representation of the open ends where the pipes would be fitted. The deviation of connections are relatively regular resulting in a nonuniform closure with spools, these anomalies might appear during fine coordination with the manufacturing and workshop teams. The visualisation achieved in the study was sufficient to determine potential misalignment of the mock-up assembly.

A study focusing on submarine design by (Fernandez, 2020) highlights the importance of submarine design using a concept of the internet of things (IoT) where Computer Aided Designs (CAD) is seamlessly integrated with Product Lifecycle Management (PLM) of a new submarine design. The aspect of industry 4.0 refers to a database of CAD approved calculations and boundary conditions which help with future designs and limiting computational effort and human dependence. This technique allows individual teams to visualise the isolated system with more focus, and with the use of 3D design, the possibilities of oversight are considerably minimised.

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The techniques used in this study are intended to showcase the application of 3D tools in ship design and modification, ship test and trials with emphasis on maritime operations (Ffooks, 1993), and simulating limited visibility weather conditions.

2. Vessel Manoeuvrability using a Simulation

The use of 3D tools to demonstrate sea acceptance trials (SAT) is intended as a visual isometric representation of the operation plan. Due to the excessive size of the cache and the exceedingly long animation rendering periods, the animation was captured using viewport resolution set to 1024p sample size running a timeline of 100 frames. The optimum application for higher resolution production would be applying the baking feature to embedded textures and materials followed by rendering using a cycle engine with 4096p sample size and enable denoise feature.

Table 1: Ocean and Wake Properties

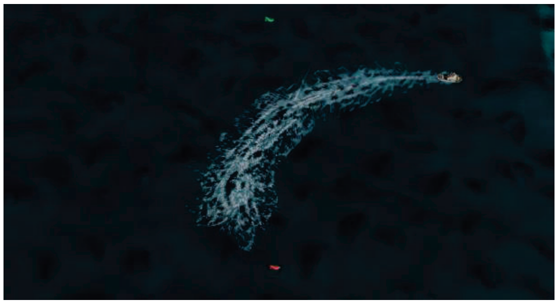
Setting	Variable	Value	Units
Ocean	Viewport Resolution	10	px
	Render Resolution	10	px
	Time	0.05-5.05	s
	Depth	3.00	m
	Size	200 x 200	m^2
	Spatial Size	50	
	Random Seed	0.00	
Wave	Scale	1.00	
	Smallest Wave	0.00	m
	Choppiness Factor	1.00	
	Wind Velocity	30	m/s
	Spectrum	Established Ocean	
Simulation (Ship)	Velocity	20	m/s
	Particle Density	250	
	Age	200	
	Particle Radius	0.02	m
	Ocean Velocity	1.00	m/s
	Noise Amount	0.002	
	Secondary Noise	0.100	

The properties of the simulation from Table 1 were used as presets to observe ship motion instead of inforgraphic representations. For the simulation the ocean parameters viewport and render resolutions were set to

10 pixels, this value makes the assets sharper in the viewport but can also affect simulation period. The time for the ocean simulation ran from 0.05-5.05 seconds, which is equivalent to 100 simulation frames, the delay is mainly due to loading assets into the viewport. The ship path was also simulated over the same 5 second period and for 100 frames, with the aim of capturing the effect of ship wake on ocean surface. The depth of the ocean domain was set to 3.0 m, and the size of the ocean surface was set to 200 x 200 m^2, which is equivalent to 4.00 in viewport grid measurement. The spatial size was set to 50 and the random seed value which controls details in the scene was set to 0, indicating randomness at default value.

The wave parameters were set to closely resemble an established ocean surface. The choppiness factor is essentially a roughness factor of the wave crest and trough which is set to 1.00. The scale of the wave reflects the cycle of each wave which is set uniformly at 1.00 for all generated waves in the viewport. The size of each wave is determined by the minimum value of 0.00 m and the highest rising crest based on wind velocity set at 30 m/s and direction.

The ship simulation was based on a conventional type of salvage tugboat with a velocity set to 20 m/s which is equivalent to 38.8 Knots. The particle density is set to 250, indicating the wake density when disturbed by generated waves and ship motion. Age refers to the wake particle retention period before complete decimation in the ocean surface domain. The particle radius is set to 0.02 m; the wake particle size would be bigger closer to the source, however due to the impact it would have on simulation and its dependency on randomness factor it was sufficient to rely on the Age variable to illustrate wake behaviour. The ocean velocity is set to 1.0 m/s when excited by ship movement where the highest value is for particles close to the ship submerged surface and displaced water. The noise amount was set to 0.002 which is another variable that affects wake behaviour, the higher this value the more pronounced the wake becomes. Noise is also directly correlated with Age; if the wake has a longer Age and a low noise amount, this will translate to a subtle but elongated footprint. The effect of these two dependent variables becomes more noticeable in a turning circle manoeuvre after completing 540° turn.



Turn STBD

Turn PORT

Straight Line

Full Astern

Stopping Distance

Turning Circle

10/10 Zigzag

Pullout Test

Figure 1: Sea Acceptance Trials

The images from Figure 1 demonstrate the different sea acceptance trials conducted using blender to model ship behaviour in an established ocean environment. The red and green flags represent the start and finish points over a distance 100 m approximately. The principal idea behind these productions is to give a detailed look at manoeuvrability crossings and ship behaviour.

The wave and wind conditions were based on the values presented in Table 1 which demonstrate the flexibility to adhere to various desired specifications. The ship path in both the starboard and port direction was drawn with approximately 10 vertices. The specific degrees of freedom including heave, roll, and pitch were handicapped to limit dynamic interference with wave motion. Moreover, the floating domain around the ship to model buoyancy requires integrating a shrinkwrap modifier which is not compatible with the wake generation pipeline.

The turning ability is a trial used to determine the vessel's wheelover using hard-over rudder in the starboard and port direction. Normally these types of trials are used to examine the rudder performance and ship handling and stability criteria including a follow-up shipwright ability particularly when used with a pullout test.

The straight-line trial is intended to measure the ability of the ship to stay due course regardless of environmental factors. The heading of the ship might change from the forward bow, however the deviation of course at different speeds is measured to determine the appropriate corrective actions. The simulation test conducted shows some deviation from course due to a uniform maximum ship speed and a preset wind and wave speeds.

The Full astern test conducted shows excessive veering off path, which is to be expected since the ship submerged volume is not designed to have a course keeping straight profile. The images demonstrate excessive wake on the port section indicating a ship resistance against incoming lateral wind. The results have successfully captured an accurate representation of the full astern trial.

The stopping distance trial was used to establish the number of ship lengths required before the ship comes to a complete stop by turning the rudder to full astern position from maximum forward speed. The results from the simulation show the head reach manoeuvre with an approximate 10 ship lengths, a similar trial can be achieved for the standard of 15 but not exceeding 20 ship lengths in addition to the track reach manoeuvre (ABS, 2017).

The turning circle trial was used to demonstrate a hard-over rudder in both the starboard and port direction with a 540° turn. One of the challenges associated with demonstrating this track was related to the effect of wake from the first circle on ship motion on the second half turn, this could not be demonstrated accurately in our trials. Moreover, self-collision between generated wake profiles at higher frames is not pronounced, however this could be due to the age value and low noise amount. In a practical sense these discrepancies are often neglected in operations and are only ever considered in hydrodynamics testing facilities.

The 10/10 zigzag manoeuvre is a slimmed down version of the 20/20 trial both of which are conducted at various rudder angles and in both the starboard and port direction (ABS, 2017) (IMO, 2002). The simulation was able to demonstrate a fraction of the 10/10 wake profile but not the entirety of the run. The limitation of the simulation run to 100 frames mandated a short profile; alternatively, the ship speed could have been increased beyond 30 m/s to capture the entire run.

The turning ability followed by a pullout test is demonstrated to indicate a lighter version of consecutive trials. The IMO standards require a detailed calculation of the first and second overshoot angle in a 10/10 zigzag manoeuvre (IMO, 2002); it is therefore possible to integrate the expected readings into the simulator to provide a more accurate result.

3. Simulation Based Channel Visibility During Channel Transit

The effect of sea state and wind although equally important, are generally manageable and predictable. Dangers associated with fog manifest in hazards related to collision, grounding, moisture build-up in sensors, and GPS. Navigational aid following rules of the road, and helmsman orders become increasingly relevant throughout this period. Extra hand at the bridge for lookout affects the sea trial inspection process as it is likely that the bridge would be overburdened with personnel carrying out duty watch whilst conducting a set number of trials.

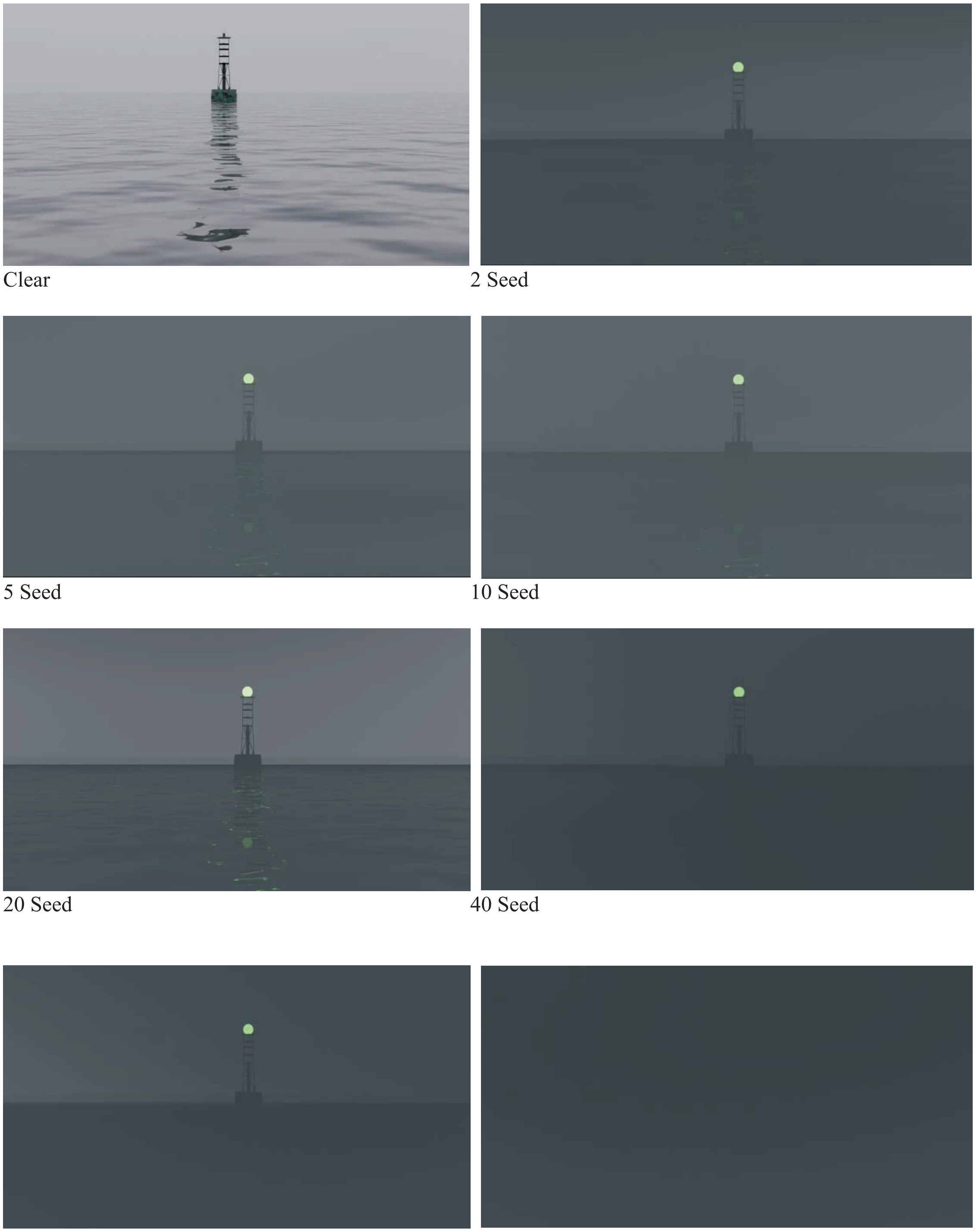
The simulating of fog effect prior to the scheduled trials is difficult to produce, and although weather forecasts can predict visibility levels using curated meteorological databases, the actual visualisation of the fog density effect cannot be captured with readings. Moreover, since the specified vessel needs to navigate tight corridors and waterways outside the channel into open waters, it is likely that port control station (PCS) and the harbour master will be involved. The allocation of a pilot and possibly a salvage boat for this operation becomes part of the of hazard mitigation plan; all these preparations, increase the associated cost to conduct those trials without completely emitting the possibility of a retrial.

The methodology prepared in this section is intended to show how procedure generated fog in a 3D simulated environment can be used as an intermediate solution to vector maps generated by expensive computational fluid dynamics software. To better understand the situation at hand the viewport assets consisted of a channel buoy at 50m from the cursor (resembling the bow of the ship). The channel buoy is fitted with a light (green) emission source. The location of the buoy is on the starboard side indicating a downstream transit. The light specification of the emission source follows the standard commercially available lighting aids at 400 W. The simulation domain resembling the boundary conditions was created with the dimensions of (68m x 55m x 24m). Further details related to fog simulation specification have been selected based on presets and indirect correlation with visibility using trial and error.

Table 2: Fog Seeding Simulation Details

Fog	Seed	Scale	Details	Roughness	Distortion	Min	Max
Fog 1	Variable	0.680	4.700	0.669	0.000	0.750 – 0.500	0.000 – 49.840
Fog 2	0.500	0.680	10.700	0.669	0.000	0.590 – 0.000	0.000 – 49.840

The presets of the procedurally generated fog are presented in Table 2 which shows the parameters used in the simulation to study visibility of a channel buoy at 50m away from the surface asset. Fog 1 indicates a sea surface cluster and Fog 2 represents the upper cluster formation in the domain boundary box. The seed value is a dimensionless parameter used to identity the fog density in the sample volume, the scale is overall cluster expansion with a preset value of 0.680. The details factor represents the clarity of the fog particle; considering the effect this value has on image generation the values were set to default. Roughness is the inverse to the smoothness factor of the fog particle which also affects render time and quality, therefore set at default. Distortion is a procedurally dependent factor which randomly populates the domain volume based on the minimum and maximum bounds. The minimum bound is a range that determines where the minimum distribution is observed and the maximum bound is used to designate the highest fog density limits.



Clear

2 Seed

5 Seed

10 Seed

20 Seed

40 Seed

60 Seed

80 Seed

Figure 2: Fog Density Based on Seed Value

The images from Figure 2 show the fog density as determined by the seed value using a procedurally generated scatter distribution system. It is important to note that an increase in seed value should result in higher fog density and subsequently less visibility; however, due to the randomness of the system, the vantage point selected might show a cluster that is less dense when viewed from a different angle. This observation is particularly noticeable when moving from a 10 seed render to 20 seed render result, the immediate observation show clearer water surface with light reflection at higher seed value. The only feasible explanation to this condition would be that from the current viewpoint at 20 seed, the fog density appears less; after changing to incremental values of 24 seed the values restored to normal with the expected visibility shortage. At other incremental instances the values turned the buoy visibility to completely blind, similar to what is observed at 80 seed.

Although the fog simulation is not a direct representation of a physics based realistic metrological model, it is designed to provide a visual representation of conditions that are comparable to those encountered in an operational environment that might otherwise be difficult to represent.

4. 3D Vessel Configuration of a Petrol Boat

The use of 3D visualisation has a crucial role in modern ship design, offering several benefits throughout the design process. In this study the use of Blender 4.1 and Autodesk Fusion 360 was sufficient in providing a high-fidelity conceptualisation of various design iterations.

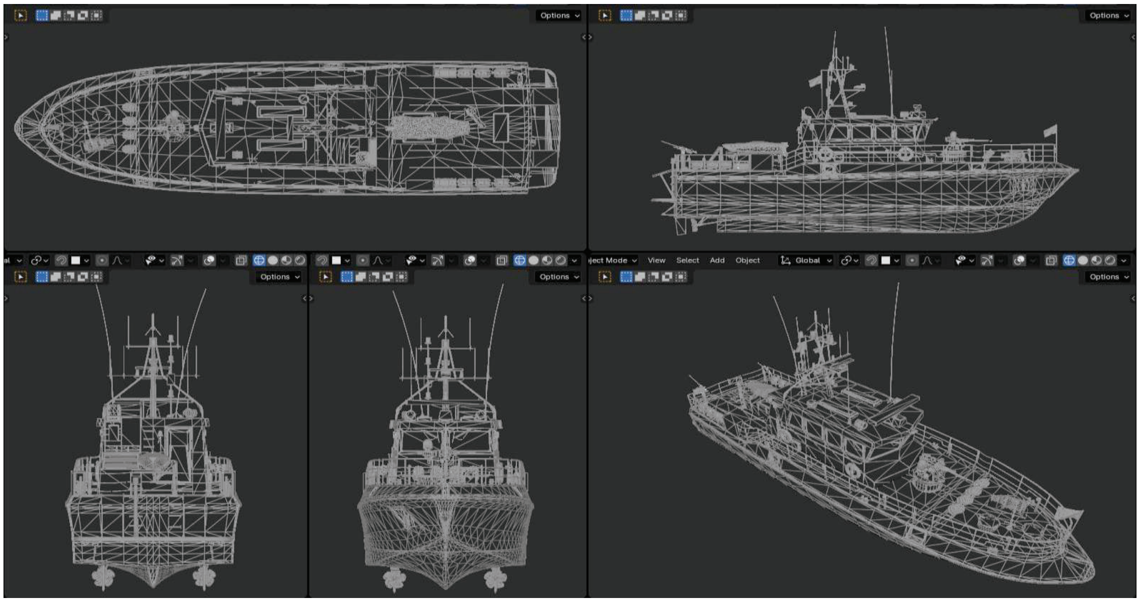
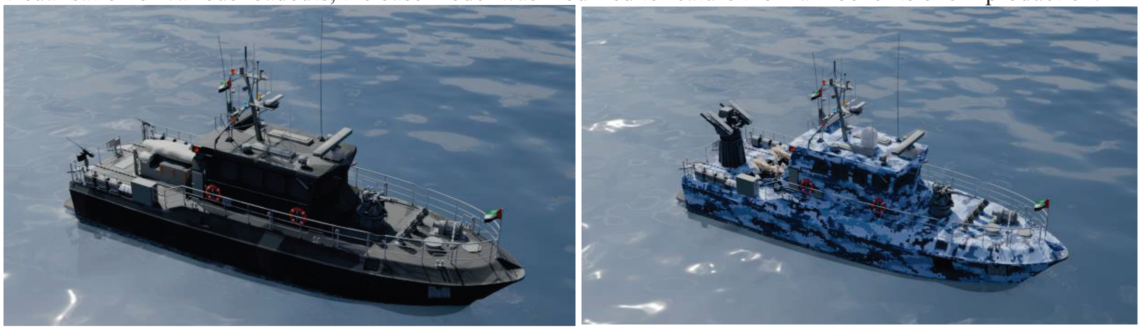


Figure 3: Patrol Boat Viewport Line Diagram

Figure 3 above the viewport shows the line drawing of a patrol boat in native format, the principal dimensions of the asset have been prepared using standard stereolithography (.stl) format which is a common form for 3D printing and CAD. The template was exported using .fbx and .obj files with embedded textures. The availability of the conversion extensions to the drawing file enables direct implementation of the visualisation tool and modification using various loadouts. The direct availability of the .stl format allows the user to modify the hull mesh and may also be used for detailed engineering studies that include stability, hydrostatics, and computational fluid dynamics (CFD). Moreover, the same file format when associated with 3D printing enables a low-cost model production using domestic 3D printers. These features can all be considered as passive advantages of 3D designs which ought to be mentioned but are not considered in this part of this study. In reference to the case related to visualisation of various loadouts, the base model was modified to feature the main benefits of 3D production.



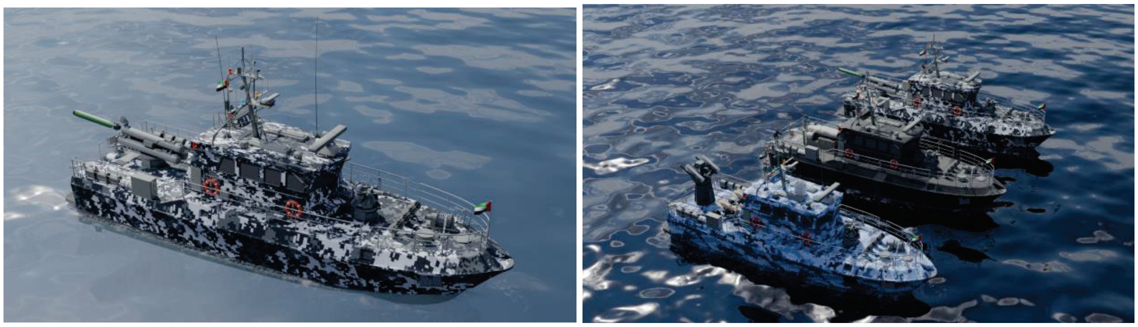


Figure 4: Patrol Boat Loadout, (a) Patrol Boat for surface intervention, (b) Patrol Boat for anti-air warfare, (c) Patrol Boat for anti-submarine warfare, (d) Heterogenous Patrol Boat Squadron.

Figure 4a shows a patrol boat fitted with a standard small caliber armament and modified to include a 25mm M242 Bushmaster remote weapon system. The specific loadout has been reworked to account for close quarter intervention particularly those associated with coastguard. The basic premise of this modification is to enable a detailed look at main gun upgrade whilst ensuring the vessel can conduct regular missions associated with maritime security, search and rescue, law enforcement, drug interdiction, and patrolling.

Figure 4b shows a version with a similar forward (SCG) but with a modified aft that removes a dedicated rigid hull-inflatable boat (RHIB) and crane and replaces it with a short range Pantsir-M close in weapon system (CIWS). The boat has been fitted with a satellite communication antenna on the superstructure and loaded the special operations all-terrain vehicles (ATV). The hull paint has also been applied with a blue electronic camouflage coating to illustrate the level of configurations that can be applied to the base model.

Figure 4c shows a version fitted with a similar (SCG) forward gun and with B515 ILAS-3 torpedo launching tube loaded with a A244S Mod-3 torpedoes. The hull has been layered with a black-white digital camouflage coating to identify it as an anti-submarine (ASW) surface vessel.

Figure 4d attempts to view all three variations in an ocean environment, which provides a visual queue of the effectiveness of the camouflage decal in a bright semi-cloudy HDRI backdrop. The endless permutations and possibilities using a 3D visualisation tool makes it possible to experiment with higher order loadouts without incurring any of the penalties associated with cost and engineering. It is also possible to reach a definitive selection of the required changes and the expected vessel roles when demonstrated using a life-like environment. This level of flexibility in design gives an otherwise missing feature to the end user in defining their requirements.

5. Conclusions

In the marine industry it is common for ships to undergo various tests and acceptance trials before they are approved for sea operation. Weather conditions play an instrumental role in defining the circumstances appropriate by an acceptance committee and the design changes to prepare for future growth. The necessity of these changes requires detailed approach in project management to mitigate the chances of unpredictable risks.

The first case study was based on showing how a visual representation of a sea-acceptance trial following the standard rules of classification societies. The visual production proved to be extremely useful in allowing any team to resort to visuals compared to a set of vector diagrams. The use of a 3D modelling software was able to capture different viewpoints of the trial complete with animation and wake generated by the surface ship. It is possible to extend these models to include more complex trials and to also alter wave and wind conditions for a more detailed simulation.

In second case study focused on using a physics-based pipeline to model a first-person point of view of fog surrounding the entrance of a channel. A navigation buoy was modelled at 50m distance from the ship bow and equipped with a light source to demonstrate how visibility is affected. The attempt to use a 3D modelling technique proved to be a solid transitional solution when a dedicated software is not readily available. The extent of the dependency on the fog generated model was intended as a demonstration of the capabilities in mimicking real-life situation thereby allowing necessary personnel to identify hazard situations that may require rescheduling.

The final case study was based on showcasing the various possibilities associated with selection of ship roles and armaments using a 3D modelling software. Considering the appropriate files are available, any type of ship modification can be applied for a quick loadout and saved in the asset browser for future use. The use of visualisation software in this study to prepare various loadouts of a patrol ship is a cost-effective method in displaying short term engineering changes without having to prepare detailed CAD drawings, this method is extremely effective when trying to find a commonality between the shipyard and the end user.

3D software has continued to evolve over the years, allowing users accessibility that is otherwise locked behind an enterprise license. Digital solutions have emerged that now ensures all parties are directly involved in the design process as well as test and trials, where traditionally those have been confined by a knowledge barrier and experience. When decisions are made based on a shadow understanding of the situation, they become biased, the use of a 3D modelling technique in this research successfully attempted to replace the uncertainties that might have been present.

Acknowledgements

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References

ABS, 2017. *Guide for Vessel Maneuverability,* s.l.: ABS.

Fernandez, R. P., 2020. *Designing submarines 4.0 with CAD/CAM/CAE tools. The application of the Industry 4.0 to submarine design.* s.l., INEC.

Ffooks, R., 1993. Natural Gas by Sea, The Development of a New Technology. In: s.l.:Witherby & Co Ltd., pp. 180-191.

IMO, 2002. *EXPLANATORY NOTES TO THE STANDARDS FOR SHIP MANOEUVRABILITY,* s.l.: IMO.

ITTC, 2017. *ITTC Quality System Manual, Recommended Procedures and Guidelines, Full Scale Manoeuvering Trials,* s.l.: ITTC.

Moreno, J. E. C., Vanegas, E. Y. S. & Gonzalez, V. H. J., 2011. *Ship maneuverability: full-scale trials of colombian Navy Riverine Support Patrol Vessel.* s.l., s.n.

Paik, J. K. & Thayamballi, A. K., 2006. *Ship-Shaped Offshore Installations.* s.l.:Cambridge University Press.

Uzcategui, F. et al., 2018. *Automatic 3D design tool for fitted spools in shipbuilding industry.* s.l., INEC.

Wang, X. & Pegg, N., 2022. *ISSC 2022 Committee IV.2: Design Methods.* s.l., Society of Naval Architects and Marine Engineers.

Molten Salt Reactors: Current technology status and the challenges for maritime applications

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Synopsis

The 2015 Paris Agreement mandates a 40% domestic reduction in GHG emissions by 2030 compared to 1990 levels. Amidst rising interest in alternative fuels to power commercial shipping, hydrogen and biofuels emerge as leading contenders. However, for military vessels, multiple fuel sources pose logistical challenges. Nuclear technology, historically developed for energy and weaponry, offers a consistent energy supply, especially for naval fleets.

Nuclear technology, rooted in 20th-century research, has seen significant advancements, particularly in Pressurised Water Reactors (PWRs) dominating commercial energy production. Molten Salt Reactors (MSRs), initially researched in the 1950s, experienced a resurgence in the early 2000s, offering potential advantages over PWRs. MSRs operate with molten salts, presenting diverse configurations and fuel options.

Advantages of MSRs include enhanced safety, economic efficiency, and environmental benefits, such as reduced nuclear waste. However, challenges like material corrosion, limited operational experience, and regulatory complexities hinder widespread adoption. Despite these hurdles, ongoing research and collaboration worldwide signal a growing interest in MSR technology, with various projects at various stages of development.

In maritime applications, integrating MSRs for propulsion and power generation presents both technical and regulatory challenges. While MSRs offer compact designs, higher thermodynamic efficiency, and reduced nuclear waste, concerns over safety, infrastructure, and regulatory frameworks persist. Addressing these challenges requires interdisciplinary collaboration and innovative solutions.

Assessing MSR technology readiness levels (TRLs) reveals progress in reactor technology but underscores the need for further development, particularly in marine applications. Despite the lower TRLs for maritime-based MSRs, exploring integration possibilities and addressing regulatory gaps are crucial steps toward realising their potential.

In conclusion, MSR technology holds promise for reducing emissions and ensuring energy security in maritime operations. However, overcoming technical, regulatory, and workforce challenges is essential for successful integration into naval and commercial fleets. Collaborative efforts across industries and regulatory bodies are imperative to advance MSR technology and navigate its complexities effectively.

Keywords: Molten salt reactor; technology readiness levels; alternative fuels; Nuclear powered ships; Occam Group.

Biography

Matthew Dunn is a Chartered mechanical engineer who works as a Senior Consultant at Occam Group Ltd. He has an MSc from Cranfield University in Advanced Materials and extensive experience working for Defence Equipment and Support prior to his employment at Occam Group. Matthew specialises in safety management, design assurance and engineering change linked to the integration of explosives onto naval ships.

1. Introduction

The 2015 Paris Agreement (The United Nations, 2015) is a legally binding international treaty on climate change and has 195 members who are party to the agreement. In response to this, the International Maritime Organisation (IMO) and Member States have adopted the Strategy on Reduction of Greenhouse Gas (GHG) Emissions from Ships (International Maritime Organisation, 2023), requiring member states to work towards its target of increasing zero or near-zero GHG emission technologies, and reduce CO_2 emissions by at least 40% by 2030, compared to 2008 levels. This legislative drive to reduce emissions means the debate surrounding alternative fuel sources for shipping has been at the forefront to enable nations and ship owners to achieve the goals of the legislation.

The global trends for alternative fuel choices in the commercial sector are trending towards one of two categories, hydrogen-based fuels, and biofuels (Raucci, McKinlay and Karan, 2023) with no clear single alternative fuel across the sector being clearly identified. This may suit the commercial sector's needs, but for military applications, using multiple fuel sources is impractical and severely restricts the global reach of a nation. Nuclear technology for ships is used by several Navies across the world (World Nuclear Association, 2023) and the ability to have a never-ending supply of energy for a ship can present significant benefits to owners and operators.

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Nuclear technology development traces its roots back to the early 20th century with most development focused during the second world war for use in the atomic bomb. Following the war, the focus changed to harnessing the energy of a nuclear reaction to generate electricity with the main driver in this field occurring in the 1950s (U.S. Department of Energy, 1995). The current reactors in nuclear power plants are dominated by Pressurised Water Reactors (PWRs) encompassing 66% of all plants across the world (Ho et al., 2019). The United States Navy drove this development to power its ships, and like most technology research, when funded sufficiently, a suitable solution develops that is employed for use across the world.

Molten Salt Reactors (MSRs) were researched in the 1950s through to the 1970s at the Oak Ridge National Laboratory (ORNL). Between 1980 and the early 2000s very little research was undertaken (LeBlanc, 2010). However, since 2002 there has been renewed interest in this field of nuclear technology.

2. Molten Salt Reactor Technology

2.1. Classification

MSRs are a nuclear reactor where molten salts (typically fluoride or chloride salts) form a significant part of the nuclear reaction. MSRs can be grouped across a broad range of technologies where the molten salt is used as a fuel, a fuel carrier, a coolant, or used to moderate the nuclear reaction. There have been several attempts classifying MSRs (Smith et al., 1974; Taube, 1978), the most comprehensive of which has been developed by the International Atomic Energy Authority (IAEA), grouping MSRs with three layers of taxonomy. Figure 1 shows the various types of MSR technology grouped under the differing classifications.

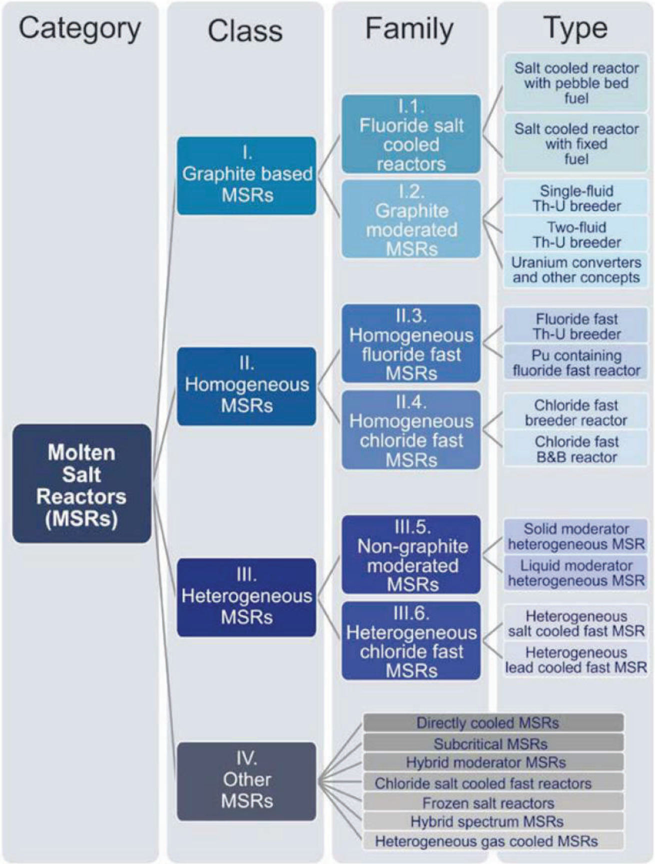

Figure 1 –Three layers of MSR taxonomy as a block diagram (Martinez-Guridi, Peguero and Reitsma, 2023)

2.2. Generic Architecture of a typical MSR

The main architecture of MSR reactors consists of a reactor vessel, reactor core and a fuel. There are coolant pumps to push the coolant through the system to maintain temperature, and a heat exchanger system that leads to the power generator. Figure *2* shows a typical MSR configuration where the salt is used as a fuel.

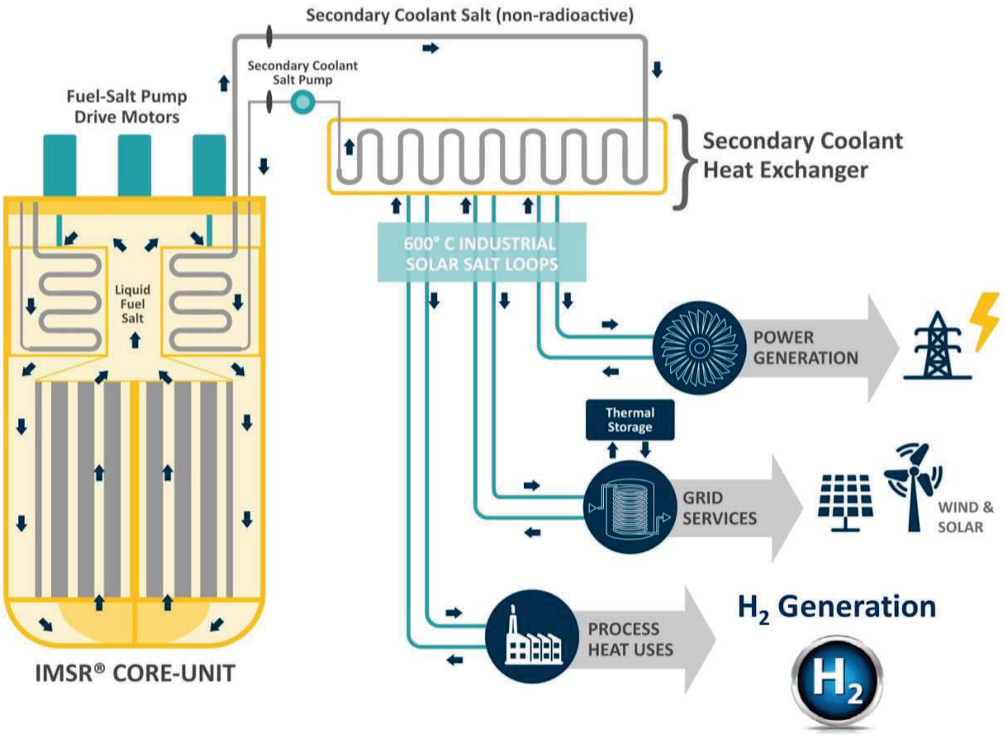

Figure 2 – MSR architecture using salt as a fuel (Terrestrial Energy, 2017)

Table 1 summarises the three major classes of MSRs and respective reactor types, however, this does not cover the other MSRs from Figure 1.

As can be seen, there is a wide variety of reactor types, configurations, reaction methods, and types of salts used in MSR technology. This diversity poses challenges for MSR developers because the range of technologies requires research and development efforts to be distributed across multiple areas rather than focused on a single technology.

2.3. Advantages and Disadvantages

MSRs have several advantages over traditional PWRs, as stated by Elsheikh, 2013; Furukawa et al., 2002; Gat and Engel, 2000:

2.3.1. Safety

- Operation at near atmospheric pressure (lower than 5 bar), reducing the risk of salt leakage or potential core breach caused by steam or hydrogen explosion.
- Molten salts are chemically inert and not flammable.
- The ability to remove fission products avoids potential pressure build up.
- As a fuel source, molten salts are in liquid form so cannot be damaged mechanically.
- Molten salts have a high boiling point, close to double the current operating temperatures in PWR's.
- Liquid fuel allows for flexibility in the fuel cycle and the fuel composition can be chemically adjusted.
- The reaction is self-regulating, as the reaction overheats, reactivity of the core automatically slows down.
- As the fuel is in liquid form, it can easily be removed from the reactor into a passively cooled dump tank.
- Less high-level waste generation than PWRs.
- The reactor fuel cycle has excellent non-proliferation credentials.

Table 1 – Comparison of the six major MSR families (Martinez-Guridi, Peguero and Reitsma, 2023)

Class	**I. Graphite Based MSRs**		**II. Homogenous MSRs**		**III. Heterogenous MSRs**	
Family	I.1. Fluoride Salt Cooled Reactors	I.2. Graphite Moderated MSRs	II.3. Homogeneous fluoride fast	II.4. Homogeneous chloride fast	III.5. Non-graphite moderated	III.6. Heterogenous chloride fast
Fuel State	Solid	Liquid	Liquid	Liquid	Liquid	Liquid
Spectrum	Thermal	Thermal	Fast	Fast	Thermal	Fast
Salt Type	Fluorides	Fluorides	Fluorides	Chlorides	Fluorides	Chlorides
Neutronics Performance	Burner, converter	Burner, converter, breeder	Burner, converter, breeder	Burner, converter, breeder, breed-and-burn	Burner, converter, breeder	Burner, converter, breeder, breed-and-burn
Actinides	Enriched U, TRU, Th as a semi-inert matrix	Enriched U, TRU, closed Th-U cycle	Enriched U, TRU, closed Th-U and U-Pu	Enriched U, TRU, closed Th-U and U-Pu	Enriched U, TRU, closed Th-U cycle	Enriched U, TRU, closed Th-U and U-Pu
Irradiation induced issues	Limited burnup of fuel in graphite matrix	Limited graphite moderator lifespan	Limited vessel lifespan	Limited vessel lifespan	Limited vessel and structural material lifespan	Limited vessel and structural material lifespan
Fuel extensive pumping	No	Yes	Yes	Yes	Yes (No if cooled by a moderator)	No
Heat Transport medium	Fluoride coolant salt	Fluoride fuel salt	Fluoride fuel salt	Chloride fuel salt	Fluoride fuel salt (or moderator)	Molten salt or lead coolant
Primary heat exchange	In-core	Ex-core	Ex-core	Ex-core	Ex-core (in-core)	In-core

2.3.2. Economic

- High boiling point of molten salts allows for operation to be conducted at higher temperatures which gives high thermodynamic efficiency.
- Low wastage from the reaction, using more of the fuel.
- Liquid fuel allows for a more compact reactor design when compared to a solid fuel PWR system.
- If Thorium is used it is about 3 times more abundant on earth than uranium.

2.3.3. Other Factors

- Reputationally, MSRs can provide a good roadmap towards de-carbonising both the land-based power generation as well as in the maritime industry.
- Certain MSRs can be used as nuclear fuel waste burners, thus providing a route to recycle spent nuclear fuel.
- There is a cadre of engineers currently supporting the build of the United Kingdom's (UK) third generation nuclear power plants, this knowledge and experience could be used to support the use of MSR technology.

MSRs have several disadvantages/challenges that currently hamper further development, as detailed by (Nuclear Innovation and Research Office, 2021; Pedersen, 2019; Roper et al., 2022; Science Innovation and Technology Committee, 2023; Wright and Sham, 2018)

2.3.4. Safety

- There is no single suitable material for the reactor core. Molten salts are highly corrosive, the reactor operates at very high temperatures introducing significant creep challenges, and high radiation dosage mean new alloys need developing as well as novel ways to manage material challenges.
- Minimal modelling and simulation data is available to understand core physics.
- The reaction produces tritium, which provides corrosion risks, containment risks, and is a significant hazard to humans. Significant progress has been made by companies such as Copenhagen Atomics who have developed several strategies to address the corrosion issues associated with MSRs.
- Reactor monitoring is a challenge due to the liquid fuel and high temperatures.
- There is no current precedent for manufacture and qualification of fuels.
- Operational experience of MSRs is severely limited across the globe.

2.3.5. Economic

- There is limited supply chain in the UK that could produce components needed to build an MSR, current estimates put about 5% of the components could be UK sourced.
- Implementation costs are not fully quantified, there is still an extremely high initial outlay required in terms of R&D to overcome the challenges.

2.3.6. Other factors

- As there is a spread of research and projects looking at differing types of MSR reactor technology, there is a significant licensing/regulatory challenge. The capacity and ability of national regulatory bodies to evaluate and approve such a broad spectrum of technologies is limited.
- As there has not been any MSRs licensed, there is a lack of testing facilities that can be used to verify new designs and new technology, coupled with the lack of expertise of MSR technology in the UK to undertake this type of testing.
- There is a significant gap of engineering capability in the UK currently. Current estimates are that the UK must recruit an average of 7,234 personnel each year until 2028 to combat the lack of personnel and the current ageing nuclear expertise in the UK.

2.4. Current MSR Research and Projects

There is a wide range of activity undertaken in MSRs, with the Nuclear Energy Agency identifying ten projects at varying stages of development in its Small Modular Reactor Dashboard. Of these ten projects, none have progressed further than design approval, and three of these designs were for marine-based applications (Cameron and Mir, 2024). Since 2000, there has been a steady trend of research linked to MSR technology.

Analysis of Google Scholar articles and Dimension articles using the search terms ‘MSR’, and ‘Molten Salt Reactor’ shows an upwards trend in academic and research articles linked to the technology. Figure 3 shows this trend, but it should be noted that this research was severely limited and to gain a more in-depth analysis of the actual published articles would require extensive modelling and research.

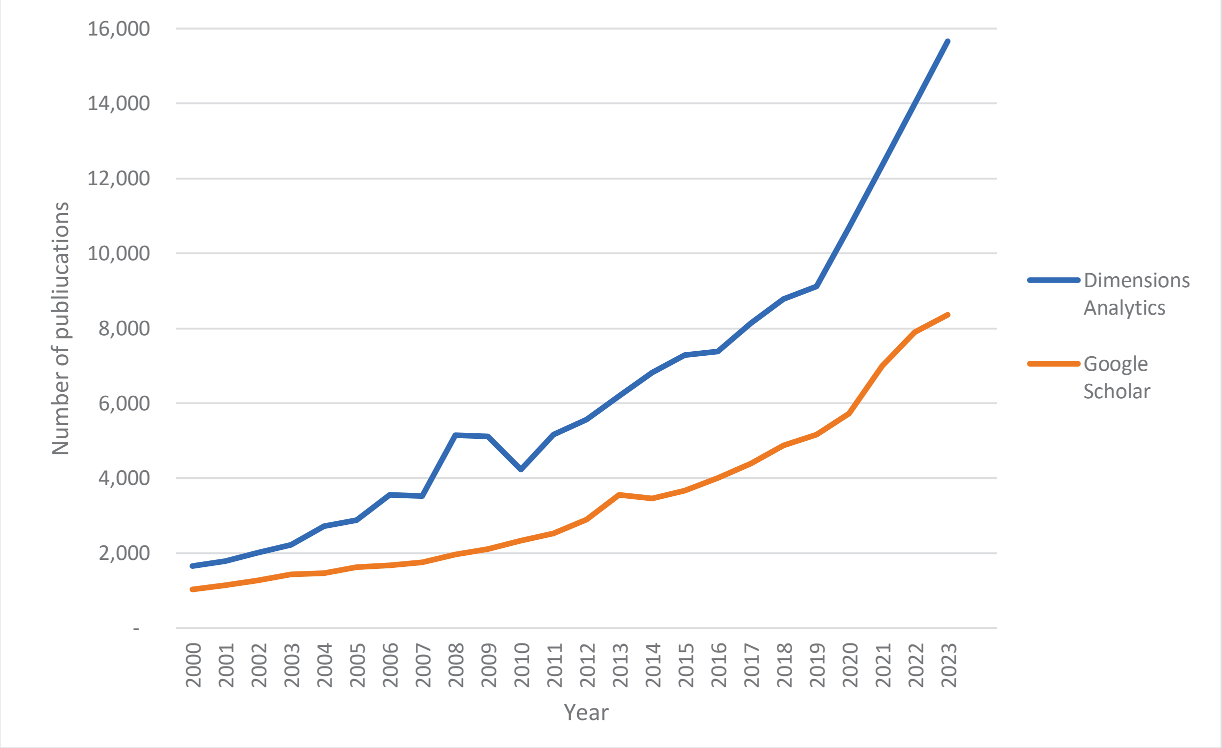

Figure 3 – Analysis of publications using key words ‘Molten Salt Reactor and MSR’ from the year 2000.

Table 2 details 15 active projects across the world with several of these projects working in collaboration to accelerate the technology to commission their MSRs. There is a strong link into the UK with Terrestrial Energy, Moltex and UK Atomics, which is a subsidiary of Copenhagen Atomics with offices in the UK that are working towards MSR technology. Alongside this, the UK Department for Energy Security and Net Zero has joined Net Zero Nuclear, a collaboration between industry and government that aims to build understanding of the value of nuclear energy, deliver the political and financial enablers to propel nuclear energy’s growth and remove the roadblocks that prevent nuclear from fully realising its contribution to global clean energy security. Several companies in this partnership are actively developing MSR technology, with some such as Terrapower and UK Atomics actively targeting the UK for deployment of their systems. There are four projects that are targeting MSR use in the marine environment.

Of these four, two projects are being undertaken by ship designers and builders, rather than organisations focusing on the reactor technology. The project through the China State Shipbuilding Corporation has only recently been announced, very little detail is available. Ulstein have significant background in ship design, ship building, and systems integration, but are not a company that has a history of work in the nuclear industry.

There is an upwards trend in interest for MSRs both in land-based applications and as prime movers or floating power stations. The use in the marine environment is beginning to gain momentum due in part to research and development of small modular reactors.

2.5. Integration of MSRs for power generation in ships

Power generation in ships is undertaken by a range of systems such as diesel, diesel-electric and gas-turbines. The latter common in naval ships where the higher power output allows for greater acceleration and manoeuvrability, as required by naval vessels. Gas turbine systems are generally only utilised when ships are above an average displacement of 3,500T, with smaller naval ships utilising conventional diesel engines (GE Marine Solutions, 2018).

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Table 2 - Current active MSR research and projects

Country	**Organisation**	**MSR Taxonomy**	**Description**	**Fuel**	**Thermal Power MW(t)**	**Electrical Power MWI**	**Target Application**	**References**
Canada / UK	Terrestrial Energy	I. Graphite based I.1 Fluoride salt cooled Salt cooled reactor with fixed fuel	Small Modular Reactor	Low-enriched uranium	400	190	Power generation	(Cameron and Mir, 2024; Hussain et al., 2018)
Canada / UK	Moltex Energy	I. Graphite based I.2 Graphite moderated Uranium convertor/other concepts	Stable Salt Reactor-Wasteburner (SSR-W) that uses recycled nuclear waste as fuel.	Recycled spent fuel	750	300	Wasteburner for countries with high levels of spent nuclear fuel.	(Cameron and Mir, 2024; Canadian Nuclear Safety Commission, 2021)
Canada / UK	MoltexFlex	I. Graphite based I.2 Graphite moderated Uranium convertor/other concepts	MoltexFlex Stable Salt thermal spectrum fast reactor with a Thorium breeding blanket	Low-enriched uranium	750	300	Power generation where there is access to low-enriched uranium fuel	Cameron and Mir, 2024; Canadian Nuclear Safety Commission, 2021)
China	China State Shipbuilding Corporation	No current reactor data	Ship based MSR	Potentially thorium	No data available	No data available	Large containership	(Riviera News, 2023)
China	Chinese Academy of Sciences	No current reactor data	Thorium-based molten salt experimental reactor	Thorium	2	No data available	Power generation	(National Nuclear Safety Administration, 2023; World Nuclear News, 2023a; Zhang et al., 2018)

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Country	Organisation	MSR Taxonomy	Description	Fuel	Thermal Power MW(t)	Electrical Power MWI	Target Application	References
Denmark / UK	Copenhagen Atomics/UK Atomics	III. Heterogenous III.5 Non-graphite moderated Liquid moderator heterogenous	Small, modularised fluoride salt based molten salt reactor encased in a 40-foot shipping container	Thorium	100	No data available	Ship or barge-based power systems. Biofuel production and desalination plants	(Cameron and Mir, 2024; Hussain et al., 2018)
Denmark	Samsung Heavy Industries / Seaborg Technologies / Korea Hydro & Nuclear Power	III. Heterogenous III.5 Non-graphite moderated Liquid moderator heterogenous	Single salt, ultracompact molten salt reactor	Low-enriched uranium	750	200	Power generation using a Power Barge to supplement other renewable energies.	(Seaborg Technologies, 2024; World Nuclear News, 2023b)
France	Naarea (in collaboration with Thorizon)		Micro-reactor using spent nuclear fuel from conventional nuclear fission reactions	Recycled spent fuel	80	40	Power generation	(Cameron and Mir, 2024; NAAREA, 2023; Thorizon, 2022)
Indonesia	ThorCon	I. Graphite based I.1 Graphite moderated Uranium convertor/other concepts	Fluoride Molten Salt Fuel Reactor	Low-enriched uranium	557	250	Reactor encapsulated in a ship's hull to provide power generation in developing nations with fragile grids, used on shoreside locations.	(World Nuclear News, 2023c)
Netherlands	Thorizon (in collaboration with Naarea)	III. Heterogenous III.5 Non-graphite moderated Liquid moderator heterogenous	Modular designed thorium reactor fuel cartridges with fuel dissolved in a molten salt	Spent nuclear fuel and thorium	250	100	Power generation	(Cameron and Mir, 2024; NAAREA, 2023; Thorizon, 2022)

Country	Organisation	MSR Taxonomy	Description	Fuel	Thermal Power MW(t)	Electrical Power MWI	Target Application	References
Norway	Ulstein	No current reactor data	Ship based MSR	Thorium	No data available	No data available	Floating, multi-purpose power station to support electric ships	(Ulstein, 2022)
Russia	Rosatom State Atomic Energy Corporation	No current reactor data	Molten Salt cooled reactor	Recycled spent fuel	10	No data available	Burning of the products of nuclear reactions	(Nuclear Engineering International, 2024)
USA	Kairos Power	I. Graphite based I.2 Graphite moderated Salt cooled reactor with pebble bed fuel	Reactor fuel combined with a low-pressure fluoride salt coolant	TRISO fuel in pebble form	320	140	Power generation	(Blandford et al., 2020; McGrath, 2023; Pérès, 2020)
USA	Southern Company and TerraPower	II. Homogenous II.4 Homogenous Chloride Chloride fast breed-and-burn	Molten Chloride Fast Reactor	High-assay low-enriched uranium	840	No data available	Power generation	(Cameron and Mir, 2024; TerraPower, 2022)
USA	Flibe Energy	I. Graphite based I.1 Graphite moderated Two-fluid Th-U breeder	Scalable Lithium Fluoride Thorium Reactor	LiF-BeF2-UF4 (FLiBeU)	600	250	Various applications, small modular reactors for use in transport/space up to power plants for power generation.	(Cameron and Mir, 2024; Flibe Energy Inc, 2024)

A concept design for a Thorium MSR using gas turbine generator was proposed in 2012 which had the reactor located centrally between four closed cycle gas turbines, as shown in Figure 4 and Figure *5* (Hill, Hodge and Gibbs, 2012).

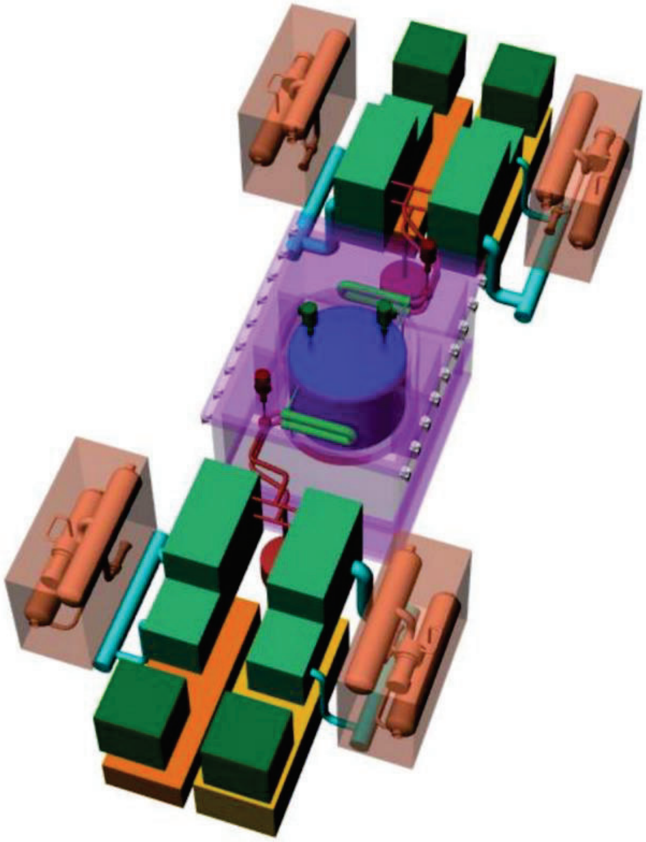

Figure 4 – Proposed Machinery and Reactor Arrangement

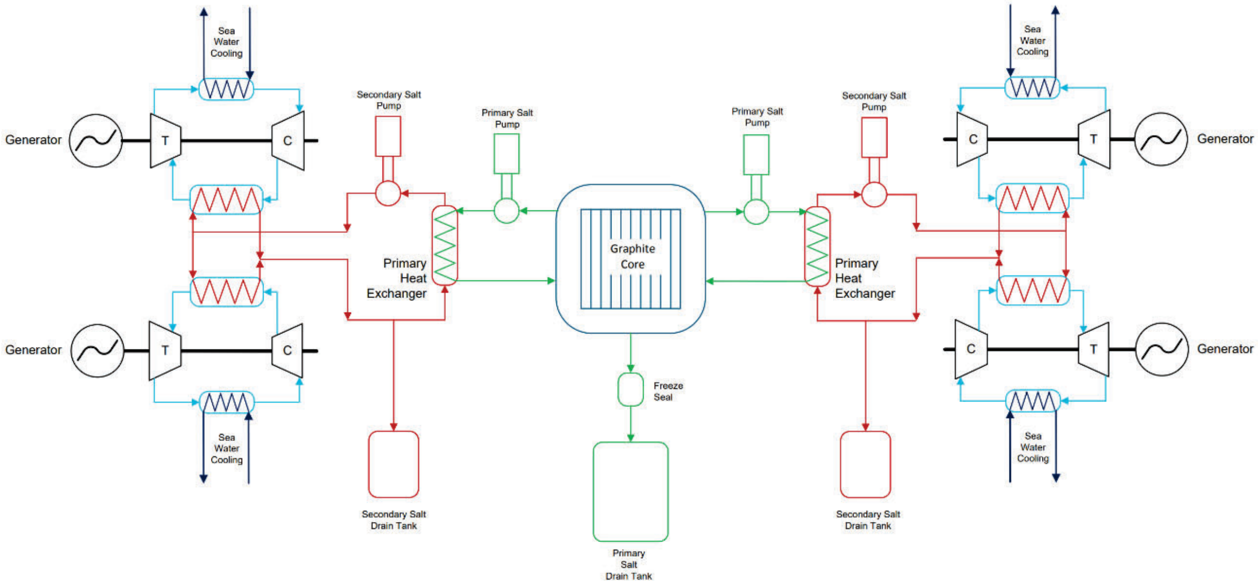

Figure 5 – Proposed diagrammatic plant layout.

The use of turbines has been identified as being the most favourable option for converting thermal power to mechanical power by other studies (Houtkoop et al., 2022) and this arrangement has several advantages, which include the prime movers being directly adjacent to the reactor compartment, reducing the piping length needed for the molten salt to travel; the prime movers being located forward and aft of the centralised reactor; and all machinery linked to the reactor is outside of the reactor compartment, allowing for maintenance activities. This design is a very good conceptual baseline that could be used to drive forward the concept of an MSR on a ship. The author noted one major disadvantage; they based the reactor design on the original ORNL designs that are outdated and sub-optimal. With some of the designs and projects identified in Table 2 reaching maturity soon, a more modern and more recently tested MSR would prove beneficial in updating this conceptual design.

There are significant advantages in employing MSRs in ships over and above those listed in paragraph 2.3, these are:

2.5.1. Technical

- With the acceleration in small modular MSR development, they potentially require less volume than current traditional power generation systems.
- With the correct selection of reactor and output, MSRs negate the energy density reduction of alternative fuels such as Hydrogen.
- There would be a significant volume reduction, as there is no need to have fuel tanks distributed around the ship, this also reduces the pipe runs and associated equipment to move the fuel, thus saving weight.
- Similar fire risk in comparison to diesel engines; Swapping diesel fuel for molten salts will require different mitigation measures, but the causal factors are not increased.
- It is envisaged that the vessel’s deadweight would decrease even when considering the shielding required to protect the ships/crew form the reactor compartment (Scott and Beard, 2022).
- The Royal Navy (RN) currently manage the safety of nuclear reactors for its submarines, if the safety case for these can be justified, then the safety case for MSRs in ships is achievable and can be brought to a level that is as low as reasonably practicable (ALARP). It should be noted however, that submarines do not generally visit as many populated port areas as ships do.
- Replenishment at sea would be minimised to solids only.
- MSRs produce less nuclear waste than conventional PWRs, with one study identifying an LFTR would produces 35 times less waste than a traditional PWR on an annual basis, where 873% of that waste would reach stable natural uranium levels after just 10 years (Pool, 2014).

2.5.2. Economic

- The need for ships to supply fuel, or for ships to go to port to bunker fuel would be removed, thus saving money in capital costs as well as through life.
- The decommissioning of an MSR reactor is likely to be cheaper as the half-life of the fissile products is significantly less than conventional plutonium.
- With the development of MSRs that use spent nuclear fuel, spent fuel can be re-purposed, providing a potential route for waste management.

2.5.3. Other advantages

- There is an established nuclear cadre and training programme in the RN in support of its submarines. Adapting this and expanding it would provide a wider pool of nuclear expertise across the navy.
- With the current construction of Hinkley Point C, and the planned construction of Sizewell C, there is a growing cadre of nuclear expertise in the civilian sector that can provide the wider support required outside of ship operations.
- There is already built infrastructure to support both in-service nuclear submarines and those in the disposal chain. However, this will need to be increased to meet future requirements.

There are a range of challenges related to MSRs being installed onto ships, such as:

2.5.4. Technical

- There is no current MSR system in use on a ship or any detailed designs that integrate an MSR as a prime mover.

- Hill, Hodge and Gibbs (Hill, Hodge and Gibbs, 2012) determined that their concept design could increase the solid vertical centre of gravity (KG) by as much as 5%. This could be offset by a reduction in the centre of gravity on other equipment associated with traditional prime movers, such as the complete removal/need for uptakes/down takes as well as other equipment reductions.
- To maintain the safety of the system the MSR needs to have dump tanks as part of the system. This brings two potential challenges:
    - The reactor would need to sit higher than current prime movers in use, as the dump tanks must be situated directly below the reactor in a vertical configuration.
    - When the molten salt is ‘dumped’ into these tanks in an emergency scenario, the ship would lose its prime mover. If this happened at sea it could cause a catastrophic loss of the ship. Redundancy systems in this event would need to be designed and built in.
- Survivability/vulnerability characteristics of MSR reactors is not understood and will require significant modelling and trialling to provide evidence of how they can remain safe to threats such as underwater shock or blast/fragmentation from conventional weapons.
- MSRs would not be suitable for all naval vessels due to their size.
- Retrofitting any MSR technology to current in-service ships will be a significant challenge and may not provide value for money.
- Maintenance will require new remote methods not widely exploited in UK naval ships.

2.5.5. Economic

- Shore facilities would need to be significantly upgraded, and the naval bases are in highly populated areas. Nuclear unarmed submarines regularly go into Devonport (Scottish Affairs Committee, 2012) so the safety case challenges are already being managed.
- The UK supply chain would need developing to support MSR ships.

2.5.6. Regulatory challenges

There are a specific set of challenges linked to the regulation of nuclear ships.

- Port state control and access is a significant blocker. There are at least ten memoranda of understanding across the globe operating under a cooperative agreement with IMO (Scott and Beard, 2022). New Zealand has banned nuclear powered or armed ships from entering its waters (Ministry of Foreign Affairs and Trade, 1987). The USA operate the Nimtz-class nuclear powered aircraft carriers and evidenced to congress that they can go to over 150 ports, in over 50 countries globally without issue (O’Rourke, 2009).
- The IMO adopted the Code of Safety for Nuclear Merchant Ships in 1981; however, its provisions in the UK were not a priority until the Maritime and Coastguard Agency (MCA) brought into law The Merchant Shipping (Nuclear Ships) Regulations 2022, implementing Chapter VIII in the Annex to the International Convention for the Safety of Life at Sea, 1974 (SOLAS), relating to commercial nuclear-powered ships.
- Whilst there are statutes in place, both flag states and classification societies have not had to actively manage the additional standards/regulation and assurance requirements for nuclear ships.
- Commissioning MSRs on UK ships would be subject to regulatory scrutiny from the MCA, Classification Societies, the Office of the Nuclear Regulator, and the Health and Safety Executive, introducing complexity into the licensing and approval system.

2.5.7. Other Challenges

- There are significant challenges related to Suitably Qualified and Experienced Personnel (SQEP):
    - There is a significant struggle to recruit nuclear submariners (Church, 2023), increasing this cadre against current engineering shortfalls (Ruane, 2023) would pose a significant challenge.
    - The need to have skilled engineers to provide shore-based support, maintenance and design activities is potentially a greater issue than many of the technical challenges listed.
    - UK shipyards do not have the SQEP; the only current SQEP linked to integrating nuclear technology for prime movers resides in the construction of the RN submarines.

  - There is no current cadre of suitably qualified and experienced nuclear engineers for surface ships, the lack of generational experienced personnel will be significant in safely implementing this concept.
- Nuclear technology has a negative reputation across several organisations and campaign groups in the UK. MSRs will be included under the large umbrella of nuclear technology.

2.6. Technology Readiness Levels (TRLs)

To define the TRL, this paper uses the Ministry of Defence (MOD) definitions which are shown in Table 3. The assessment looks at the TRL of the reactor concepts, and then of any potential TRL of these concepts in ships. This paper aims to examine the overall TRL of MSRs, but the supporting technology and systems are vital to its success.

Table 3 - MOD TRL Definitions

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Technology basic validation in a laboratory environment
5	Technology basic validation in a relevant environment
6	Technology model or prototype demonstration in a relevant environment
7	Technology prototype demonstration in an operational environment
8	Actual technology completed and qualified through test and demonstration
9	Actual technology qualified through successful mission operations

MSR technology has moved on considerably, there are several regulators across the world actively issuing licences for reactor builds and development of novel and new MSR technologies. There is a trend in academia and industrial research that has continued to grow year on year, this is enabling the progress towards proven MSR designs that will be commissioned and in use for power generation in the very near future. The assessment undertaken in Table *4* shows reactor technology is advancing. Previous studies have shown MSR reactors to be at lower TRL. There are several state-backed companies advancing MSR technology at considerable pace for land-based systems, driving not only MSR reactors, but supporting technology levels and supply chains. There are several prototype demonstrator reactors planned to be commissioned before the end of this decade, with at least three companies expecting to have commissioned reactors by 2028.

2.7. The Next Steps for Shipping

To integrate MSRs into future ships, it is crucial to address the challenges. An evaluation of these challenges against the Defence Lines of Development (DLOD) has been undertaken and detailed in Table 5. This analysis has been extended to encompass a DLOD+ approach, specifically aimed at tackling regulatory issues that go beyond the conventional DLOD framework. The DLOD+ analysis includes a projected timeline for achieving Initial Operating Capability (IOC) for naval ships powered by MSRs. It is important to note that this assessment focuses solely on new ship construction and does not encompass retrofitting existing ships, it also does not focus on the economic aspects of implementing MSR's onto ships, this is a topic worthy of several academic papers on its own.

Table 4 - Current TRL Status of Reactor and ship concepts

Country	**Organisation**	**Current Status**	**Planned Development**	**Reactor TRL**	**Ship Based Application TRL**
Canada	Terrestrial Energy	Design has passed the first 2 stages of the Canadian licensing process (Pre-licensing vendor design review)	early 2030's - Planned Commissioning of the first power plant	4	NA
Canada/UK	Moltex Energy	Design has passed the first stage of the Canadian licensing process	early 2030's - Planned Commissioning of the first operational reactor	4	NA
Canada/UK	Moltex Energy	Design has passed the first stage of the Canadian licensing process	early 2030's - Planned Commissioning of the first operational reactor	4	NA
China	China State Shipbuilding Corporation	Concept Stage	No project data available, concept announced in Dec 23	No reactor data available	2
China	Chinese Academy of Sciences	Operating license issued	373 MWt reactor built by 2030	5	NA
Denmark	Copenhagen Atomics	Non-fission prototype proven	2025 - Criticality test on demonstrator reactor 2027 - Final design review 2028 - First waster burner commissioned	4	NA
Denmark	Samsung Heavy Industries / Seaborg Technologies / Korea Hydro & Nuclear Power	Concept Design	2026 - Commercial Prototype built 2028 - Production of power barges	4	2
France	Naarea (in collaboration with Thorizon)	Concept Design	2023 - Finalization of a digital twin 2028 - Submitting the safety options dossier (DOS) for commissioning of a prototype 2030 - Launching mass production	4	NA
Indonesia	ThorCon	Concept design in preparation for licensing	2029 - Demonstration plant fully commissioned	4	2
Netherlands	Thorizon (in collaboration with Naarea)	Concept Design	2035 Commissioning of a pilot reactor	2	NA

Country	Organisation	Current Status	Planned Development	Reactor TRL	Ship Based Application TRL
Norway	Ulstein	Concept Stage	10-15 years for launch of Thor	No reactor data available	2
Russia	Rosatom State Atomic Energy Corporation	Preliminary design completed	2031 - Plant in operation	4	NA
USA	Kairos Power	Construction permit issued by US Nuclear Regulatory Commission	2027 - Initial deployment of a demonstration plant 2028 - The first plant produces domestic power	4	NA
USA	Southern Company and TerraPower	Design testing using an Integrated Effects Test (non-nuclear)	2025 - Molten Chloride Reactor Experiment completed early 2030's - Demonstrator commissioned 2035 - Full commercial operations planned.	3	NA
USA	Flibe Energy	Pre-licensing activity / concept design	2030-2035 - Power generation plants in operation	4	NA
USA	Transatomic Power	Concept design completed, currently undertaking lab-scale experimentation.	No timescale available, plan is to: Create the detailed blueprint specs. Refine reactor design Complete a demonstration reactor	3	NA

Table 5 - DLOD+ to IOC Analysis

DLOD	Challenge	Potential Solutions to support DLOD maturity	Indicative timescales to achieve potential Initial Operating Capability (Years)	References
Training	Naval nuclear training delivery needs expanding	Utilise civilian personnel with MSR knowledge to supplement training, noting there is currently limited MSR SQEP globally Expand all naval engineering training to include nuclear/MSR technology at the earliest opportunity Develop bespoke training for MSR maintenance and support	3 - 6	(Butler, 1990; Department of the Navy, 2016)
	Limited SQEP across maritime domain in Nuclear Technology	Sponsor naval personnel to undertake apprenticeships and degrees into MSR and nuclear technology Arrange for naval engineers to go on secondment to in-build or in-service MSR plants to increase SQEP and enable them to support the development of personnel	5 - 10	(McGee, 2021)

Equipment	The TRL of any ship based systems is very low, meaning there is significant technical risk in deciding to implement MSR technology early	Implementing a programme to specifically drive the MSR technology to a suitable TRL in ships will allow for a focused approach to the risks to be managed effectively and for the technology to be developed to a high TRL Early engagement with MSR manufacturers to be undertaken through DASA/DSTL Work to set the outline requirements for all MSR based systems needs to be undertaken to enable concept system designs to be developed and increasing the TRL for ship systems	15 - 25	(Riviera News, 2023; World Nuclear News, 2023d)
	Maintenance will require new remote methods	Employ methods used in current nuclear submarines Work with MSR manufacturers to modify current technology for use in ships	5 - 15	
	Survivability/vulnerability characteristics of MSR reactors is not understood and will require significant modelling and trialling to provide evidence of how they can remain safe to threats such as underwater shock or blast/fragmentation from conventional weapons	Implement a specific project to model and assess the reaction of MSR's to threats such and UNDEX, fragment etc to assess the safety of MSR's in the Naval Environment	5 - 15	(Harinath et al., 2022)
	Impact of pitch and roll on MSR's in not understood	Implement a specific project to model and assess the reaction of MSR's to a variety of pitching and rolling motions and understand the safety and performance aspects Instigate trials non a non-fissile system to prove modelling outputs	3 - 5	

	Impact of dumping all Molten Salts into the drain tanks, stopping the fissile reaction in an emergency could have significant safety implications at sea as the prime mover potentially loses all power	Undertake a study to identify potential scenarios when this would need to occur, undertake hazard analysis and identify suitable controls and mitigations that need to be in place	3 - 5
	Shielding requirements are unknown	Implement a specific project to model and assess the amount of shielding required and how it would be maintained	3 - 5
Personnel	There is a significant challenge in recruiting nuclear submariners, introducing MSR's onto ships could impact the in-flow of engineers into the submarine service	Review naval career structures to allow for an expanded movement of personnel between surface and submarine service	3 - 5
	There are limited shore-based SQEP nuclear engineers available to handle the increased workload needed to support the fleet	Implement a national training programme for nuclear engineers from apprenticeships through to degrees to support MSR's Through life-support contracts will require suppliers to have sufficient SQEP	10 - 15
	The lack of generational experience in nuclear technology in the RN will have a significant impact on safely implementing MSR's onto ships	Setup a programme to retain submariner nuclear SQEP at the end of their careers so they can support the initial implementation and next generation	3 - 6
	UK Flag state (MCA) and classification societies have not had to actively manage the additional standards/regulation and assurance requirements for nuclear ships	Arrange for personnel to upskill and work with other nuclear operators to generate expertise	5 - 10
Information	Information from systems to manage and monitor reactor health and status need defining	Work with MSR manufacturers to modify current systems for use in ships Monitoring of MSR fuel status is vital to understand the fissile status of the reactor to enable re-fuelling to be undertaken	2 - 5
Concepts & Doctrine	Impact on current doctrine is not defined	Undertake an analysis on all CONUSE, CONEMP and CONOPS in-service to identify impacts	5 - 10

	New CONUSE, CONEMP and CONOPS are required for ships	Develop as part of the initial requirements setting and implementation	2 - 5	
	Current CONUSE, CONEMP and CONOPS and other doctrine for interfacing systems will require updating	Update these as the MSR implementation progresses using the Capability Planning Group system	5 - 10	
	Impact of MSR on operational doctrine is not defined	Undertake a study to identify area in naval doctrine and to understand where this will require changing	2 - 4	
	Port state control and access could be an issue	Understand global limitations and determine the impact on global deployments. USA and France both operate nuclear powered ships so global deployment doctrine through NATO collaboration and LFE could provide suitable solutions	5 - 10	
Organisation	Additional units/expansion of existing organisation to support the assurance of Nuclear ships is required, e.g. Operational Sea Training, Defence Regulators, Naval Base safety teams	A full study to understand the changes and impacts to the organisation is required to take a holistic view of the impact on the defence operating model and how to implement the change	5 - 10	
Infrastructure	Extended shore based facilities will be required to support training and such as operator training simulators, shore based prototypes and other classroom based systems	Undertake a full study on the requirements to understand what shore based systems are needed	5 - 10	
	Dockside facilities need expanding to support nuclear ships, this could come at a significant cost	Undertake a study to identify exactly what facilities will be required, the costs of these and the wider impacts	3 - 6	(Navy Lookout, 2020)
	Commercial dockyards and the supply chain are not setup to support ships with nuclear reactors	Development of commercial dockyards to support MSR's in ships needs to be supported from UK Government Strategy. National shipbuilding strategy needs to be updated to support MSR technology and support the drive for a UK wide approach National funding needs identifying to support a significant increase in infrastructure to support MSR through life	5 - 15	

https://doi.org/10.24868/11181

	Thorium salt reprocessing plant could be required to manage the supply chain	Build a reprocessing plant to support both naval and commercial thorium re-processing, this could provide a good commercial market for the UK in re-processing thorium form across the world Identify a short term solution for Thorium reprocessing until sovereign capability can be achieved	5 - 25
Logistics	The required supply chain to support MSR's is not understood	Undertake a supply chain analysis to identify high level requirements to inform the strategy for implementing	2 - 5
	Supply chain in the UK is not established to support MSR implementation	National shipbuilding strategy needs to be updated to support MSR technology and support the drive for a UK wide approach Funding and grants should be made available to encourage supply chains to diversify and develop the knowledge and expertise necessary to support MSRs as part of the UK Plc initiative Current supply chain supporting PWR's could expand to support MSR's	5 - 15
	Support facilities for maintenance globally need to be identified and agreements in place to berth nuclear ships with flag states	Work with NATO partners to mirror current global support arrangements and best practice	5 - 10
Regulatory	Commissioning MSRs on UK ships would be subject to regulatory scrutiny from the MCA, Classification Societies, the Office of the Nuclear Regulator, Defence Nuclear Safety Regulator and the Health and Safety Executive, introducing complexity into the licensing and approval system	Agree the approach for licensing and regulations of ships between all regulators, with agreed primacy as appropriate in line with current nuclear submarine approach	2 - 5
	Current commercial regulations need a significant re-write as they focus on PWR	Update regulations to apply to non-conventional reactor types	4 - 10

Interoperability	Exact implications of nuclear powered ships and their interoperability is not understood	Undertake analysis to identify all the areas of interoperability that could be impacted both positively and negatively to implement MSR technology	5 - 10

2.8. Conclusions

MSR technology is advancing rapidly, prompting ship designers and various countries to explore its potential benefits for ship-based applications. While most are considering MSR systems primarily as marine power generation facilities, China stands out with its ambitious concept for a 24,000 TEU container ship aimed at maximizing MSR advantages. Marine-based MSR concepts are currently at a lower TRL, largely due to the predominant focus on reactor technology development. Despite this, stakeholders such as sponsors, ship owners, and designers should not overlook MSRs. Now is an opportune moment to delve into the technical integration aspects of MSRs in ships and to evaluate their broader implications in maritime environments. The technical challenges for integrating MSR's onto ships are significant, but if work to assess the challenges were to be undertaken at risk ahead of mature MSR reactors being available, solutions could be easily identified allowing for designs to be matured ahead of the wider systemic issues being addressed.

Although previous MSR-based power generation system concepts exist, specific design work remains unexplored. Advancing the TRL of marine-based MSRs hinges on undertaking interdisciplinary design work across Naval Architecture, Marine Engineering, and System Engineering disciplines. This approach would also facilitate the detailed development of regulations, standards, and certification processes by flag states and classification societies.

Deploying MSRs on ships, whether commercial vessels or naval ships, poses significant systemic challenges, particularly in non-technical areas. Regulatory environments, for instance, are intricate and necessitate comprehensive definition and resource allocation. Currently, only three nuclear-powered commercial vessels have ever been commissioned globally, with the Russian cargo vessel Sevmorput, commissioned in 1988, being the sole operational example today. UK regulators and assurance bodies, lacking prior experience in consulting on nuclear-powered ship commissioning, face a steep learning curve traditionally handled by the MOD and RN.

Another critical systemic issue is the shortage of SQEP in nuclear engineering within the UK. This scarcity could potentially hinder the deployment of nuclear power on ships, whether on board or in supporting shore-based roles. Increased demand for SQEP engineers not only risks impacting projects such as next-generation nuclear power plants and the RN Submarine Service but also underscores the need for substantial investment in expanding infrastructure across military and commercial yards to support nuclear ships.

In summary, while MSR technology holds promise for ship-based applications, addressing regulatory complexities, enhancing technical readiness, and bolstering nuclear engineering capabilities are essential steps towards realizing its full potential in maritime operations.

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References

Blandford, E., Brumback, K., Fick, L., Gerardi, C., Haugh, B., Hillstrom, E., Johnson, K., Peterson, F., Rubio, F., Sarikurt, F., Sen, S., Zhao, H. and Zweibaum, N. (2020) '*KAIROS POWER THERMAL HYDRAULICS RESEARCH AND DEVELOPMENT*' Available at: https://www.sciencedirect.com/science/article/abs/pii/S0029549320301308 (Accessed: 26 March 2024).

Butler, L. (1990) *Curriculum Development System for Navy Technical Training.* Available at: Must specify DOI or URL if using the accessed field (Accessed: 3 July 2024).

Cameron, D. and Mir, L. (2024) *The NEA Small Modular Reactor Dashboard: Second Edition*. Available at: https://www.oecd-nea.org/jcms/pl_90816/the-nea-small-modular-reactor-dashboard-second-edition (Accessed: 26 March 2024).

Canadian Nuclear Safety Commission (2021) *Phase 1 pre-licensing vendor design review executive summary: Moltex Energy*. Available at: https://www.cnsc-ccsn.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/moltex-energy-executive-summary/ (Accessed: 22 March 2024).

Church, S. (2023) 'We are effectively in a war for talent in this country': The First Sea Lord interview, *The House*, 20 June. Available at: https://www.politicshome.com/thehouse/article/we-are-effectively-in-a-war-for-talent-in-this-country-the-first-sea-lord-interview-86344 (Accessed: 17 April 2024).

Department of the Navy (2016) *NETC Instruction 1500.19 - Training Requirement Submission, and Course Development, Delivery and Maintenance End-to-End Process*. Pensacola.

Elsheikh, B.M. (2013) 'Safety assessment of molten salt reactors in comparison with light water reactors', *Journal of Radiation Research and Applied Sciences*, 6(2) Elsevier, pp. 63–70. Available at: 10.1016/J.JRRAS.2013.10.008 (Accessed: 11 March 2024).

Flibe Energy Inc (2024) *Thorium Energy*. Available at: https://flibe.com/energy/ (Accessed: 27 March 2024).

Furukawa, K., Simonenko, V., Mitachi, K., Furuhashi, A., Yoshioka, R., Chigrinov, S., Lecocq, A. and Kato, Y. (2002) 'Thorium cycle implementation through plutonium incineration b..|INIS', *Thorium fuel utilization: Options and trends*., pp. 1–123. Available at: https://inis.iaea.org/search/search.aspx?orig_q=RN:33068573 (Accessed: 11 March 2024).

Gat, U. and Engel, J.R. (2000) 'Non-proliferation attributes of molten salt reactors', *Nuclear Engineering and Design*, 201(2–3) North-Holland, pp. 327–334. Available at: 10.1016/S0029-5493(00)00276-4 (Accessed: 11 March 2024).

GE Marine Solutions (2018) *GE Marine Gas Turbines for Frigates*.

Harinath, Y. V., Mohan, T.V.K., Rangarajan, S. and Albert, S.K. (2022) '*Structural Materials for Molten Salt Reactors*', Springer, Singapore, pp. 169–191. Available at: 10.1007/978-981-16-9302-1_10 (Accessed: 3 July 2024).

Hill, R., Hodge, C.G. and Gibbs, T. (2012) '*The potential of the molten salt reactor for warship propulsion*' Available at: https://thoriumenergyalliance.com/wp-content/uploads/2020/02/bmtdsl-molten-salt-reactor-confpaper-inec-may12.pdf (Accessed: 5 April 2024).

Ho, M., Obbard, E., Burr, P.A. and Yeoh, G. (2019) 'A review on the development of nuclear power reactors', *Energy Procedia*, 160 Elsevier, pp. 459–466. Available at: 10.1016/J.EGYPRO.2019.02.193 (Accessed: 7 March 2024).

Houtkoop, K.C.F., Visser, K., Sietsma, J. and De Vries, N. (2022) 'New potential for integration of nuclear power in marine propulsion systems', *Conference Proceedings of INEC* Available at: 10.24868/10647 (Accessed: 25 April 2024).

Hussain, M., Reitsma, M., Subki, M.H. and Kiuchi, H. (2018) '*Advances in Small Modular Reactor Technology Developments*' Available at: https://aris.iaea.org/Publications/SMR_Book_2020.pdf (Accessed: 22 March 2024).

International Maritime Organisation (2023) *2023 IMO Strategy on Reduction of GHG Emissions from Ships*. *International Maritime Organisation*. Available at: https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx (Accessed: 7 March 2024).

LeBlanc, D. (2010) 'Molten salt reactors: A new beginning for an old idea', *Nuclear Engineering and Design*, 240(6) North-Holland, pp. 1644–1656. Available at: 10.1016/J.NUCENGDES.2009.12.033 (Accessed: 7 March 2024).

Martinez-Guridi, G., Peguero, L. and Reitsma, F. (2023) 'Status of Molten Salt Reactor Technology', *International Atomic Energy Authority, Technical Reports Series No. 489*

McGee, D. 'Skip' (2021) 'The Marine Corps' Technical Skill and Leadership Divergence | Proceedings - April 2021 Vol. 147/4/1,418', *U.S. Naval Institute Proceedings*, 147(4) Available at: https://www.usni.org/magazines/proceedings/2021/april/marine-corps-technical-skill-and-leadership-divergence (Accessed: 3 July 2024).

McGrath, J. (2023) *Kairos Power to Build First US Molten-Salt Reactor in Over 50 Years*., *Business Insider* Available at: https://www.businessinsider.com/molten-salt-reactor-kairos-power-triso-2023-12 (Accessed: 22 March 2024).

Ministry of Foreign Affairs and Trade (1987) *New Zealand Nuclear Free Zone, Disarmament, and Arms Control Act 1987 No 86*. Available at: https://www.legislation.govt.nz/act/public/1987/0086/latest/DLM115116.html (Accessed: 17 April 2024).

NAAREA (2023) *NAAREA'S PROJECT*. Available at: https://www.naarea.fr/en/naarea-project (Accessed: 22 March 2024).

National Nuclear Safety Administration (2023) *Notice on issuance of operating license for 2MWt liquid fuel thorium-based molten salt experimental reactor*. Available at: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk09/202306/t20230613_1033619.html (Accessed: 26 March 2024).

Navy Lookout (2020) *Upgrading the Royal Navy's nuclear submarine support facilities*. Available at: https://www.navylookout.com/upgrading-the-royal-navys-nuclear-submarine-support-facilities/ (Accessed: 3 July 2024).

Nuclear Engineering International (2024) *Russia completes R&D on molten salt research reactor project*. Available at: https://www.neimagazine.com/news/newsrussia-completes-rd-on-molten-salt-research-reactor-project-11486550 (Accessed: 22 March 2024).

Nuclear Innovation and Research Office (2021) *Advanced modular reactors (AMRs): technical assessment - GOV.UK*. Available at: https://www.gov.uk/government/publications/advanced-modular-reactors-amrs-technical-assessment (Accessed: 11 March 2024).

O'Rourke, R. (2009) *Navy Nuclear-Powered Surface Ships: Background, Issues, and Options for Congress*. Available at: https://apps.dtic.mil/sti/citations/ADA524189 (Accessed: 7 May 2024).

Pedersen, T.J. (2019) Available at: https://www.youtube.com/watch?v=-J70XaXbmws (Accessed: 3 July 2024).

Pérès, M. (2020) *Kairos Power MSR Workshop 2020*., *MSR Workshop 2020* Available at: https://msrworkshop.ornl.gov/wp-content/uploads/2020/11/41_Kairos_Power_Update_MSR_Workshop_2020_Final1.pdf (Accessed: 26 March 2024).

Pool, L.M. (2014) *Environmental impact assessment of the Molten Salt Reactor (MSR) compared to the Pressurized Water Reactor (PWR) and offshore wind power*. University of Nottingham.

Raucci, C., McKinlay, C. and Karan, A. (2023) *The future of maritime fuels report | LR*. Available at: https://www.lr.org/en/knowledge/press-room/press-listing/press-release/shipping-industry-faces-two-alternative-decarbonisation-paths-with-hydrogen-based-fuels-and-biofuels-vying-for-prominence/ (Accessed: 7 March 2024).

Riviera News (2023) *China reveals molten-salt nuclear reactor-driven 24,000-TEU box ship design*. Available at: https://www.rivieramm.com/news-content-hub/news-content-hub/china-reveals-molten-salt-nuclear-reactor-driven-24000-teu-box-ship-design-78845 (Accessed: 22 March 2024).

Roper, R., Harkema, M., Sabharwall, P., Riddle, C., Chisholm, B., Day, B. and Marotta, P. (2022) 'Molten salt for advanced energy applications: A review', *Annals of Nuclear Energy*, 169 Pergamon, p. 108924. Available at: 10.1016/J.ANUCENE.2021.108924 (Accessed: 11 March 2024).

Ruane, J. (2023) *Engineering Skills Gap: Evolving the industry to inspire the new modern workforce*. Available at: https://www.stonehavenglobal.com/engineering_skills_gap_evolving_the_industry_to_inspire_the_new_modern_workforce (Accessed: 17 April 2024).

Science Innovation and Technology Committee (2023) 'Delivering nuclear power - Science, Innovation and Technology Committee', *Delivering nuclear power*. Available at: https://publications.parliament.uk/pa/cm5803/cmselect/cmsctech/626/summary.html (Accessed: 18 April 2024).

Scott, B. and Beard, T. (2022) 'An Investigation into the Potential of the Molten Salt Reactor for the Propulsion of Surface Ships', *RINA: Scaling Decarbonisation Solutions - Reducing Emissions by 2030*. Available at: https://www.researchgate.net/publication/366066622_AN_INVESTIGATION_INTO_THE_POTENTIAL_OF_THE_MOLTEN_SALT_REACTOR_FOR_THE_PROPULSION_OF_SURFACE_SHIPS (Accessed: 5 April 2024).

Scottish Affairs Committee (2012) *The Referendum on Separation for Scotland: Terminating Trident-Days or Decades?*., *Scottish Affairs Committee - Fourth Report The Referendum on Separation for Scotland* Available at: https://publications.parliament.uk/pa/cm201213/cmselect/cmscotaf/676/67602.htm (Accessed: 17 April 2024).

Seaborg Technologies (2024) *Our Technology*. Available at: https://www.seaborg.com/the-reactor (Accessed: 27 March 2024).

Smith, J., Simmons, W.E., Asher, R.C., Long, G., McKay, H.A.C. and Reed, D.L. (1974) *AN ASSESSMENT OF A 2500 MWe MOLTEN CHLORIDE SALT FAST REACTOR EDITED BY: AN ASSESSMENT OF A 2 500 MWe MOLTEN CHLORIDE SALT FAST JEACTOR*.

Taube, M. (1978) *Fast reactors using molten chloride salts as fuel* Available at: http://inis.iaea.org/Search/search.aspx?orig_q=RN:11541842 (Accessed: 7 March 2024).

TerraPower (2022) *TerraPower and Southern Company to demonstrate the world's first fast-spectrum salt reactor at Idaho National Laboratory - TerraPower*. Available at: https://www.terrapower.com/southern-terrapower-mcre-agreement/ (Accessed: 22 March 2024).

Terrestrial Energy (2017) *Terrestrial Energy Integral Molten Salt Reactor (IMSR) Architecture*.

The United Nations (2015) *United Nations Treaty Collection*. Available at: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en (Accessed: 7 March 2024).

Thorizon (2022) *Thorizon raises €12,5 million to turn Nuclear waste into CO2-free energy*, Available at: https://www.thorizon.com/press-release-thorizon-raises-e125-million-to-turn-nuclear-waste-into-co2-free-energy/ (Accessed: 22 March 2024).

Ulstein (2022) *Ship design concept from Ulstein can solve the zero emission challenge*. Available at: https://ulstein.com/news/ulstein-thor-zero-emission-concept (Accessed: 22 March 2024).

U.S. Department of Energy (1995) *The History of Nuclear Energy*.

World Nuclear Association (2023) *Nuclear-Powered Ships*. Available at: https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx (Accessed: 7 March 2024).

World Nuclear News (2023a) *Operating permit issued for Chinese molten salt reactor*. Available at: https://www.world-nuclear-news.org/Articles/Operating-permit-issued-for-Chinese-molten-salt-re (Accessed: 26 March 2024).

World Nuclear News (2023b) *Seaborg switches fuel plans because of HALEU timeline risks : Uranium & Fuel*. Available at: https://world-nuclear-news.org/Articles/Seaborg-switches-fuel-plans-due-to-HALEU-supply-is (Accessed: 22 March 2024).

World Nuclear News (2023c) *ThorCon begins pre-licensing consultation in Indonesia : Regulation & Safety*. Available at: https://www.world-nuclear-news.org/Articles/ThorCon-begins-pre-licensing-consultation-in-Indon (Accessed: 22 March 2024).

World Nuclear News (2023d) *Samsung completes design of CMSR Power Barge : New Nuclear - World Nuclear News*., *World Nuclear News* Available at: https://www.world-nuclear-news.org/Articles/Samsung-completes-design-of-CMSR-Power-Barge (Accessed: 3 July 2024).

Wright, R.N. and Sham, T.-L. (2018) ‘*Status of Metallic Structural Materials for Molten Salt Reactors*’, Idaho Falls, ID (United States) Available at: 10.2172/1467482 (Accessed: 11 March 2024).

Zhang, D., Liu, L., Liu, M., Xu, R., Gong, C., Zhang, J., Wang, C., Qiu, S. and Su, G. (2018) ‘Review of conceptual design and fundamental research of molten salt reactors in China’, *International Journal of Energy Research*, 42(5) John Wiley & Sons, Ltd, pp. 1834–1848. Available at: 10.1002/ER.3979 (Accessed: 26 March 2024).

Addressing the modern need for electrical skills in the maritime sector

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Synopsis

Following the global concern and IMO directives, in particular for greener shipping, ships and ports tend to become more efficient in terms of environmental friendliness, energy consumption as well as services provided. A similar path with some particular common if not identical points is met in offshore power plants. This paper aims at highlighting the needs for cultivation of branches of knowledge required in electrical areas of maritime industry, summarizing the new initiatives to substantially respond to these challenges providing ways to reinforce relevant skills and expertise of crews onboard ships but also of technical staff working in ports or to support offshore plants. Moreover, the discussion is enriched by propositions of measures and courses of actions by extending the deep electrical knowhow already cultivated within Universities but also electrical energy Authorities like the Grid Operators and via the substantial support of relevant International Organizations.

Keywords: marine electrical engineering, shore side electricity, port electrification, offshore platforms for RES, CPD courses.

1. Introduction

Marine electrical engineering issues have been recognized for long as of major importance especially due to the extensive electrification of all system onboard ships according to the All Electric Ship (AES) concept. Nowadays, that green shipping policy has become predominant based upon IMO's and EU resolutions, electrification is the ultimate key towards achieving difficult goals. Besides using electrical means to increase environmental performance of ships, an additional example being a large-scale project at international level is the implementation of shore side electricity so that ships while at berth shut down completely their engines and get electricity from shore which is, in general, produced by more environmentally friendly methods. The latest challenge emerged is related with the offshore plants used to host wind generators or even Photo-Voltaic (PV) panels in the deep sea.

Within this context a new Continuous Professional Development (CPD) course is under development by the University of Strathclyde via the cooperation of the National Technical University of Athens in order to develop and/or upgrade the required skills of the personnel engaged in all the aforementioned initiatives.

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The Institute of Marine Engineering, Science and Technology (IMarEST) has recognized the augmenting demands in the electrical related area since the 1990's and has been relatively activated. Following the great series of dedicated papers, special events and conferences (including the hosting INEC), a Special Interest Group on Marine Electrical issues has been formed and resulted in the MECSS Special Interest Group (SIG) and the homonym series of successful conferences coordinated by Kevin Daffey. Currently, this MECSS Special Interest Group (SIG) has been slightly renamed as Marine Electrical Special Interest Group (MESIG) and using the substantial background of MECSS it to be rejuvenated.

The Institute of Electrical and Electronic Engineers (IEEE) has been addressing the advancements in electrical engineering as a mission and regarding the maritime sector has been promoting the corresponding technological support via the standards, workshops and conferences of its Power and Energy Society (PES) in conjunction with the Industrial Application Society via the Marine System Coordinating Committee (MSCC). A representative result of these efforts consists in the well-known IEEE 45 and IEC/ISO/IEEE 80005 series of standards on ship electric energy systems and shore-to-ship power interfaces (between the port and the ship grids) respectively.

Taking into account that shore and ship grids are coming close to one another, with big amounts of energy transactions quite often at high voltage levels and with penetration of Renewable Energy Sources (RES) in combination with Energy Storage Systems (ESS), it becomes mandatory that a tight cooperation between the maritime industry and the Grid operators must be developed. Within this context, a synergistical scheme with Grid operators in terms of training but also in further developing technical knowledge is also sought.

This paper is to highlight the needs for cultivation of branches of knowledge required in electrically related areas of maritime industry, summarizing the new initiatives to substantially respond to these challenges providing ways to reinforce relevant skills and expertise of crew onboard ships but also of technical staff working in ports or supporting offshore plants.

2. The increased needs for marine electrical knowledge

In this section, the various marine technical areas with increased electrical interest are briefly outlined and discussed.

2.1 Improving ship performance via electrical means

Ship performance improvement has been an objective of a plethora of studies after the mandates of International Maritime Organization (IMO) aiming at green shipping, since the first decade of the new millennium. As it is well known the ship performance is measured and monitored via a number of indicators (EEDI, EEXI, CII) all of which are strongly related to the environmental footprint of each vessel (namely the CO2 produced) versus her useful work produced ie the transported cargo at a specific speed. Within this context, a variety of measures with electricity being the driving force have been tested and accredited to ameliorate the ship environmental footprint during sailing or during their berth in ports. Some of them are enumerated and described in brief next, see also Figure 1, (Soghomonian et al 2016, Souflis-Rigas et al 2021, Prousalidis et 2019, Lyridis et al 2019, Sulligoi et al 2015).

>Optimal selection of generator sets: following a good electric load analysis where the electrical needs of the ship in all operating modes is made, a successful selection of the rated power of generators as well as their optimum combination of their simultaneous operation is reflected to their fuel consumption and consequently the emissions produced. It is worth mentioning that due to high electrification of all equipment installed, it has been shown that special attention must be paid to meeting the total needs for reactive power besides those of the active power.

>Shaft Generator systems: These systems also called as Power Take Off (PTO) systems generate electricity exploiting the power of the main engine. Nowadays, that 'slow steaming" and "main engine limiting" techniques are often applied as performance improving measures, PTO's provide an additional degree of freedom towards the same target. More specifically, they can optimize the operating point of the main engine improving the fuel consumption without any increase in the vessel speed but by exploiting the rotating energy of the shaft and produce electricity instead. The electricity produced can be either injected to the ship grid or stored in batteries. Moreover, in certain cases, these systems can act as Power Take In (PTI's) by reversing the power flow and boost the main propulsion mechanism in a hybrid manner. All combinations mentioned can be exploited to improve the total ship performance. Finally, a PTI can act as an emergency propulsion system in case of severe damage of the main engine.

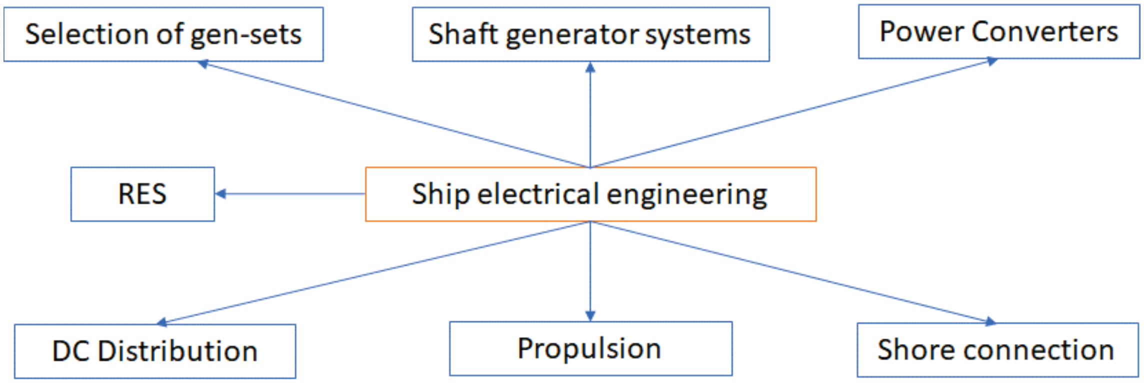

Figure 1. Major components of ship electrical engineering related to sustainable decarbonization.

> Power converters: power electronic converters can be introduced as interfaces between the main ship electric energy system and a motor driven piece of equipment in an attempt to improve the total energy consumption and consequently the ship efficiency. The key aspect the converters contribute is adjusting the no-load losses of the electric motors by regulating the applied voltage. Provided that any harmonic distortion or other power quality problems are resolved, power converters can provide numerous solutions to improve efficiency onboard.

> Renewable energy sources: several environmentally friendly energy sources generate electricity as the latter is flexible to manage, distribute, store and consume. These green energy sources provide an improvement to the efficiency of the ship they are installed adjusting the corresponding indicators. Among the most successful although of limited rated capacity are the PV's deployed in any available surfaces onboard and the waste heat recovery units either based on Organic Rankine Cycle (ORC) technology or on Thermo-Electric Generators (TEG's).

> Direct Current Distribution: the exploitation of DC offers the merit of eliminated reactive power circulation and, hence, of decreased losses in the cables and the entire distribution network, in general. Moreover, it consists a flexible Grid platform where RES's like PV's which also generate DC electric energy can be directly connected.

> Electric propulsion: the electrification of the main propulsion in combination with green electric power supply provides an almost zero-emission ship solution at least from the so called "tank-to-wake" point of view. When all equipment onboard are electric and monitored and managed by a central Energy Management System, then ship has no adverse environmental footprint while it can be controlled in a fairly optimal way ascertaining minimum losses.

> Ship to shore interconnection (cold ironing): Ships being at berth in ports shut down their main engines but not their auxiliary engines (electric generators) and, hence they still pollute the broader area via their emissions. However, if these emissions can be eliminated if they are supplied by the shore Grid via appropriate interfaces matching voltage, frequency and other operating parameters. Taking into consideration that electricity in inland grids is generated via environmentally friendly methods e.g. RES's, this option has become an imperative measure in many countries all over the world after IMO's resolutions. Based on the ship type and size, the power demands of the ships can be of significant magnitude reaching, if not exceeding, in the case of cruise ships 16 MVA. This measure is the foundation stone of the sustainable transformation of ports outlined in brief next.

2.2 Shore power and Energy transformation of ports

Ports nowadays, being the transportation hubs, are also facing significant challenges in terms of providing innovative services of superior quality as well as high financial, environmental and societal impact. To this end, all ports tend to re-establish their strategic mission according to which they are subject to a transformation into smart energy hubs where electrification, once again, plays a key-role. In particular, the smart hub assets and services of a modern port can include, (Antonopoulos et al 2014, Prousalidis et al 2019, Bosich et al 2023, Kanellos 2017, Kanellos 2018, Lyridis et al 2023, Manos 2023, Manos et al 2023), see also Figure 2.

- *Shore to Ship electric interconnection (Cold Ironing):* as described in the previous section, the foot print of ships can be improved if not completely eliminated if cold ironing facilities are deployed and exploited in ports supplying ships at berth with green electric energy.

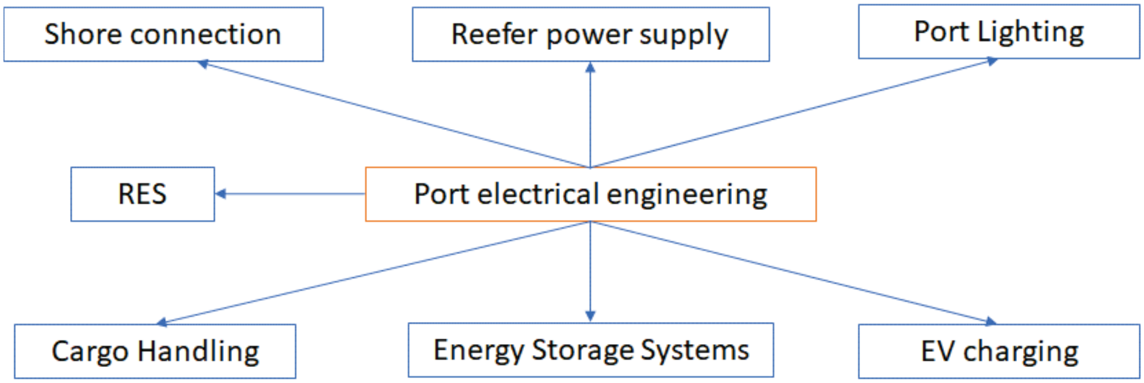

Figure 2. Major components of port electrical engineering related to sustainable decarbonization.

- *Reefer power supply*: reefers which are temporarily connected to port dedicated power supply facilities have been designed to preserve their contents having high thermal inertia, which allows for non-continuous power supply with only short duty cycles. Thus, they can be seen as a flexible load the power demand of which can be treated as a degree of freedom in the total power demands of the ports
- *Port Lighting*: currently, cutting edge LED technology provides high illumination services with smart lighting capabilities (of hot or cold like colors as well as with smart dimming and/or switching on/off depending on the activities taking place) at fairly low power demands. Moreover, fast internet connections (through Li-fi) can be attained.
- *Renewable energy sources (RES)*: Arrays of photo-voltaic cells (PV's) in possible combination with small scale wind-generators can be installed in appropriate areas (e.g. on top of buildings, in parking areas, etc) within the port jurisdiction producing green energy that can be consumed within the port or stored in batteries or injected to the main Grid at the outermost region of the port. Moreover, as wind or solar potential is usually high in port extended areas port authorities can develop offshore or nearshore wind or PV parks and integrate their operation with port electric system (Kanellos, 2017).
- *Cargo handling equipment:* such equipment mostly referring to cranes and/or pumps with integrated regenerative braking capabilities have a low mean energy demand on an average daily basis as the lifting-down movements offset to a great extent the lifting-ups. Thus, this type of equipment provides some flexibility to the energy demand provided a well designed operating scheme is followed.
- *Energy storage systems*; mainly batteries which can be used either for buffering energy from any renewable energy sources installed in the port pr during off-peak hours or (bunkering and buffering)
- *Electric vehicle charging stations*: charging stations can be deployed in available port areas (e.g. existing parking stations) so that any electric vehicles owned by the port authority (internal transportation) or by travelers can be served.

2.3 Offshore power plants

In the previous decades offshore power plants have been developed mainly in order to help the extrusion of oil in the middle of deep seas. Complicated but also advanced infrastructures have been designed and built havinga common denominator with ships, i.e. the fact that they have been autonomous energy systems.

Nowadays with the decarbonization policy predominating, offshore or nearshore plants have changed their mission hosting in most cases green energy generation sources like wind-generators and/or photovoltaic cells. The energy produced in these plants is either stored locally in energy storage devices most frequently electric batteries or it is injected to the National Grid via submersed power transmission cables. There are also some initiatives that the electric energy generated is used to produce locally zero-carbon fuels like hydrogen which is also stored locally.

In all cases, the proper operation of such offshore plants necessitates the exploitation of specific multi-purpose support vessels. The design and operation of the latter is a major novel challenge that needs to be addressed accordingly.

A figurative representation of the offshore electrical engineering components is depicted in Figure 3.

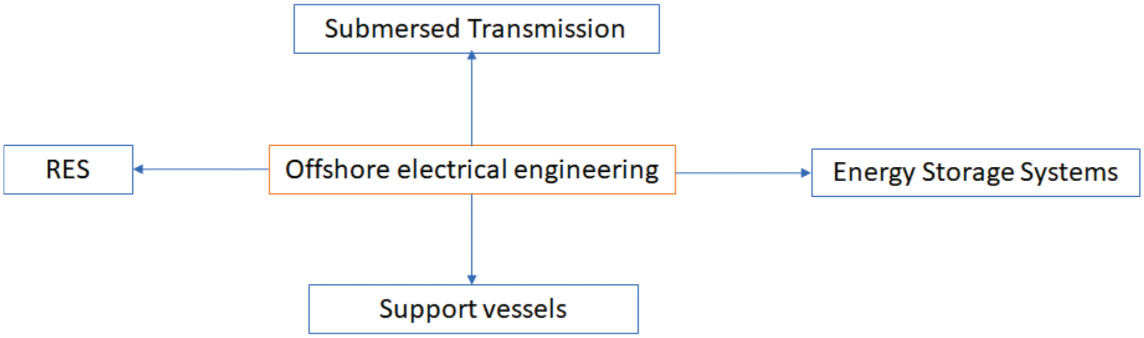

Figure 3. Major components of offshore electrical engineering related to sustainable decarbonization.

It is worth noting that the three different domains of increased electrical engineering interest are interrelated as ports are expected to act both as transportation hubs for all ships (including their cargo/passengers) but also as energy hubs. The necessary infrastructure required for all sophisticated and often bidirectional energy transactions must be carefully designed and installed, while it must also be operated by skilled and well trained personnel, which is further discussed next.

3. Developing, Cultivating and Disseminating knowledge

3.1 The modules to be covered

Based on the above discussion about the areas of expertise that must be developed to address the challenges of sustainable decarbonisation the following branches of knowledge have been recognised:

> Fundamentals: electric quantities, electric circuitry analysis principles,
> Rotating electric machinery: synchronous generators, asynchronous motors, synchronized operation of generators, active and reactive load sharing
> Power distribution: transformers, cables, switchboards, circuit breakers and switching devices
> Protection systems: short circuit calculations, selectivity, protection coordination
> Earthing/Grounding: protective earthing, system earthing, common mode earthing
> Power electronic converters: power electronic switches, bridges, rectifiers, inverters, converters, power/torque/frequency control techniques
> Renewable energy sources: PV’s, wind-generators, waste heat recovery units
> Energy storage systems: batteries, other units of energy buffering
> Electric energy systems: design and operation principles, High Voltage
> Shore power interconnection interfaces
> Smart grids: integrated optimum operation of multiple power sources via a supervisory monitoring Energy Management System. Applications in ships, ports and offshore plants
> Power Quality: harmonic distortion, transients, dips and spikes

Taking into consideration that all these courses are strongly related to the maritime sector, their contents can be based on the STCW/ETO modules namely the training material dedicated to provide technical and electrical knowledge to the seafarers in order to comply with IMO conventions.

Depending on the background of the people to assimilate the aforementioned knowledge, the components above can be integrated in either a Continuing Professional Development (CPD) short seminar course or a Master of Engineering (MEng) curriculum of fairly longer duration. The former will be addressed to technicians who must get acquainted in a short time interval (about 15 days) with the core knowledge, while the latter will be most appropriate to graduate engineers who wish to acquire deeper knowledge and develop expertise in a more thorough manner.

The three different disciplines of marine electrical engineering as discussed will face a diversification of the modules as indicatively shown in Figure 4.

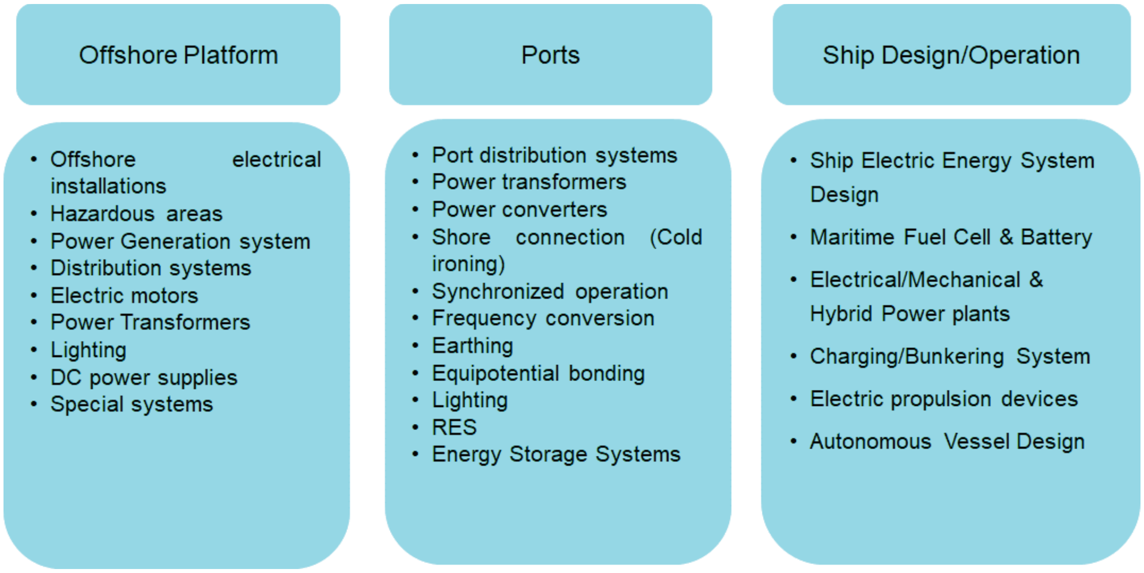

Figure 4. Indicative Grouping of training modules per specialty of marine electrical engineering.

3.2 The role of Institutions

The curricula discussed are to be initiated and developed by universities (like the University of Strathclyde and the National Technical University of Athens) but they need the support of several other stakeholders, the role of which is analyzed in brief next.

IMarEST

As already mentioned, the Institute of Marine Engineering, Science and Technology (IMarEST) has already been active in marine electrical issues for quite a long. Taking into account its long experience its role can comprise:

- Accreditation of the CPD courses
- Promotion of the curricula via its branches worldwide and via the series of events related to marine engineering (workshops, conferences, webinars etc)
- Support the training via high quality instructional material based on its publications but also via instructors-members of IMarEST
- Develop novel training material within the framework of SIG's like MESIG. The latter could have a substantial role in all the activities of the curricula which will encourage the whole effort to restart its productivity

IEEE

The Institute of Electrical and Electronic Engineers in the maritime related issues has been particularly active in developing standards and recommendations which provide priceless instructions to system designers. More specifically, IEEE/PES/Marine system Coordinating Committee has as predominant task to develop/amend a big series of standards; in coordination with the IEEE Industrial Application Society (IAS) a number of standards have been developed and published:

- IEEE 45.1-8, Recommended Practice for Electrical Installations on Shipboard
- IEEE 1580, Recommended Practice for Marine Cable for Use on Shipboard and Fixed or Floating Platforms
- IEEE 1662, RP for the Design and Application of Power Electronics in Electrical Power Systems
- IEEE 1709, Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships

It is worth noting that 45.1, 45.2, 45.3 and 45.7 are in amendment process (each one at different stage). Anyhow, it is underlined that standards have among others an instructional role, providing the accumulated experience of the Past to design engineers. In the case of marine electric energy systems where safety and reliability are of uttermost importance, these standards or recommended practices are priceless and, hence, extracts of them can consist the core material of the CPD or MSC modules under discussion.

Grid Operators (DSO's and/or TSO's).

Grid Operators namely Distribution System Operators-DSO's and Transmission System Operators-TSO's) have cultivated for long the massive electrification of many sectors of human activities. Within this context, their role, in particular that of DSO's, encompasses the provision of the electrical supply to ports for the electric interconnection of ships. Moreover, they are responsible for the deployment of offshore plants in the sea and their interconnection with the mainland Grid. In the particular case of Greece, HEDNO is the sole Distribution System Operator in Greece and has been engaged in the implementation of decarbonized energy transformation of ports in parallel to the sustainable transformation of its own distribution networks.

Thus, HEDNO, on the one hand has to retrofit its network by installing modern, environmentally friendly and high efficiency components (e.g. underground cables, low loss transformers) upgrade its network so that RES are easily plugged-in, but also extend its network so that ports with their advanced role as energy hubs be served, too.

Therefore, HEDNO can be recognized as the Institution that has the expertise to pave some of the major next steps, and hence should contribute to the development of the relevant know-how not only for itself but for the entire society, too. Within this frame, HEDNO has established a multi-purpose CPD program for its own personnel, but in view of the upcoming challenges in the maritime related electrical applications wishes to get engaged in the CPD discussed in this paper, too. Some indicative cases include the quasi-real field and/or laboratory environment in its own Schools, where trainees can get accustomed with the components of the new highly advanced electrical technology described above.

As a summary the schematic of the CPD/MSc post-graduate curriculum with the roles of the associated partners i.e. Institutes, Universities and Grid Utilities is illustrated in Figure 5.

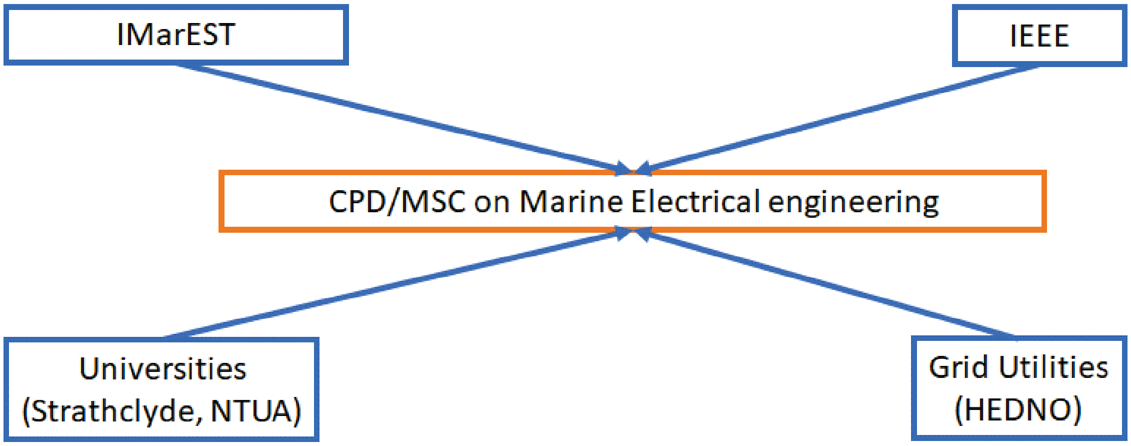

Figure 5. Figurative Schematic of the proposed curriculum on marine electrical engineering.

4. Conclusions

This paper makes the effort to highlight the needs for cultivating the branches of knowledge required in electrical areas of maritime industry, summarizing the new initiatives and substantially respond to the new challenges. The concept of a new curriculum either in a CPD or in MEng format is developed aiming at reinforcing relevant skills and expertise of crew onboard ships but also of technical staff working in ports or in supporting services of offshore plants. *The host of this effort is the University of Strathclyde (Glasgow) but will be substantially supported by NTUA, too. Moreover, IMarEST can promote and accredit the course, while IEEE could support the course, too via its electronic database of standards. Moreover, a Grid Utility like HEDNO, can enrich the syllabus by providing quasi-real field testing environment.*

Nomenclature

AES	:	All Electric Ship
CII	:	Carbon Intensity Indicator
CPD	:	Continuous Professional Development
DSO	:	Distribution System Operator
EEDI	:	Energy Efficiency Design Index
EEXI	:	Energy Efficiency Existing Index
ESS	:	Energy Storage Systems
EU	:	European Union
HEDNO	:	Hellenic Electricity Distribution Network Operator
IEC	:	International Electrotechnical Committee
IEEE	:	Institute of Electrical and Electronic Engineers
IMarEST	:	Institute of Marine Engineering, Science and Technology
IMO	:	International Maritime Organization
LED	:	Light Emitting Diode
MECSS	:	Marine Electrical and Control Systems Safety Conference
MSCC	:	Marine System Coordinating Committee
NTUA	:	National Technical University of Athens
ORC	:	Organic Rankine Cycle
PTO	:	Power Take Off
PTI	:	Power Take In
PV	:	Photo-Voltaic
RES	:	Renewable Energy Sources
TEG	:	Thermo-Electric Generator
TSO	:	Transmission System Operator

References

Antonopoulos G., Patsios C., Greig A. , and Bucknall R., “Green shipping in emission controlled areas: Combining smart grids and cold ironing”, Proceedings of International Conference on Electrical Machines (ICEM), in Proceedings of International Conference on Electrical Machines (ICEM), Berlin (Germany), 2-5 Sep 2014, pp. 2299–2305, doi: 10.1109/ICEL-MACH.2014.6960506.

Bosich D., Chiandone M., Feste M-D, Sulligoi G., “Cold Ironing Integration in City Port Distribution Grids: Sustainable electrification of port infrastructures between technical and economic constraints”, IEEE Electrification Magazine, March 2023, Vol.11, No 1, doi: 10.1109/MELE.2022.3232965.

IMO Model Course 7.08- Electro-Technical Officer, 2014 Edition.

Kanellos F. D.: “Real-Time Control Based on Multi-Agent Systems for the Operation of Large Ports as Prosumer Microgrids”, IEEE Access, vol. 5, pp. 9439-9452, 2017.

Kanellos F. D.: “Multiagent-System-Based Operation Scheduling of Large Ports’ Power Systems with Emissions Limitation”, IEEE Systems Journal, 2018 (Article in Press). Online Available: https://ieeexplore.ieee.org/document/8411546

Kanellos F, Tsekouras G., Nikolaidis V., Prousalidis J,”Toward Smart Green Seaports”, ”, IEEE Electrification Magazine, March 2023, Vol.11, No 1, pp. 33-42, doi: 10.1109/MELE.2022.3232980.

Lyridis D, Prousalidis J, Lekka A-M, Georgiou V, Nakos L. ”Holistic energy transformation of ports – The Proteus plan”, IEEE Electrification Magazine, March 2023, Vol.11, No 1, doi: 10.1109/MELE.2022.3232923.

Manos A., “How the Vision of a Distribution System Operator Encompasses the Green Energy Transformation of Ports”, IEEE Electrification Magazine, March 2023, Vol.11, No 1, doi: 10.1109/MELE.2022.3232922.

Manos A., Lyridis D., Prousalidis J., "The Maritime Sector in the Electric Energy Markets", Proceedings of ESARS-ITEC 2023, Venice (Italy), 29-31 Mar 2023, doi: 10.1109/ESARS-ITEC57127.2023.10114842.

Prousalidis J., Kanellos F., Lyridis D. , Dallas S, Spathis D., Georgiou V., Mitrou P.: "Optimizing the operation of port energy systems", Proceedings of 2019 International Conference on Environment and Electrical Engineering (EEEIC-2019), paper No 203, Genoa, Italy, 11-14 June 2019, doi: 10.1109/EEEIC.2019.8783476.

Prousalidis J., Georgiou V., Spathis D., Lyridis D., Kanellos F., , Mitrou P., Dallas S: Elaborating Sustainable Port services for Greener Shipping, Proceedings of ICMET 2019, Oman, Nov 2019, doi: 10.24868/icmet.oman.2019.018.

Prousalidis J., D' Agostino F., Manos A., Bosich D, "The SSE-ID Card of Ships in the Sustainable Maritime Framework", Proceedings of ESARS-ITEC 2023, Venice(Italy), 29-31 March 2023, 10.1109/ESARS-ITEC57127.2023.10114812.

Soghomonian Z., Prousalidis J., Kanellos F., Dallas S., Spathis G., Kourmpelis T., Tsekouras G., "The role of efficiency of electric machinery on green shipping" in Proceedings of International Conference on Electrical Machines (ICEM), Lausanne (Switzerland), 4-7 Sep, 2016, doi: 10.1109/ICELMACH.2016.7732946.

Souflis-Rigas A., Prousalidis J, Dimopoulos G., "Assessing the implementation of Power Take Off (PTO) system onboard Liquified Natural Gas (LNG) carriers", Proceedings of ESTS 2021, 3-6 Aug 2021, 10.1109/ESTS49166.2021.9512353.

Sulligoi G., Bosich D., Pelaschiar R., Lipardi G, and Tosato F., "Shore-to-ship power," Proc. IEEE, vol. 103, no. 12, pp. 2381–2400, Dec. 2015, doi: 10.1109/JPROC.2015.2491647.

Chartering a Greener Course: A review of Mature Technologies for Lowering Vessel GHG Emission

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Synopsis

In response to the escalating challenge of climate change, the International Maritime Organization (IMO) adopted a groundbreaking strategy during its 72nd Maritime Environmental Protection Committee (MEPC) session in 2018 which was revised in 2023. In line with the IMO's ambitious targets for 2050, this study tries to explore the effective deployment of mature technologies to significantly reduce greenhouse gas (GHG) emissions in maritime transport. The main aim of this research is to evaluate the effectiveness of mature emission-reducing technologies that are either ready for immediate deployment or near market readiness, and to establish a structured framework assisting maritime stakeholders in aligning their operational decisions with environmental objectives. Impact in the naval sector has also been explored. The study employs a systematic literature review, analysing sources from Google Scholar and Web of Science databases collected up to December 2023. It categorises technologies into four main groups: fossil fuel technologies, renewable energy solutions, fuel cells, and alternative fuels, assessing their maturity and implementation feasibility. The research highlights the technological potential and challenges, tries to provide a clear depiction of current trends and future directions in maritime emission reduction. Findings indicate that despite the varying maturity levels of these technologies, there is a tangible shift from traditional fossil fuel solutions towards more sustainable alternatives such as fuel cells and alternative fuels. An integrated approach involving policy support, technological advancement, and international cooperation is essential for the successful real-world application of these technologies. This approach will help overcome existing barriers to implementation, such as high costs and technical challenges, and pave the way for more sustainable maritime operations.

Keywords: GHG emission, Shipping, Propulsion system, Literature survey, Alternative fuel, Current technologies,

1. Introduction:

As the urgency of global climate challenges increases, IMO has escalated its commitments to reduce GHG emissions from maritime sources, aligning with the ambitious Paris Agreement Goals. In 2018, the IMO set a groundbreaking target to reduce GHG emissions from ships by at least 50% by 2050 compared to 2008 levels, with a strategy revised in 2023 aiming for net-zero emissions around 2050. This revised strategy also set out some indicative checkpoints for 2030 and 2040. The main indicative checkpoints are reducing total GHG emissions from international shipping by 20% (striving for 30%) by 2030 and 70% (striving for 80%) by 2040 (DNV -2023).

Amidst a backdrop of increasing shipping activities and corresponding rises in GHG emissions, which saw a 9.6% increase in 2018 compared to 2012 (IMO, 2021), the maritime industry faces the dual challenges of boosting economic growth and reducing environmental impact.

By consolidating a wide range of studies and findings from 2018 to 2023, the main rationale for this paper are two: firstly, to assess the current landscape of mature technologies that are immediately deployable or close to market readiness for reducing emissions; and secondly, to provide a structured framework that aids various maritime stakeholders in making informed decisions that align with both environmental goals and operational feasibility.

Furthermore, the introduction of "indicative checkpoints" by the IMO for 2030 and 2040 demands accelerated efforts and immediate action. This paper also tries to chart a feasible course for emission reduction by meticulously evaluating the potential of four category technology groups i) fossil fuel technologies, ii) renewable energy solutions, iii) fuel cells, and iv) alternative fuels highlighting both their advancements and the hurdles they face in contributing to the IMO's emission reduction targets with the help of "SCORE" analysis method.

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2. Methodology

2.1. Research Design

This study conducted an extensive literature review using the Google Scholar and Web of Science (WoS) databases. This approach enabled a comprehensive collection of academic literature pertinent to the research objective. The search was executed in December 2023, ensuring the relevance and recency of the data collected.

2.2. Data Sources and Selection Criteria

For Google Scholar, this study considered articles containing specific keywords in their titles, indicative of the scope of technologies targeting GHG emission reductions in shipping. Keywords included combinations such as "Ship and emission," "Ship and GHG emission," and "Ship and renewable energy," among others. The initial search yielded 390 articles, narrowed down to 127 after applying filters for publication years (2018-2023) and excluding citations. A review of the abstracts further refined this list to 53 articles for in-depth analysis.

2.2.2 Web of Science

Within the WoS database, the "Topic" search function was utilized with the keyword "Ship*" in conjunction with various terms related to emissions and energy sources, including "emission*," "GHG*," "fuel cell*," and "renewable energy*." This initial search resulted in 2,854 publications, which were filtered down to 1,054 after removing non-article publications and applying the same year-of-publication criteria as for Google Scholar. A subsequent abstract review led to the selection of 61 articles for further review.

2.3. Analysis Methodology

“SCORE” analysing technique is used for further analysing the various technologies discussed in various categories. "S" represents Strengths, highlighting the inherent capabilities. "C" stands for Challenges, identifying the obstacles. "O" emphasizes Opportunities, pointing out the trends that can be leveraged for success. "R" is for Response, detailing the actions taken to capitalize on strengths, mitigate challenges, and seize opportunities. Lastly, "E" stands for Evaluation, involving a critical assessment of the outcomes and tries to suggest future strategies.

2.4. Classification Framework

A total of 114 (Appendix A) publications, comprising 53 articles from Google Scholar and 61 from Web of Science, were meticulously categorized into four distinct groups:

Category 1 - Technologies Using Fossil Fuels
Category 2 - Technologies Using Renewable Energy
Category 3 - Technologies Using Fuel Cells
Category 4 - Technologies Using Low Carbon/Alternative Fuels

Figures 1 to 4 presents year-wise distribution and analysis of articles across these categories, reflecting the research community's growing interest in sustainable and innovative solutions to maritime GHG emissions.

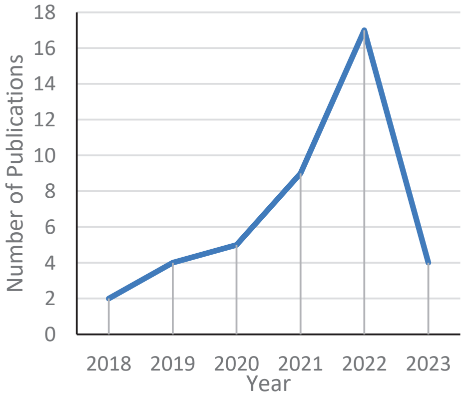

Figure 1: Year Wise Distribution Category-1

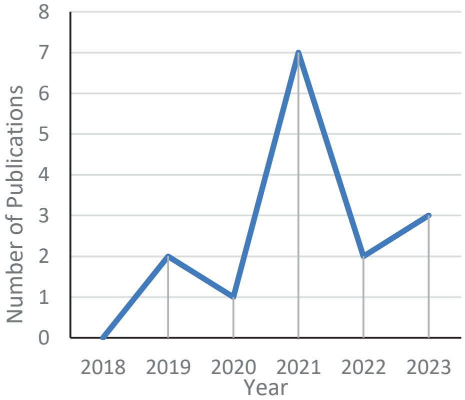

Figure 2: Year Wise Distribution Category-2

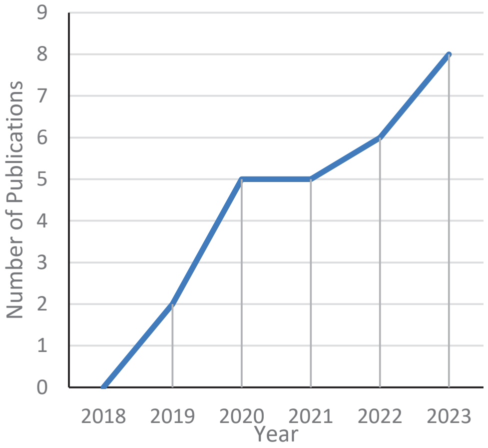

Figure 3: Year Wise Distribution Category-3

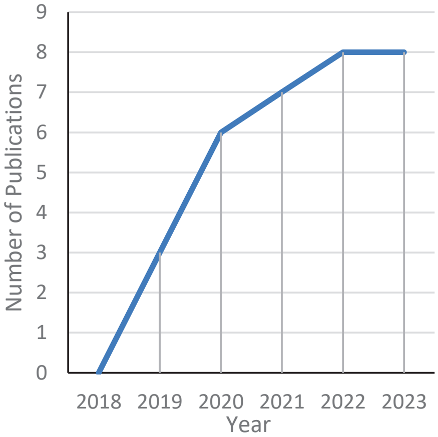

Figure 4: Year Wise Distribution Category-4

3. Review and Analysis of Selected Articles

3.1. Distribution of publication by years

3.1.1 Category 1- Technologies that uses fossil fuels.

Figure 5 shows an increasing trend in the number of publications from 2018 to 2022, starting with 2 publications in 2018 and peaking at 17 in 2022. However, there's a significant drop to 4 publications in 2023, indicating a possible shift in focus towards more sustainable technologies.

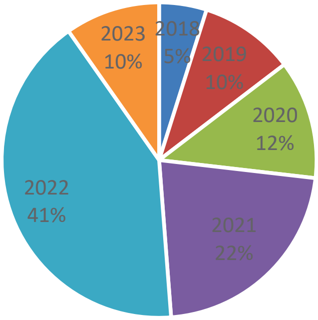

Figure 5: Distribution over Years in Category 1 (2018-2023)

3.1.2 Category 2 - Technologies Using Renewable Energy:

Figure 6 demonstrates a slow start with no publications in 2018, a slight increase to 2 in 2019, and a peak at 7 publications in 2021. The number of publications decreases in 2022 to 2 but sees a slight rise to 3 in 2023, suggesting a fluctuating but ongoing interest in renewable energy technologies for vessels.

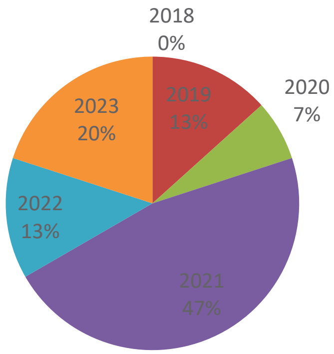

Figure 6:Distribution over Years in Category 2 (2018-2023)

3.1.3 Category 3 - Technologies Using Fuel Cells:

Similar to category 2 publications in the category 3 as shown in Fig 7 also starts with no publications in 2018 but shows a more consistent increase in the number of publications over the years. The count rises from 2 in 2019 to a peak of 8 in 2023, highlighting a growing interest and investment in fuel cell technology as a sustainable alternative for vessels.

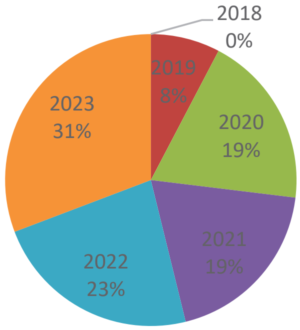

Figure 7: Distribution over Years in Category 3 (2018-2023)

3.1.4 Category 4 - Technologies Using Low Carbon/Alternative Fuels:

There were no publications in 2018, but there has been a steady increase from 3 in 2019 to 8 in both 2022 and 2023. This trend indicates a strong and sustained interest in exploring low carbon and alternative fuels for reducing vessel GHG emissions.

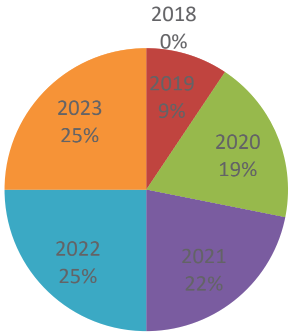

Figure 8: Distribution over Years in Category 4 (2018-2023)

4. Results

4.1. *Category 1 – Technologies that uses fossil fuels.*

4.1.1 Technology Evaluation

Key technologies considered includes i) technical methods like wet scrubbing with electrolyzed seawater, and energy efficiency improvements like EEDI, SEEMP, and EEOI, and ii) operational methods like slow steaming, weather routing, trim optimization, and hull and propeller maintenance.

Technical methods, Wet scrubbing technology, particularly through electrolysed seawater, demonstrates significant promise in reducing sulphur oxides (SOx), nitrous oxide (NOx) and particulate matter (PM) emissions. Data reveal (Yang, 2018) removal efficiencies reaching up to 92% for NOx and nearly 100% for SOx, showcasing its potential to meet stringent international regulations. Study (Jimenez, 2022) highlights the potential of various energy efficiency improvement methods and the importance of accurate reporting by shipping companies to improve transparency and accountability and ultimately improving energy efficiency contribution.

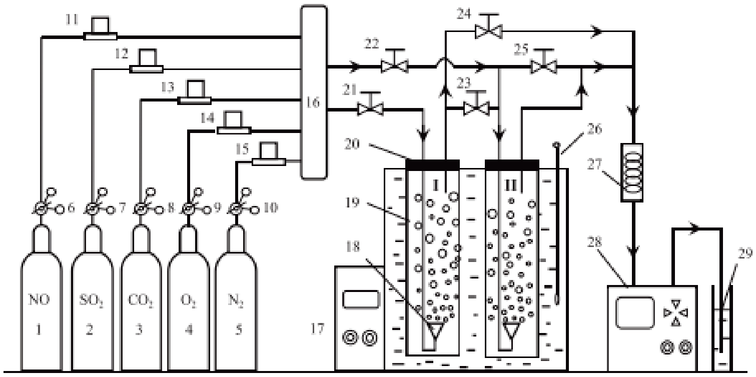

Figure 9 - (1–5) gas cylinders used for the stimulation of the flue gas emitted from ships; (6–10) reduced valves; (11–15) mass flow controllers; (16) gas mixer; (17) constant temperature water bath; (18) gas distributor; (19) bubble column; (20) rubber plug; (21–25) block valves; (26) thermometer; (27) electronic condenser.

Figure 9: Experimental Model Used in the Study by (Yang, 2018)

Operational measures involving lowering ship speed, weather routing, trim optimization, hull, and propeller condition maintenance reduces resistance and energy requirements exponentially. These techniques not only address the environmental impact but also enhance the operational efficiency and lifespan of maritime vessels (Elkafas, 2021).

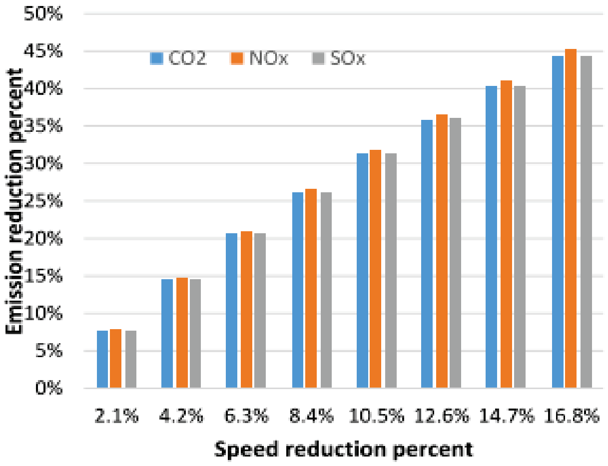

Figure 10- Results from the case study (Elkafas, 2021)

4.2. Category 2 – Technologies that uses renewable energy.

4.2.1 Technology Evaluation

Solar Power and Photovoltaic Systems: Operational benefits of these systems include powering onboard systems, thereby reducing diesel generator loads and contributing to fuel savings and GHG emission reductions. A case study on cruise ship (Ghenai, 2019) demonstrate a reduction of 9.84 % GHG emission compared to the baseline using Diesel Engine. Figure 11 shops a typical power distribution arrangement using solar power system.

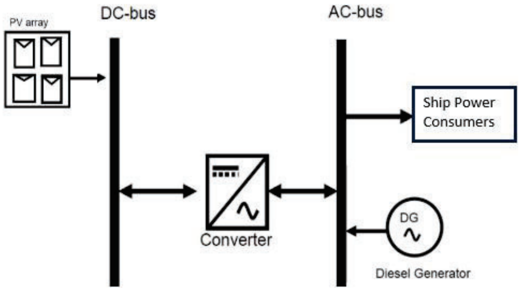

Figure 11: A typical solar power distribution system.

Wind-Assisted Propulsion Systems (WASP): Innovations like flettner rotors, towing kites, wing sails, and soft sails have reintroduced wind power as a feasible and efficient source of propulsion thus reducing reliance on fossil fuels. Vessels equipped with these systems report (Wang, 2022) emission reduction and fuel savings up to 20%, showcasing the potential of wind power in enhancing maritime fuel efficiency and sustainability.

Figure 12 -Representation from Wang, 2022

Hybrid Power Systems: Hybrid systems blend renewable energy with traditional power sources to create efficient, sustainable solutions for ships. Advanced energy management maximizes renewable use and minimizes emissions. Numerous case studies affirm the role of hybrid systems in the future of green shipping (Setiawan-2021, Huang-2021, Gabbar-2021, Stamatakis-2021, Cheng-2022, Dolatabadi-2023).

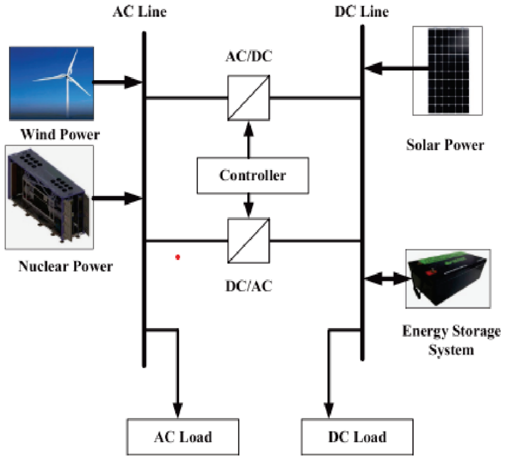

Figure 13: Typical Hybrid Arrangement (Gabbar - 2021)

4.3. *Category 3 – Technologies that uses Fuel Cells*

4.3.1 Technology Evaluation

The evaluation of Proton Exchange Membrane (PEM) and Solid Oxide Fuel Cells (SOFCs) in maritime applications shows significant progress toward zero-emission transport. Each technology has distinct advantages: PEM Fuel Cells offer efficiency, rapid start-up, low operating temperatures, and high-power density, reducing fuel consumption by 9% and CO2 emissions by 5.5% in auxiliary power applications (Matulić, 2018). PEM fuel cells, with their operational advantages and environmental benefits, are closer to mainstream adoption, evidenced by various pilot projects and case studies (Matulic -2018, Cavo – 2021 and Saloniemi -2022). SOFCs boast high efficiency and fuel flexibility, operating on various fuels and reducing GHG emissions by 34% (Baldi, 2020). However, high operating temperatures and cost barriers challenge SOFCs' widespread adoption.

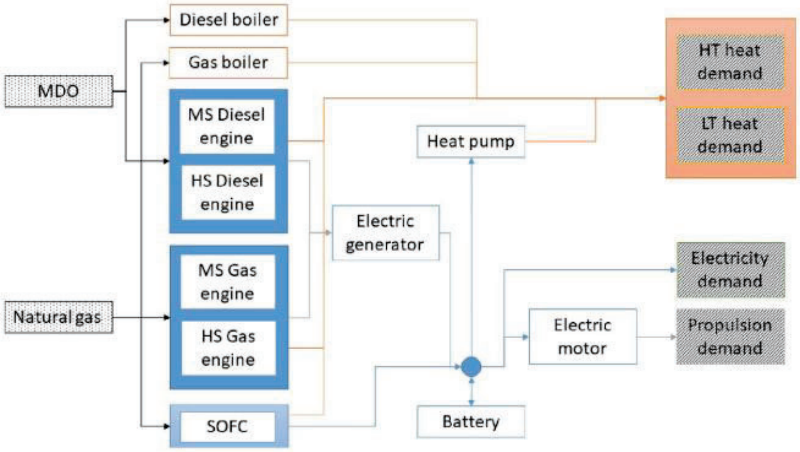

Figure 14- Proposed SOFC ship energy system (Baldi, 2020)

4.4. *Category 4 – Technologies that uses Low Carbon/Alternative Fuels*

4.4.1 Technology Evaluation

Fuels such as LNG, methanol, ethanol, biofuels, hydrogen, and ammonia have shown a CO_2 reduction range from 20% to 100%, with the specific potential varying based on the type of fuel (Xing, 2021).

LNG, compared to HFO, typically delivers a modest 10% reduction in GHGs. It is considered the most practical short-term option for cutting CO2 emissions due to its cost-effectiveness and the existing infrastructure (Balcombe, 2019).

Biofuels are highlighted for their compatibility with existing marine engines and potential to lower emissions of GHGs and pollutants. While presenting a renewable alternative, concerns around feedstock sustainability, environmental impact, and the need for technological integration persist.

Methanol and Ethanol offer cleaner burning options and does not contain sulphur.

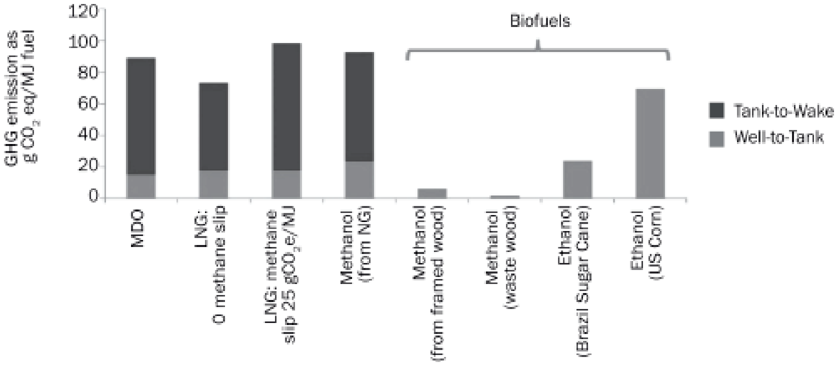

Figure 15: GHG emission from a case study (Radonja, 2019)

Ammonia is commonly produced in a commercial amount using the Haber-Bosch (H-B) process. A simplified block diagram is shown in Figure 16 (Al-Aboosi, 2021) on H-B process. Its economic and efficiency advantages, alongside significant environmental benefits, position it as a viable alternative for maritime fuel. However, challenges related to toxicity, storage, and the development of efficient propulsion technologies must be addressed.

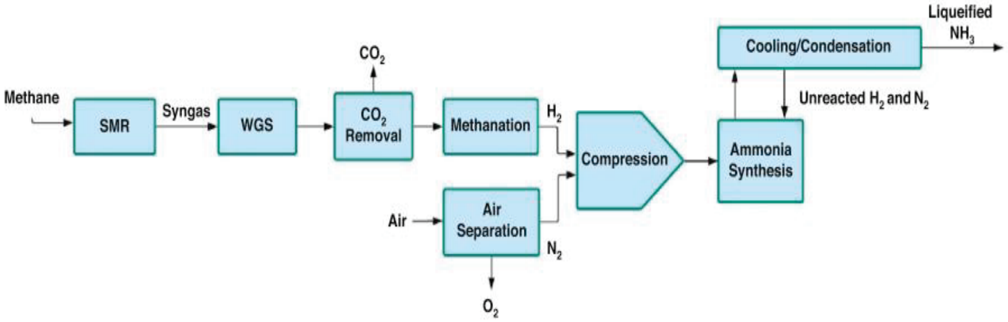

Figure 16: Simplified NH_3 production process using H-B process (Al-Aboosi, 2021).

Innovative Propulsion Technologies, such as green hydrogen and nuclear energy, represent cutting-edge approaches. Nuclear power, with its high energy density and operational efficiency, could drastically cut emissions if safety, regulatory, and public acceptance challenges can be surmounted.

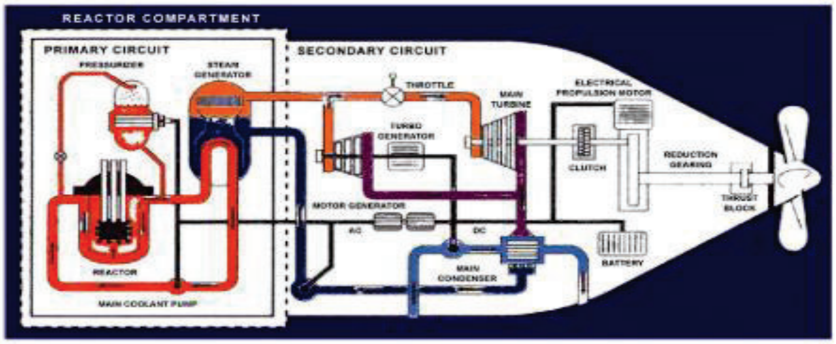

Figure 17: Pressurised Water Reactor based Nuclear Marine Propulsion (C. D. Kunze-2022)

5. Discussion

5.1. Category 1 – Technologies that uses fossil fuels.

Strength	*Electrolysed Seawater Wet Scrubbing: High Removal Efficiency:* Study (Yang, 2018) shows that this technology stands out for its ability to remove up to 92% of NOx emissions and nearly 100% of SOx emissions, showcasing remarkable efficiency in purifying ship exhaust gases.
	Energy Efficiency Methods: Optimizing structural design and propulsion systems with EEDI, SEEMP, and EEOI leads to significant fuel savings and reduced GHG emissions, supporting global climate change mitigation efforts.
	Operational Methods: Implementing effective operational methods decreases water resistance and selection of fuel-efficient paths thus drastically cutting fuel consumption, lowering GHG emissions and extending engine lifespan.

Challenges	*Regulatory Complexities:* The maritime industry operates globally under diverse regulations. Compliance with international, regional, and local standards, particularly in emission control areas (ECAs), requires extensive regulatory knowledge and operational flexibility.
	Technological and Operational Adaptability: *Integration with Existing Systems:* Advanced emission control technologies require not only physical space but also compatibility with existing propulsion and operational frameworks, which may not be designed for such integration. *Dynamic Maritime Environment:* The effectiveness of emission reduction operational methods are highly dependent on external conditions like weather, sea states, and port regulations. Adapting while maintaining efficiency and compliance adds complexity.

Opportunities	*Innovations in Scrubbing Technologies*: The development of wet scrubbing technology using electrolyzed seawater shows promise for reducing SOx and particulate matter emissions.
	Digitalization and AI in Operations: Integrating AI and big data into maritime operations allows real-time optimization of routes, speed, and fuel efficiency. These technologies can predict energy-efficient paths by considering weather, currents, and vessel specifics, leading to substantial emissions reductions.

Response	*Collaborative Efforts for Sustainable Practices:* The maritime industry increasingly values collaboration among shipbuilders, engine manufacturers, operators, regulators, and environmental advocates.
	Adaptation to Regulatory and Environmental Changes: In response to stricter regulations, ship operators are retrofitting vessels with emission control technologies and opting for environmentally sustainable new ships along with adopting digital technologies like AI and big data analytics for optimal route planning to reduce fuel consumption and emissions.

Evaluation	*Operational and Economic Benefits*: Beyond environmental benefits, these initiatives offer operational advantages, including fuel savings, enhanced engine lifespan, and reduced maintenance costs.
	Challenges and Adaptability: While commendable strides have been made, the articles highlight challenges of high initial costs, regulatory complexity, and the need for adaptability in technology and operations.

5.2. Category 2 – Technologies that uses renewable energy.

Strength	*Innovative Renewable Energy Technologies:* Modern solar panels are highly efficient, lightweight, and durable, designed for marine conditions. Wind-assisted propulsion systems, like flettner rotors, kites, wing sails, and soft sails, harness wind energy. Hybrid systems combining renewable and conventional power optimize energy use, reduce emissions, and provide versatile operational solutions.
	Economic Advantages: By reducing reliance on volatile fossil fuel markets, companies can achieve more predictable operational costs and long-term savings.

Challenge	*Technical and Logistical Challenges: Integration into Existing Designs:* Retrofitting ships with solar panels, wind-assisted propulsion, or hybrid power is complex, requiring extensive structural modifications and sophisticated new electrical systems. *Intermittent Nature of Renewable Energy:* Wind and solar energy are variable and intermittent, making it challenging to maintain a stable and reliable onboard power supply.
	Economic Considerations: Long Payback Periods: High initial investment costs and long payback periods may deter companies from adopting green technologies.

Opportunities	*Innovative Wind Propulsion Mechanisms:* Optimized rotor sails, automated kites, and advanced wing sails enhance performance and adapt to varying wind conditions.
	High-Capacity, Lightweight Battery Systems: Advanced battery technologies like solid-state batteries and supercapacitors offer higher energy density, faster charging, and improved safety, essential for storing renewable energy and ensuring a stable power supply during voyages.
	Integration of Digital Technologies: AI and machine learning can optimize energy usage based on load demand, weather, and battery status.

Response	*Policy Development and Regulatory Support:* Governments and international organizations are offering incentives and subsidies to offset the high initial costs of renewable energy adoption, encouraging shipping companies to transition.

Evaluation	Integrating new technologies into existing fleets poses technical and logistical challenges, along with significant economic investment. Advances in renewable energy, energy storage, and digitized energy management can help overcome these barriers. Achieving sustainable maritime practices with renewable energy requires ongoing innovation, supportive policies, and global cooperation.

5.3. Category 3 – Technologies that uses Fuel Cells

Strength	*PEM* Fuel Cells offer rapid start-up times and high-power density, crucial for maritime vessels' dynamic power needs. A 2018 study by Matulić showed significant environmental benefits, reducing diesel fuel consumption by 9% and CO2 emissions by 5.5% in a one-hour voyage simulation.
	SOFC's efficiency levels often exceeding 60% and potentially reaching over 85% in combined heat and power (CHP) systems, mark a significant stride towards reducing fuel consumption and operational costs (Micoli, 2021).

Challenges	*Hydrogen Infrastructure:* The widespread adoption of hydrogen fuel cells faces challenges in hydrogen production, storage, safety, and bunkering facilities.
	Regulatory and Safety Standards: *Regulatory Framework:* Comprehensive regulations for the unique challenges and safety of hydrogen fuel cells in maritime applications are not yet fully developed. *Safety Considerations:* Hydrogen, the primary fuel for many fuel cell systems, is highly flammable and difficult to detect leaks, posing significant safety challenges.

Opportunities	*Technological Innovations:* Advancements in materials science and system design are essential for improving fuel cell performance and integration into maritime vessels, making them more appealing to shipowners and operators
	Regulatory Momentum: Through incentives, subsidies, and regulations supporting clean energy adoption boosts the attractiveness of fuel cell solutions for maritime use, fostering investment and innovation.

Response	*Enhanced Research and Development Initiatives:* Effective integration of fuel cell systems into vessel designs requires collaboration between shipbuilders, fuel cell manufacturers, regulators, and maritime operators
	Educational and Training Programs: Adopting fuel cells widely necessitates training ship crews on their operation, maintenance, and hydrogen fuel safety protocols.

Evaluation	*Technological Maturity and Infrastructure Development:* Advancements in fuel cell design, materials science, and system integration, along with hydrogen production, storage, and distribution networks, are essential for the technology's feasibility and success.
	Regulatory Frameworks and Safety Standards: A crucial part of the evaluation process is creating regulatory frameworks and safety standards for fuel cell technology. These regulations must balance safety and innovation, ensuring fuel cell adoption does not compromise maritime safety.

5.4. Category 4 – Technologies that uses Low Carbon/Alternative Fuels

Strength	*Economic and Efficiency Advantages:* Adopting alternative fuels in propulsion technologies can improve maritime operations' efficiency. Using biofuels and green hydrogen in engines and fuel cells enhances energy efficiency, reducing fuel consumption and operational costs.
	Environmental Benefits: By switching to alternatives like ammonia, biofuels, methanol, and green hydrogen, the maritime industry can significantly lower its CO_2, SOx, and NOx emissions.

Challenge	*Storage and Handling:* Ammonia, ethanol, and methanol pose significant storage and handling challenges.
	Economic Barriers: Transitioning to alternative fuels requires significant costs for building new ships or retrofitting existing ones.
	Regulatory and Infrastructure Readiness: *Lack of Global Regulatory Framework:* The maritime sector lacks a comprehensive regulatory framework for alternative fuels, causing uncertainty for shipowners about future compliance and investments. *Infrastructure Development:* Widescale adoption of alternative fuels requires significant development in fuelling infrastructure, which is currently insufficient.

Opportunities	*Regulatory Frameworks and Incentives:* The development and implementation of comprehensive regulatory frameworks and incentives play a vital role in accelerating the transition to alternative fuels.
	Infrastructure Development and Global Standards: Establishing the necessary fuelling infrastructure for new fuels at major ports around the world is essential for their widespread adoption.

Responses	*Industry-Wide Collaboration and Partnerships:* Forming joint ventures between maritime companies, engine manufacturers, and research institutions to speed up technological advancements and commercialize new fuel systems.
	Financial Mechanisms and Incentives: Implementing government subsidies and grants for research into alternative fuels and for retrofitting existing vessels with new propulsion systems.

Evaluation	*Technological Readiness and Innovation:* Scaling new low-carbon or alternative fuel technologies and integrating them into existing fleets pose significant challenges.
	Economic Viability: While alternative fuels offer long-term environmental and regulatory benefits, their short-term economic impact is a considerable challenge for many operators.
	Regulatory and Policy Frameworks: A harmonized international regulatory approach would facilitate a smoother transition and enable a more level playing field.

6. Impact on Naval Sector

Among the 115 articles shortlisted for this study, only 9 were relevant to the naval sector. This limited number of relevant papers can be attributed to the niche and specialized nature of naval operations, which necessitate unique technological adaptations, stringent regulatory and safety compliance, rendering general studies on marine technologies not always directly applicable or sufficient for naval needs. The assessed papers mainly focused on the use of nuclear fuel, hybrid systems, and fuel cells for power generation.

Nuclear fuel offers the advantage of providing high energy density and continuous power output for long-duration missions without generating GHG emissions. However, it poses significant challenges in terms of safety, radioactive waste management, and high initial investment costs. A study by Balcombe in 2019 estimated that in 2016, there were 166 operational naval reactors: 85 owned by the US, 48 by Russia, and 33 spread across other countries. At the same time, only four commercial nuclear vessels have existed, with only one active at 2019 (Balcombie, 2019).

Hybrid systems can significantly reduce GHG emissions by optimizing fuel consumption and enhancing energy efficiency. However, they present disadvantages, such as the complexity of integration, space margins higher maintenance requirements, and the need for sophisticated energy management systems to balance power loads effectively (Gaber, 2021).

Fuel cells are another promising technology for reducing GHG emissions in naval operations. They offer high efficiency, low noise, and almost no GHG emissions. From a naval perspective, other advantages of fuel cells include their scalability for different vessel sizes, silent propulsion, low thermal and acoustic signatures, low maintenance requirements, and the possibility of air independence. However, fuel cells face disadvantages such as high costs, limited hydrogen infrastructure, and challenges related to hydrogen storage and handling (van Rheenen, 2022).

7. Conclusion

Across all categories, the industry faces common challenges, including high initial costs, regulatory complexities, and the need for global collaboration for widespread implementation. Transitioning to sustainable maritime operations involves not only choosing the right technologies but also fostering an ecosystem that supports innovation, infrastructure development, and regulatory flexibility.

Fossil fuel technologies align with the 2030 IMO checkpoints, but broader adoption and further innovation are needed to meet the 2040 goals. Despite their ability to reduce environmental impact, economic and regulatory hurdles could slow their implementation without significant advancements.

Renewable energy technologies, like solar and wind propulsion systems, are emerging as feasible alternatives that could transform maritime operations and meet both the 2030 and 2040 IMO emission reduction targets. However, integration challenges, intermittent energy supplies, and high initial costs remain barriers.

Fuel cells, particularly PEM fuel cells, show significant potential for reducing maritime emissions, with several pilot projects indicating a move towards mainstream adoption. By 2040, advancements in PEM and SOFC technologies could enable broader application across various vessel types. However, technological maturity, cost issues, and the need for a global hydrogen infrastructure are critical factors affecting adoption.

Alternative fuels such as ammonia, biofuels, methanol, and ethanol are progressing towards commercial viability and could align with the IMO's short-term emission goals. The medium to long-term potential of these fuels, along with green hydrogen and nuclear propulsion, depends on overcoming substantial technological and infrastructural challenges.

In comparing various technologies, three main challenges/benefits are noted as below:

i) Environmental Impact: Renewable energy and fuel cells offer significant emission reductions. Fossil fuel technologies, while beneficial, involve trade-offs like operational changes and potential environmental risks.

ii) Economic and Operational Benefits: All technologies promise long-term savings, but renewable energy and alternative fuels face high upfront costs. Fossil fuel technologies offer more immediate economic benefits due to their maturity and existing infrastructure.

iii) Regulatory and Adoption Challenges: Fuel cells and alternative fuels face substantial barriers in regulatory acceptance and necessary infrastructure development. Fossil fuel and renewable energy technologies have more straightforward paths to integration despite facing some regulatory hurdles.

8. Future Work

To further accelerate the adoption of these technologies, future research should focus on:

Enhancing the efficiency and integration of renewable energy systems within maritime vessels to address the challenges of energy intermittency and storage.

Scaling up the production and infrastructure for fuel cells to better meet the operational demands of larger vessels.

Interdisciplinary studies that integrate technological advancements with economic, policy, and environmental considerations to facilitate a smoother transition to greener technologies.

References

Al-Aboosi, FY, El-Halwagi, MM, Moore, M & Nielsen, RB 2021, 'Renewable ammonia as an alternative fuel for the shipping industry', Current Opinion in Chemical Engineering.

Balcombe, P, Brierley, J, Lewis, C, Skatvedt, L, Speirs, J, Hawkes, A & Staffell, I 2019, 'How to decarbonise international shipping: Options for fuels, technologies and policies', Energy Conversion and Management.

Baldi, F, Moret, S, Tammi, K & Maréchal, F 2020, 'The role of solid oxide fuel cells in future ship energy systems', Energy.

Cavo, M, Gadducci, E, Rattazzi, D, Rivarolo, M & Magistri, L 2021, 'Dynamic analysis of PEM fuel cells and metal hydrides on a zero-emission ship: A model-based approach', International Journal of Hydrogen Energy.

Cheng, P, Pan, T, Li, R & Liang, N 2022, 'Research on optimal matching of renewable energy power generation system and ship power system', IET Renewable Power Generation

Dolatabadi, SH, Ölçer, AI & Vakili, S 2023, 'The Application of Hybrid Energy system (Hydrogen Fuel cell, wind, and solar) in shipping', Renewable Energy Focus.

DNV - IMO GHG revised 2023 strategy, https://www.dnv.com/maritime/hub/decarbonize-shipping/key-drivers/regulations/imo-regulations/ghg-vision/

Elkafas, AG & Shouman, MR 2021, 'ASSESSMENT OF ENERGY EFFICIENCY AND SHIP EMISSIONS FROM SPEED REDUCTION MEASURES ON A MEDIUM SIZED CONTAINER SHIP', International Journal of Maritime Engineering.

Gabbar, HA, Adham, MI & Abdussami, MR 2021, 'Analysis of nuclear-renewable hybrid energy system for marine ships', Energy Reports.

Ghenai, C, Bettayeb, M, Brdjanin, B & Hamid, AK 2019, 'Hybrid solar PV/PEM fuel Cell/Diesel Generator power system for cruise ship: A case study in Stockholm, Sweden', Case Studies in Thermal Engineering.

Huang, MY, He, W, Incecik, A, Cichon, A, Królczyk, G & Lie, ZX 2021, 'Renewable energy storage and sustainable design of hybrid energy powered ships: A case study', Journal of Energy Storage.

IMO 2021, Fourth IMO GHG Study 2020. https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

Jimenez, VJ, Kim, H & Munim, ZH 2022, 'A review of ship energy efficiency research and directions towards emission reduction in the maritime industry', Journal of Cleaner Production.

Lindstad, E, Borgen, H, Eskeland, GS, Paalson, C, Psaraftis, H & Turan, O 2019, 'The Need to Amend IMO's EEDI to Include a Threshold for Performance in Waves (Realistic Sea Conditions) to Achieve the Desired GHG Reductions', Sustainability.

Matulić, N 'SIMULATION OF FUEL AND EMISSION BENEFIT ON A RANDOM SHIP VOYAGE BY POWERING THE AUXILIARY CONSUMERS WITH PEM FUEL CELL' 2018.

Micoli, L, Coppola, T & Turco, M 2021, 'A case study of a solid oxide fuel cell plant on board a cruise ship', Journal of Marine Science and Application.

Radonja, R, Bebic, D & Glujic, D 2019, 'METHANOL AND ETHANOL AS ALTERNATIVE FUELS FOR SHIPPING', Promet-Traffic & Transportation.

Pham, V, Kim, H, Choi, JH, Nyongesa, AJ, Kim, J, Jeon, H & Lee, WJ 2022, 'Effectiveness of the Speed Reduction Strategy on Exhaust Emissions and Fuel Oil Consumption of a Marine Generator Engine for DC Grid Ships', Journal of Marine Science and Engineering.

Saloniemi, V-M 2022, 'Space demand of a hydrogen fuel cell powered propulsion system in a passenger cruise ship'.

Setiawan, B, Putra, ES & Siradjuddin, I 2021, 'Hybrid renewable energy photovoltaic and darrieus VAWT as propulsion fuel of prototype catamaran ship', Bulletin of Electrical Engineering and Informatics.

Stamatakis, ME & Ioannides, MG 2021, 'State Transitions Logical Design for Hybrid Energy Generation with Renewable Energy Sources in LNG Ship', Energies.

Wang, Y, Zhang, X, Lin, S, Qiang, Z, Hao, J & Qiu, Y 2022, 'Analysis on the Development of Wind-assisted Ship Propulsion Technology and Contribution to Emission Reduction', in IOP Conference Series: Earth and Environmental Science

Xiaoliang, D 2020, 'Ship Energy Saving And Emission Reduction', in E3S Web of Conferences.

Xing, H, Stuart, C, Spence, S & Chen, H 2021, 'Alternative fuel options for low carbon maritime transportation: Pathways to 2050', Journal of Cleaner Production.

Yang, S, Pan, X, Han, Z, Zhao, D, Liu, B, Zheng, D & Yan, Z 2018, 'Removal of NOx and SO2 from simulated ship emissions using wet scrubbing based on seawater electrolysis technology', Chemical Engineering Journal.

Appendix A: Articles shortlisted for this study.

Ait Allal, A, Mansouri, K, Youssfi, M & Qbadou, M 2019, 'Ship operational measures implementation’s impact on energy-saving and GHG emission', in Advanced Intelligent Systems for Sustainable Development (AI2SD’2018) Vol 2: Advanced Intelligent Systems Applied to Energy.

Aksoyoglu, S, Jiang, JH, Ciarelli, G, Baltensperger, U & Prévôt, ASH 2020, 'Role of ammonia in European air quality with changing land and ship emissions between 1990 and 2030', Atmospheric Chemistry and Physics.

Al-Aboosi, FY, El-Halwagi, MM, Moore, M & Nielsen, RB 2021, 'Renewable ammonia as an alternative fuel for the shipping industry', Current Opinion in Chemical Engineering.

Al-Douri, A, Alsuhaibani, AS, Moore, M, Nielsen, RB, El-Baz, AA & El-Halwagi, MM 2022, 'Greenhouse gases emissions in liquified natural gas as a marine fuel: Life cycle analysis and reduction potential', Canadian Journal of Chemical Engineering.

Ammar, NR & Seddiek, IS 2020, 'An environmental and economic analysis of emission reduction strategies for container ships with emphasis on the improved energy efficiency indexes', Environmental Science and Pollution Research.

Ankathi, S, Lu, ZF, Zaimes, GG, Hawkins, T, Gan, Y & Wang, M 2022, 'Greenhouse gas emissions from the global transportation of crude oil: Current status and mitigation potential', Journal of Industrial Ecology.

Atilhan, S, Park, S, El-Halwagi, MM, Atilhan, M, Moore, M & Nielsen, RB 2021, 'Green hydrogen as an alternative fuel for the shipping industry', Current Opinion in Chemical Engineering.

Baldi, F, Moret, S, Tammi, K & Maréchal, F 2020, 'The role of solid oxide fuel cells in future ship energy systems', Energy.

Balcombe, P, Brierley, J, Lewis, C, Skatvedt, L, Speirs, J, Hawkes, A & Staffell, I 2019, 'How to decarbonise international shipping: Options for fuels, technologies and policies', Energy Conversion and Management.

Benet, A, Villalba-Herreros, A, Amore-Domenech, R & Leo, TJ 2022, 'Knowledge gaps in fuel cell-based maritime hybrid power plants and alternative fuels', Journal of Power Sources.

Boekhout, M 2020, 'Hydrogen Powered Ship Propulsion for High-Speed Craft: The implementation of Fuel Cell Battery Propulsion Systems'.

Bortuzzo, V, DE DOMENICO, M & Bucci, V 2022, 'Strategies for Ship Decarbonisation: Technical Measure for Reducing Energy Efficiency Existing Ship Index', in Technology and Science for the Ships of the Future, IOS Press.

Cai, AD & Rozario, Z 2022, 'Direct Ammonia Fuel Cells A general overview, current technologies and future directions', Johnson Matthey Technology Review.

Cavo, M, Gadducci, E, Rattazzi, D, Rivarolo, M & Magistri, L 2021, 'Dynamic analysis of PEM fuel cells and metal hydrides on a zero-emission ship: A model-based approach', International Journal of Hydrogen Energy.

Center, ENR 'An Intelligent Energy Management System for Ship Hybrid Power System Based on Renewable Energy Resources'.

Chalfant, J, Kite-Powell, H, Bonfiglio, L & Chryssostomidis, C 2022, 'Decarbonization of the Cargo Shipping Fleet', Journal of Ship Production and Design.

Chen, JH, Fei, YJ & Wan, Z 2019, 'The relationship between the development of global maritime fleets and GHG emission from shipping', Journal of Environmental Management.

Cheng, P, Liang, N, Li, R, Lan, H & Cheng, Q 2019, 'Analysis of influence of ship roll on ship power system with renewable energy', Energies.

Cheng, P, Pan, T, Li, R & Liang, N 2022, 'Research on optimal matching of renewable energy power generation system and ship power system', IET Renewable Power Generation.

Cherkaev, GV 2021, 'Analysis of pollutant emissions from marine engines when burning traditional and alternative fuels', Marine Intellectual Technologies.

Chin, CS, Tan, YJ & Kumar, MV 2022, 'Study of Hybrid Propulsion Systems for Lower Emissions and Fuel Saving on Merchant Ship during Voyage', Journal of Marine Science and Engineering.

Chiong, MC, Kang, HS, Shaharuddin, NMR, Mat, S, Quen, LK, Ten, KH & Ong, MC 2021, 'Challenges and opportunities of marine propulsion with alternative fuels', Renewable & Sustainable Energy Reviews.

d'Amore, F & Romano, MC 2023, 'Optimal ship-based CO2 transport chains from Mediterranean emission points to the North Sea', in Computer Aided Chemical Engineering, Elsevier.

DNV - IMO GHG revised 2023 strategy, https://www.dnv.com/maritime/hub/decarbonize-shipping/key-drivers/regulations/imo-regulations/ghg-vision/

Dolatabadi, SH, Ölçer, AI & Vakili, S 2023, 'The Application of Hybrid Energy system (Hydrogen Fuel cell, wind, and solar) in shipping', Renewable Energy Focus.

Eide, IS & Weidemann, MAT 2023, 'Concept Development of a Sailing Cruise Ship Powered by Alternative Fuel'.

Elkafas, AG & Shouman, MR 2021, 'ASSESSMENT OF ENERGY EFFICIENCY AND SHIP EMISSIONS FROM SPEED REDUCTION MEASURES ON A MEDIUM SIZED CONTAINER SHIP', International Journal of Maritime Engineering.

Feng, Y, Zhu, H & Dong, Z 2022, 'Simultaneous and Global Optimizations of LNG Fueled Hybrid Electric Ship for Substantial Fuel Cost, CO2 and Methane Emission Reduction', IEEE Transactions on Transportation Electrification.

Feng, YB, Zhu, HJ & Dong, ZM 2023, 'Simultaneous and Global Optimizations of LNG-Fueled Hybrid Electric Ship for Substantial Fuel Cost, CO₂, and Methane Emission Reduction', IEEE Transactions on Transportation Electrification.

Foretich, A, Zaimes, GG, Hawkins, TR & Newes, E 2021, 'Challenges and opportunities for alternative fuels in the maritime sector', Maritime Transport Research.

Gabbar, HA, Adham, MI & Abdussami, MR 2021, 'Analysis of nuclear-renewable hybrid energy system for marine ships', Energy Reports.

Gan, S 2022, 'Alternative Fuel for Ship Propulsion', in Encyclopedia of Ocean Engineering.

Ghaemi, MH & Zeraatgar, H 2022, 'Negative impact of constant RPM control strategy on ship NOx emission in waves', International Journal of Energy and Environmental Engineering.

Ghenai, C, Bettayeb, M, Brdjanin, B & Hamid, AK 2019, 'Hybrid solar PV/PEM fuel Cell/Diesel Generator power system for cruise ship: A case study in Stockholm, Sweden', Case Studies in Thermal Engineering.

Gila, CL 2020, 'Alternative marine fuel transition: a multi-criteria appraisal with insights for container ship operators'.

Goicoechea, N & Abadie, LM 2021, 'Optimal Slow Steaming Speed for Container Ships under the EU Emission Trading System', Energies.

Gusti, AP, Semin Dinariyana, A, Irawan, MI & Furusho, M 2019, 'Reduction in ship fuel consumption and emission by sailing at slow speeds', J. Mar. Sci. Eng.

Hederić, Ž, Vučinić, D, Brlić, M, Bezovnik, M, Rutnik, I, Cuković, M, Čačić, M, Hmura, A, Jukić, D & Švarcmajer, M 2022, 'Conceptual Design of Zero-Emission Sailing Ship Renewable Energy Challenges', in Applications of Computation in Mechanical Engineering: Select Proceedings of 3rd International Conference on Computing in Mechanical Engineering (ICCME 2021).

Herdzik, J 2021, 'Decarbonization of Marine Fuels-The Future of Shipping', Energies.

Hessevik, A 2022, 'Green shipping networks as drivers of decarbonization in offshore shipping companies', Maritime Transport Research.

Huang, MY, He, W, Incecik, A, Cichon, A, Królczyk, G & Lie, ZX 2021, 'Renewable energy storage and sustainable design of hybrid energy powered ships: A case study', Journal of Energy Storage.

İNAL, ÖB & Deniz, C 2021, 'Emission analysis of LNG fuelled molten carbonate fuel cell system for a chemical tanker ship: a case study', Marine Science and Technology Bulletin.

Inal, OB, Zincir, B & Deniz, C 2022, 'Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia', International Journal of Hydrogen Energy.

Irena, K, Ernst, W & Alexandros, CG 2021, 'The cost-effectiveness of CO2 mitigation measures for the decarbonisation of shipping. The case study of a globally operating ship-management company', Journal of Cleaner Production.

Jimenez, VJ, Kim, H & Munim, ZH 2022, 'A review of ship energy efficiency research and directions towards emission reduction in the maritime industry', Journal of Cleaner Production.

Karvounis, P, Dantas, JL, Tsoumpris, C & Theotokatos, G 2022, 'Ship power plant decarbonisation using hybrid systems and ammonia fuel—A techno-economic–environmental analysis', Journal of Marine Science and Engineering.

Karvounis, P, Dantas, JLD, Tsoumpris, C & Theotokatos, G 2022, 'Ship Power Plant Decarbonisation Using Hybrid Systems and Ammonia Fuel-A Techno-Economic-Environmental Analysis', Journal of Marine Science and Engineering.

Kesieme, U, Pazouki, K, Murphy, A & Chrysanthou, A 2019, 'Biofuel as an alternative shipping fuel: technological, environmental and economic assessment', Sustainable Energy & Fuels.

Kim, K, Roh, G, Kim, W & Chun, K 2020, 'A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments', Journal of Marine Science and Engineering.

Kiss, AA, Zondervan, E, Lakerveld, R & Özkan, L 'From renewable energy to ship fuel: ammonia as an energy vector and mean for energy storage'.

Kistner, L 2023, 'Potentials and challenges of the fuel cell technology for ship applications. A comprehensive techno-economic and environmental assessment of maritime power system configurations'.

Klakeel, TM, Anantharaman, M, Islam, R & Garaniya, V 2023, 'Effectiveness of Current Technology in GHG Reduction - A literature Survey', Transnav-International Journal on Marine Navigation and Safety of Sea Transportation.

Kunze, CD 2022, 'The role of generation IV nuclear reactors in decarbonising international shipping: a multi-criteria decision making (MCDM) framework for matching potential decarbonisation pathways to different ship types and size'.

Law, LC, Mastorakos, E & Evans, S 2022, 'Estimates of the Decarbonization Potential of Alternative Fuels for Shipping as a Function of Vessel Type, Cargo, and Voyage', Energies.

Lee, HY 2020, 'Comparative Analysis of On-board Methane and Methanol Reforming Systems combined with HT-PEM Fuel Cell for Hydrogen Fueled Ship Application'.

Lindstad, E, Borgen, H, Eskeland, GS, Paalson, C, Psaraftis, H & Turan, O 2019, 'The Need to Amend IMO's EEDI to Include a Threshold for Performance in Waves (Realistic Sea Conditions) to Achieve the Desired GHG Reductions', Sustainability.

Lindstad, E, Lagemann, B, Rialland, A, Gamlem, GM & Valland, A 2021, 'Reduction of maritime GHG emissions and the potential role of E-fuels', Transportation Research Part D-Transport and Environment.

Livaniou, S & Papadopoulos, GA 2022, 'Liquefied Natural Gas (LNG) as a Transitional Choice Replacing Marine Conventional Fuels (Heavy Fuel Oil/Marine Diesel Oil), towards the Era of Decarbonisation', Sustainability.

Mäkitie, T, Steen, M, Saether, EA, Bjorgum, O & Poulsen, RT 2022, 'Norwegian ship-owners' adoption of alternative fuels', Energy Policy.

Mao, X, Ying, R, Yuan, Y, Li, F & Shen, B 2021, 'Simulation and analysis of hydrogen leakage and explosion behaviors in various compartments on a hydrogen fuel cell ship', International Journal of Hydrogen Energy.

Matulić, N 'SIMULATION OF FUEL AND EMISSION BENEFIT ON A RANDOM SHIP VOYAGE BY POWERING THE AUXILIARY CONSUMERS WITH PEM FUEL CELL'.

McKinlay, CJ, Turnock, SR & Hudson, DA 2021, 'Fuel cells for shipping: To meet on-board auxiliary demand and reduce emissions', Energy Reports.

Meng, L, Wang, X, Jin, J & Han, C 2023, 'Optimization Model for Container Liner Ship Scheduling Considering Disruption Risks and Carbon Emission Reduction', Journal of Marine Science and Engineering.

Micoli, L, Coppola, T & Turco, M 2021, 'A case study of a solid oxide fuel cell plant on board a cruise ship', Journal of Marine Science and Application.

Mihail-Vlad, V, Fanel-Viorel, PM & Panaitescu 2020, 'Renewable energy and devices onboard ship', Journal of Marine Technology and Environment Year 2020.

Moshiul, AM, Mohammad, R & Hira, FA 2023, 'Alternative Fuel Selection Framework toward Decarbonizing Maritime Deep-Sea Shipping', Sustainability.

Mukherjee, A, Bruijnincx, P & Junginger, M 2020, 'A Perspective on Biofuels Use and CCS for GHG Mitigation in the Marine Sector', Iscience.

Oh, D, Cho, D-S & Kim, T-W 2023, 'Design and evaluation of hybrid propulsion ship powered by fuel cell and bottoming cycle', International Journal of Hydrogen Energy.

Olberg, VR 2022, 'Thermal energy recovery and storage for a hydrogen fuel cell and battery driven cruise ship.

Pawelec, A, Chmielewski, AG, Sun, YX, Bulka, S, Torims, T, Pikurs, G & Mattausch, G 2021, 'Plasma technology to remove NOx from off-gases', Nukleonika.

Pelic, V, Mrakovcic, T, Radonja, R & Valcic, M 2020, 'Analysis of the Impact of Split Injection on Fuel Consumption and NO Emissions of Marine Medium-Speed Diesel Engine', Journal of Marine Science and Engineering.

Pham, V, Kim, H, Choi, JH, Nyongesa, AJ, Kim, J, Jeon, H & Lee, WJ 2022, 'Effectiveness of the Speed Reduction Strategy on Exhaust Emissions and Fuel Oil Consumption of a Marine Generator Engine for DC Grid Ships', Journal of Marine Science and Engineering.

Puskár, M, Kopas, M, Sabadka, D, Kliment, M & Soltésová, M 2020, 'Reduction of the Gaseous Emissions in the Marine Diesel Engine Using Biodiesel Mixtures', Journal of Marine Science and Engineering.

Puskár, M, Tarbajovsky, P, Lavcák, M & Soltésová, M 2022, 'Marine Ancillary Diesel Engine Emissions Reduction Using Advanced Fuels', Journal of Marine Science and Engineering.

Qi, M, Zheng, J & Ni, L 2021, 'Optimization of ship speeds and sailing paths under emission control areas: From the perspective of a single liner shipping service', in 2021 6th International Conference on Automation, Control and Robotics Engineering (CACRE).

Radonja, R, Bebic, D & Glujic, D 2019, 'METHANOL AND ETHANOL AS ALTERNATIVE FUELS FOR SHIPPING', Promet-Traffic & Transportation.

Reusser, CA & Osses, JRP 2021, 'Challenges for Zero-Emissions Ship', Journal of Marine Science and Engineering.

Rodriguez, CG, Lamas, MI, Rodríguez, JD & Abbas, A 2022, 'Possibilities of Ammonia as Both Fuel and NO Reductant in Marine Engines: A Numerical Study', Journal of Marine Science and Engineering.

Russo, R, Coppola, T, Micoli, L & Pietra, A 2023, 'Preliminary Investigation of a Multi-MW Solid Oxide Fuel Cell Power Plant to be Installed on Board a Cruise Ship', Chemical Engineering Transactions.

Saloniemi, V-M 2022, 'Space demand of a hydrogen fuel cell powered propulsion system in a passenger cruise ship'.

Sánchez, A, Rengel, MM & Martín, M 2023, 'A zero CO2 emissions large ship fuelled by an ammonia-hydrogen blend: Reaching the decarbonisation goals', Energy Conversion and Management.

Savu, SV, Marin, RC, David, A, Olei, AB, Dumitru, I, Tarnita, D, Maternova, A & Savu, ID 2022, 'Reducing NOx Emissions through Microwave Heating of Aftertreatment Systems for Sustainable Transport in the Inland Waterway Sector', Sustainability.

Schwarzkopf, DA, Petrik, R, Hahn, J, Ntziachristos, L, Matthias, V & Quante, M 2023, 'Future Ship Emission Scenarios with a Focus on Ammonia Fuel', Atmosphere.

Setiawan, B, Putra, ES & Siradjuddin, I 2021, 'Hybrid renewable energy photovoltaic and darrieus VAWT as propulsion fuel of prototype catamaran ship', Bulletin of Electrical Engineering and Informatics.

Seyam, S, Dincer, I & Agelin-Chaab, M 2023, 'An innovative study on a hybridized ship powering system with fuel cells using hydrogen and clean fuel blends', Applied Thermal Engineering.

Shakeri, N, Zadeh, M & Nielsen, JB 2020, 'Hydrogen Fuel Cells for Ship Electric Propulsion: Moving Toward Greener Ships', Ieee Electrification Magazine.

Stamatakis, ME & Ioannides, MG 2021, 'State Transitions Logical Design for Hybrid Energy Generation with Renewable Energy Sources in LNG Ship', Energies.

Stark, C, Xu, YX, Zhang, M, Yuan, ZM, Tao, LB & Shi, WC 2022, 'Study on Applicability of Energy-Saving Devices to Hydrogen Fuel Cell-Powered Ships', Journal of Marine Science and Engineering.

Stathatou, PM, Bergeron, S, Fee, C, Jeffrey, P, Triantafyllou, M & Gershenfeld, N 2022, 'Towards decarbonization of shipping: direct emissions & life cycle impacts from a biofuel trial aboard an ocean-going dry bulk vessel', Sustainable Energy & Fuels.

Sui, CB, de Vos, P, Stapersma, D, Visser, K & Ding, Y 2020, 'Fuel Consumption and Emissions of Ocean-Going Cargo Ship with Hybrid Propulsion and Different Fuels over Voyage', Journal of Marine Science and Engineering.

Tan, ECD, Harris, K, Tifft, SM, Steward, D, Kinchin, C & Thompson, TN 2022, 'Adoption of biofuels for marine shipping decarbonization: A long-term price and scalability assessment', Biofuels Bioproducts & Biorefining.

Tavakoli, S 2021, 'Ship Propulsion Dynamics and Emissions Gas Engine Methane Slip Reduction at Dynamic Loads'.

Thies, F & Ringsberg, JW 2023, 'Wind-assisted, electric, and pure wind propulsion - the path towards zero-emission RoRo ships', Ships and Offshore Structures.

Tran, NK & Lam, JSL 2022, 'Effects of container ship speed on CO2 emission, cargo lead time and supply chain costs', Research in Transportation Business & Management.

Trodden, D & Haroutunian, M 2018, 'Effects of ship manœuvring motion on NOX formation', Ocean Engineering.

Vairo, T, Cademartori, D, Clematis, D, Carpanese, MP & Fabiano, B 2023, 'Solid oxide fuel cells for shipping: A machine learning model for early detection of hazardous system deviations', Process Safety and Environmental Protection.

van Rheenen, E, Padding, J, Slootweg, C & Visser, K 2022, 'A review of the potential of hydrogen carriers for zero emission, low signature ship propulsion systems', in Conference Proceedings of INEC.

Wang, X, Mi, X, Lv, X & Weng, Y 2022, 'Fast and stable operation approach of ship solid oxide fuel cell-gas turbine hybrid system under uncertain factors', International Journal of Hydrogen Energy.

Wang, Y, Cao, Q, Liu, L, Wu, Y, Liu, H, Gu, Z & Zhu, C 2022, 'A review of low and zero carbon fuel technologies: Achieving ship carbon reduction targets', Sustainable Energy Technologies and Assessments.

Wang, Y, Zhang, X, Lin, S, Qiang, Z, Hao, J & Qiu, Y 2022, 'Analysis on the Development of Wind-assisted Ship Propulsion Technology and Contribution to Emission Reduction', in IOP Conference Series: Earth and Environmental Science.

Wu, S, Miao, B & Chan, SH 2022, 'Feasibility assessment of a container ship applying ammonia cracker-integrated solid oxide fuel cell technology', International Journal of Hydrogen Energy.

Xiaoliang, D 2020, 'Ship Energy Saving And Emission Reduction', in E3S Web of Conferences.

Xing, H, Stuart, C, Spence, S & Chen, H 2021, 'Alternative fuel options for low carbon maritime transportation: Pathways to 2050', Journal of Cleaner Production.

Xu, H & Yang, D 2020, 'LNG-fuelled container ship sailing on the Arctic Sea: Economic and emission assessment', Transportation Research Part D: Transport and Environment.

Xu, X & Wang, S 2020, 'Comprehensive utilization system of waste heat of hydrogen fuel cell powered ship', in IOP Conference Series: Earth and Environmental Science.

Yang, JC, Tang, TB, Jiang, Y, Karavalakis, G, Durbin, TD, Miller, JW, Cocker, DR & Johnson, KC 2021, 'Controlling emissions from an ocean-going container vessel with a wet scrubber system'.

Yang, S, Pan, X, Han, Z, Zhao, D, Liu, B, Zheng, D & Yan, Z 2018, 'Removal of NOx and SO2 from simulated ship emissions using wet scrubbing based on seawater electrolysis technology', Chemical Engineering Journal.

Yin, J, Yang, J, Li, G, Huo, Q, Wei, T & Xin, K 2019, 'Research on Integration Model of Shore-to-ship Power Supply System with High Proportion Renewable Energy', in IOP Conference Series: Earth and Environmental Science.

Yu, H, Fang, Z, Fu, X, Liu, J & Chen, J 2021, 'Literature review on emission control-based ship voyage optimization', Transportation Research Part D: Transport and Environment.

Yuksel, O & Koseoglu, B 2023, 'Numerical simulation of the hybrid ship power distribution system and an analysis of its emission reduction potential', Ships and Offshore Structures.

Zou, JH & Yang, B 2023, 'Evaluation of alternative marine fuels from dual perspectives considering multiple vessel sizes', Transportation Research Part D-Transport and Environment.

Design for Adaptation - Ships and the Systems of the Future

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Synopsis

Tomorrow's warships must break free from the handcuffs of yesterday's technology. In a world where the lifecycles of combat and mission systems are dramatically shorter than those of the ships that deploy them, a fundamental design challenge exists for ship designers. That is, to design a ship that can adapt and evolve alongside whatever the next generations of emergent technology might throw at it. When one fails to comprehend or address this challenge from the outset of design, they resign themselves to a static capability that will be rapidly surpassed and render its crew ill-equipped for the fight of the future. What may once have been a prized asset at delivery quickly becomes a costly liability for inefficient upgrade or disposal taking considerable sunken costs with it to the grave.

So how can the design of a warship mitigate the risks of future technology integration and increase the likelihood of successful capability upgrades throughout its life? This paper explores the effectiveness of conventional methods such as growth margins, modular systems and controlled sub-system interfaces in the context of past programs and experiences. Issues of spatial allocation and the trade-offs associated with compartment and deck arrangements for a generic next-generation surface combatant from a previous paper by the authors is summarised. Its second-order impacts and inter-dependencies with several design features including topside design, survivability, and ship performance are expanded upon. Lastly, a set of guiding principles are offered as an aid for requirements development in the early stages of naval ship acquisition programs in order to ensure a sensible balance of adaptability is specified and achieved.

Keywords: Ship design; Adaptability; Upgrade; Obsolescence

1 Introduction

The rate of advancement of combat system technologies is rapid and at odds with the longevity of our warships. In order to remain relevant in its operational context, it is important that warships maintain technological advantage or at least equivalency with adversaries. Therefore, over the span of a warships life it is not a matter of 'if' but 'when' combat system elements need upgrading. The questions of 'which elements?', 'where located?' and 'how often?' produce greater consternation and demand deliberate trade-offs.

Representing major capital investments at a national level, the number of warship platforms that can be afforded and supported is limited and faces constant public scrutiny. This is particularly true for middle-power navies including Australia. As a result, enabling longevity of warships is core concern of decision-makers seeking to maximise their 'return on investment'. However, long-lived warships are expected to see greater technological changes, and with them increasing pressures for combat system upgrades. While being upgraded, warships are effectively idle and offer no return on investment. For smaller fleets, the absence of individual warships may even jeopardise national security assumptions. Therefore, the level of efficiency achieved in upgrades is critical both in calculating the total cost of ownership as well as managing operational availability.

One major driver of inefficiency in warship upgrades is the rework of platform systems needed to support new combat system elements. Through a deliberate and disciplined approach to early-stage design of future warships,

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Authors' Biographies
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the authors of this paper believe that warship platforms can be better configured to tolerate combat system upgrades, thereby increasing operational availability and cost effectiveness over their service lives.

This paper summarises the traditional approaches for managing the warship upgrade ‘problem’ and explores practical options that improve the chances of compatibility with future combat system needs. It also considers how the physical arrangement of combat system elements affects warship performance and survivability. Finally, it seeks to offer practical guidance for sponsors and designers when developing future warships.

2 Traditional Approaches

Traditional approaches for managing combat system upgradability and the interface with platform systems include the use of margins, modularity, standardisation, and wholesale redesign (including batch building). Previous discussion and findings by the authors [Cole, Smith & Barden, 2024] are summarised in this section.

2.1 Margins

Margins are the most common way that ships are designed and built to endure future change. Margins are the difference between the ship’s status in a certain characteristic and a limiting value of that characteristic. Typically, margins for space, weight, stability, power and cooling are allocated for one or more phases of the capability lifecycle (i.e. design, build, in-service). These margins attempt to identify and control sources of growth and enable trade-off decisions. However, margins alone are insufficient to guarantee compatibility with desired changes. Once built, a warship’s ability to tolerate combat system upgrade is affected by many additional factors including routing of cabling and piping, capacity and quality of power, interactions of electromagnetic interferences and security considerations both physical and cyber. Although there are several technical and programmatic benefits of applying margin management, it is important to recognise their limitations particularly in the context of major upgrades.

2.2 Modularity and Standardisation

Modularity has been adopted by many vessels for various purposes, often by design customisation or operational flexibility. The Blohm & Voss MEKO 200 family of frigates is an example of the former, featuring modular design features which have enabled rapid tailoring of a core design to the unique needs of eight independent navies over almost 40 years. The US Navy Littoral Combat Ship (LCS) and the Danish STANFLEX system are examples of modularity which were intended to allow ships to be rapidly reconfigured for different missions.

Modularity relies on standardised unitisation. In the context of upgrade, this can be advantageous when units with the same external interfaces allow replacement with upgraded functions or performance levels. Once interfaces are defined, modularity allows for much of the design, build, outfitting and testing to be carried out independently from the ship itself. As a result, cost savings and improved operational availability can be generated because of the shortened time that the warship is idle during upgrade. However, the penalty of modularity is that the defined interfaces are also hard constraints which force sub-optimal design compromises. Examples of these unintended modularity consequences include inefficient use of weight and space for structural ‘packaging’, use of additional connectors and adaptors that are otherwise avoidable, and unnecessary duplication of common elements when scaled for overall capacity using multiple modules. Since it is difficult to anticipate the correct interfaces of unknown future technologies, over-reliance on modularity can constitute a liability for future upgrades.

2.3 Wholesale Redesign

Where the level of change required for an upgrade is beyond the available margins and/or interfaces of an existing platform system, then additional redesign may present as the only option. An example is the anti-ship missile defence focussed upgrade of the Australian ANZAC Class frigates. In order to increase buoyancy and stability needed for mast and radar upgrades, the aft quarterdeck was enclosed and ballast was added. Another speculative example is the US Navy Arleigh Burke Flight IIA DDG MOD 2.0 upgrades, where increased cooling capacity associated with combat system upgrades may force a change to primary machinery arrangements. The refit period for this upgrade is predicted to take between 12 and 26 months [Hutchinson, 2023]. Although achievable, extensive design change is expensive and jeopardises operational capability until completed.

The level of platform design change required to support some upgrades may be beyond the limits of existing warships and a new build may be the only feasible alternative. Although generally more expensive, this approach has the benefit of avoiding impacts to extant fleet operations. Batch building is prevalent in many countries, reflecting an explicit intent to address technology development directly through build rather than upgrade, while retaining the many commercial and operational benefits of commonality and continuity. The Arleigh Burke program has demonstrated the ability to incorporate an improved helicopter capability in the Flight IIA by lengthening the hull through the batch building process. Such a change would not have been viable through an upgrade of earlier existing hulls. However, the downsides of a batch-building approach include higher costs associated with a larger fleet sizes, overheads of managing multiple configuration baselines of sub-classes, and omission to address degraded capabilities of earlier builds.

3 Concept for Enabling Combat System Upgrade

The authors previously outlined a novel approach to warship design that anticipates and accommodates significant change within the combat system [Cole, Smith & Barden, 2024]. The concept was underpinned by a spatial arrangement with two large combat system equipment ‘enclaves’ connected by dedicated ‘galleries’ for associated cabling and services. These spaces formed a key physical interface between combat and platform systems at the highest possible level. The concept is illustrated in Figure 1 and 2, where red zones denote the two combat system enclaves. Constraints associated with lower-level standardisation and modularity were deliberately avoided and the installation designer was instead empowered to optimise within the physical boundaries of the enclaves for a particular installation configuration. This was intended to mitigate the integration risks of future upgrades by reducing the impact of change rather than constraining it. This section expands on some of the features that were explored as part of the concept's development.

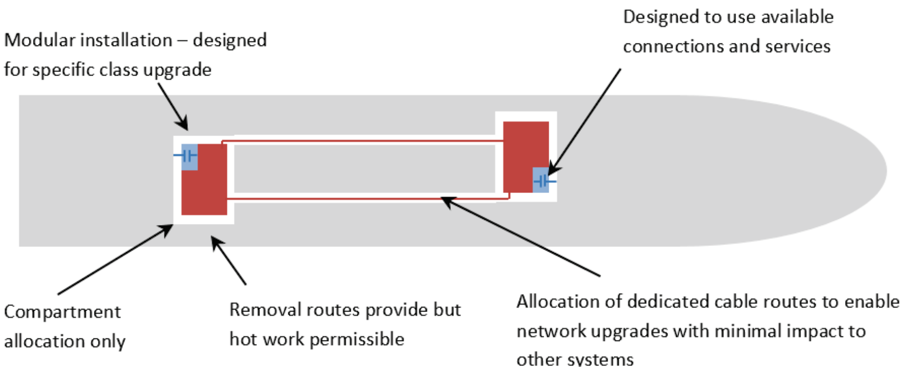

Figure 1: Concept illustration.

Figure 2: Indicative implementation of combat system enclaves (red) linked by galleries (pink).

3.1 Modularity for Upgrade

The approach presented previously and expanded in this paper is primarily focused on simplifying the interface between combat and platform systems to the level of the compartment boundary. The decision to include modularity within these spaces at a container or rack level or totally reconfigure compartments are deferred to the installation designer. This treatment of modularity, standardisation and flexibility may provide an advantage for upgrades. Examples of modular installations include the DDG 1000 Electronic Modular Enclosures and the CVN Flexible Infrastructure program [Doerry, 2012]. Taking inspiration from installations like the Astute Class Command Deck Module, large modules could potentially be developed based on entire compartment footprints. Although this would come with some penalties in module structure weight and the requirement for large removal routes, it allows significant groups of equipment to be pre-integrated, tested and installed as a unit.

Returning to the authors' concept arrangement shown in Figure 3, several considerations are required when arranging a 'standard interface' modular system such as one based on an ISO container footprint. As the aim for the modular system is not mission flexibility but upgradability, the ability to swap modules in and out in a timeframe of hours is not necessary. As such, hard patches requiring hot work were judged to be acceptable, and removable soft patches were not deemed necessary. The other major consideration of the example arrangement is that installation paths for some modules are blocked by other modules which are closer to the patch. In the example installation arrangement, only three of the seven modules can be removed without removing others. Verification that any equipment temporarily removed for access was replaced and retested may add schedule and cost to an upgrade. As discussed previously, modular installations present opportunities to test equipment independent of the ship. As such, the net impact to schedule of removing, replacing and retesting obstructing modules may still be neutral or positive.

Figure 3: Combat system equipment room modular installation example.

In this concept, modularity remains deliberately at the discretion of the designer. Seeking to keep the future upgrade designer in mind, the initial designer may implement forms of modularity that support anticipated levels of upgrade. A continually evolving enterprise combat system provides additional opportunities to manage the long term aims across different generations of installation designs. The illustrated 'ISO container' arrangement is only one example of a modular solution, and alternatives might include modularity among electronics racks, compartments and/or entire enclaves. In this context, standardisation is not the objective, but larger formats simply provide a common foundation to enable pre-integration, test and installation to reduce upgrade times. These could be unique to each compartment installation design.

3.2 Topside Design and Mast Arrangements

In addition to the internal spaces, the upper deck arrangement or ‘topside’ design also represents a key area where balance between the platform and combat systems is needed. Considerations include combat system equipment positioning, cabling and electromagnetic interaction, alongside other arrangement drivers such as the bridge visibility, machinery exhausts routing and flight deck placement.

For the survivability of mission critical equipment, separation and redundancy of key sensor capabilities such as air search radars is advantageous. This can be achieved by separating the installations of equipment between fore and aft superstructures or masts. There are several examples of this kind of separation in warship programs. The US Navy Ticonderoga Class distributes the faces of the SPY1 array over opposite corners of the forward and aft superstructures. The German F125 separates the faces of its phased array radar over different forward and aft masts. The US Navy San Antonio Class LPD has integrated composite masts, which support a number of sensors and emitters including radars. The Thales I-Mast fitted to Royal Netherlands Navy warships constitutes an integrated mast solution. Each of these different configurations has different implications for balancing whole of ship design and represents an early-stage decision in the design process for each class which would be difficult to alter later in an upgrade context. Figure 4 illustrates how the internal arrangement concept discussed previously might be combined with different examples of mast configurations, each with unique performance, survivability and integration implications.

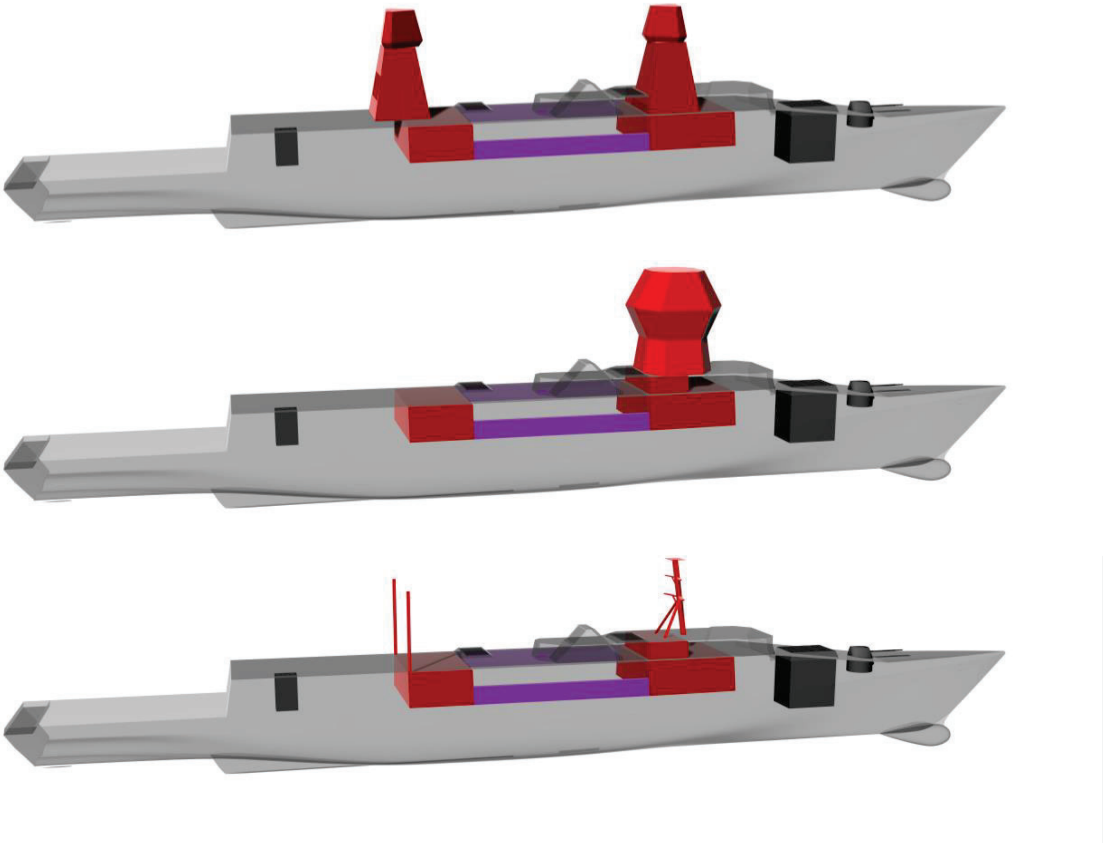

Figure 4: Examples of different mast configurations.

Once a warship has been designed to support a particular mast and topside arrangement it is difficult to make substantial changes to it without compromising the platform design. The extent of topside redesign undertaken by both the ANZAC and Hunter Class programs demonstrates the complexity of this activity and the associated compromises that become necessary in other aspects of the capability.

Platform and combat system objectives can be in considerable tension when it comes to mast arrangements, necessitating trade-offs to balance the design. Beyond the allocation of equipment weights and centres of gravity, the above-water lateral area silhouette is another crucial factor in the determination of vessel stability. As wind heeling criteria often produce limiting cases for warship stability compliance, operability can be quickly eroded by growth in combat system elements, particularly when mounted high on masts.

Upper deck arrangements are also sensitive to separation distances to prevent electromagnetic interference between equipment and sensors as well as clear arcs for transmitting or receiving communications, deploying weapon systems, or operating aircraft. To enable future upgrades of equipment located on the topsides, it may also be of benefit to include explicit provisions for spatial margins for these areas. Such margins could be represented explicitly in 3D models to inform arrangements and linked to design calculations for windage and electromagnetic interaction.

In the case of complex upgrades, changes to the mast and topside design should be treated holistically. Parametric constraints such as weight, centre of gravity, spatial allocation and wind profile would allow flexibility for the upgrade installation designer, analogous to the recommendations for treatment of internal combat system enclaves. For example, an installation designer may choose to mount sensors or equipment internally within oversized mast structures, or leverage opportunities for bolted rather than welded structural connections for mast foundations. However, caution should be exercised against arbitrarily standardising interfaces which may increase initial complexity and cost, while also constraining the options available to future upgrade installation designers.

3.3 Survivability

The distribution of key sensors and effectors across two separate masts provides potential survivability advantages. In the event that one mast experiences damage or failure, the remaining mast remains capable of providing some level of coverage. For example, if a phased array radar with six faces were distributed between two masts so that the three faces on each mast achieved a near 360-degree coverage, then a high level of survivability is achieved. Coupled with separate and redundant internal combat system enclaves and protected cable routing within dedicated galleries, the concept has potential to achieve a very high level of combat system survivability that would be consistent with other key systems such as propulsion. The ability to achieve separation maximises the benefits available from existing levels of equipment redundancy, meaning that significant survivability improvements may be achievable with limited additional equipment.

4 Guidance on Adaptability Requirements

4.1 Guidance for Capability Sponsors

A capability sponsor (or ‘end-user' representative) must weigh several competing factors when determining the ‘what’ and ‘how’ to manage their project or program outcomes. For warship acquisition in an Australian context, the ‘how’ is increasingly pressured by the time to deliver initial capability. This approach has been reaffirmed by the recent 2024 National Defence Strategy which has shifted focus toward ‘minimum viable capability’ and ‘places greater emphasis on speed to acquisition’ [Australian Government, 2024]. It is important that decision-makers are aware of the opportunities and limitations that warship adaptability (or lack thereof) will have upon the enduring capability relevance over a platform’s typical 20-30 year service life. For warship programs, the following upgrade considerations should be assessed:

1. Are there known system upgrades that will be incorporated during the ship’s service life? Early identification of foreseen upgrades allows designers to enable successful integration, by incorporating necessary aspects with minimum impact to other design elements. Where specific details of future upgrades are known, they can be captured and communicated via “Fitted For But Not With” contract provisions.
2. How mature and resilient are the operating and support concepts against disruption by emerging technologies? Where foundational concepts are susceptible to significant change over the ship’s service life, then design adaptability may be necessary to retain capability relevance. Furthermore, high-level identification and communication of candidate systems that are most likely to be affected may warrant prioritised design arrangements which simplify their mid-life replacement.
3. How consistent is the upgrade philosophy with the relative costs of the platform and combat systems? If a platform system is significantly cheaper than its combat system, then batch-building new platforms for future combat systems may offer a more cost-effective approach than upgrading mid-life. However, as platform system costs are rarely trivial, the barrier to early replacement of warship platforms remains high. In practice warships operate for 30 years or more and capability gaps manifest when existing warships exhaust their ability to upgrade their combat systems.

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4. How tightly constrained is the broader requirement set? Given that warships are a compromise of myriad trade-offs, design feasibility must be ensured. If the possible solutions are already heavily constrained (e.g. physical dimensions, performance, cost) then provisions for future adaptability may force unacceptable compromise in the initial capability.
5. Does the design and build strategy support decoupled development of platform and combat systems? A longer platform build timeline may mean that combat system elements are rendered obsolete before or soon after delivery. There may be opportunities to commence construction on the platform system ahead of the combat system, opting to integrate the newest possible combat system elements into the build. This approach carries technical and commercial risk, but has potential to achieve a better capability outcome.
6. Does the concept proposed in this paper suit the operational context and end-user needs? If the upgradeability and/or survivability benefits of decoupled platform and combat system design are desirable features, then the initial capability needs and requirements that inform the acquisition strategy should reflect these principles. Consideration should also be given to how the proposed approach supports a continuously evolving enterprise combat system.

4.2 Guidance for Design Authorities

Once a decision is made to incorporate adaptability as a central tenant of a program, the responsibility for achieving effective adaptability is transferred to the design authority. Specific considerations for platform system as well as combat system installation design to maximise the likelihood of withstanding future upgrades include:

1. Adaptable platform design is predicated on having sufficient growth margins for support services such as electrical power and cooling system supply. To minimise platform system disruption during upgrade, these support services need to provide margins at the combat system interface. Margins should also be considered for cabling and piping as well as penetrations between combat system elements and supporting platform machinery spaces.
2. Whole of ship performance margins such as speed and range should be considered, especially where degradation below a certain threshold may compromise the operational needs. Traditional stability margins relating to displacement and vertical centre of gravity remain important, but additional novel metrics such as above-water area margins which capture wind heeling impacts of topside arrangement changes may be of benefit.
3. Combat system arrangement designers should be cognisant of elements which are expected to undergo early upgrades or are subject to high technology refresh rates. These elements should be arranged in positions that allow for replacement via dedicated routes and have provisions for flexibility in mounting and connectivity.
4. Where combat system equipment removal routes are established, these should be clearly identified and captured in configuration documentation and protected from unintended obstruction by other design changes.
5. Dedicated cabling and piping routes for combat systems, such as via combat system technical galleries, should be considered for the benefit they provide in controlling the scope of systems impacted by upgrade work. The inclusion of technical galleries may also reduce the number of bulkhead penetrations and increase the physical security of sensitive cabling.
6. Where combat system spaces can be co-located to form ‘combat system enclaves’, this would reduce the complexity of interfaces and minimise constraints to upgrade. Such an approach affords maximum flexibility to upgrade installation designers, while avoiding extensive rework of platform systems.
7. The initial spatial allocation of topside arrangements and any combat system enclaves should be based on conservative assessments of current and anticipated combat system elements, and include margins for design, build and upgrade.
8. Once adopted, the allocations for topside arrangements and any combat system enclaves (including their interfaces and margins), should be considered as constraints for the installation design of future combat system upgrades.
9. Where improved warship survivability is desired, the designer might consider the distribution of equipment across topside arrangements and enclaves to maximise separation and redundancy .

5 Conclusions

Warships are significant national investments that must remain relevant amidst constantly evolving technologies and changing threat environments over decades of service. As the refresh rates of platform and combat system elements are not aligned, upgrades are unavoidable and provisions are needed within warship designs that enable upgrade while mitigating the total cost of ownership and minimising distribution to operational availability. While traditional approaches such as margins, modularity and spatial arrangements all affect upgradeability, there are some unique and novel opportunities for the consideration of capability sponsors and designers if a disciplined approach is adopted from the earliest stages of design. The concepts discussed in this paper also identify synergetic opportunities to improve the survivability of warships alongside improved upgradeability. While it is recognised that some future technologies will drive changes beyond the abilities of even the most adaptable warships, it is possible that the approaches outlined in this paper may provide an occasional and valuable exception to this rule.

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The views expressed in this paper are those of the authors and do not necessarily represent the views and opinions of the broader Australian Department of Defence. The authors acknowledge and value the sharing of experience and lessons learnt with colleagues across the naval enterprise, and in particular those involved in the ANZAC Class upgrade programs.

References

Australian Government, 2024. National Defence Strategy.

Cole J., Smith A., Barden, G., 2024. Design for Upgrade – Managing the Platform to Combat System Interface, In: Warship 2024: Future Surface Combatants.

Doerry, N.H., 2012. Institutionalizing Modular Adaptable Ship Technologies. In: SNAME.

Hutchinson, T., 2023. Guided Missile Destroyer (DDG MOD) 2.0. In: NAVSEA.

Sorensen, K., 2015. The Danish Experience with Flexible Warships. In: ASNE Day 2015.

UK Ministry of Defence, 2022. Maritime Modularity Concept.

Analysis of the current regulatory landscape for autonomous and remotely operated vessels in development and use by the Australian Defence maritime enterprise.

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Synopsis

The development and use of autonomous and remotely operated vessels (‘autonomous vessels’) is a focus area for militaries across the globe, including the Australian Defence Force. These vessels offer opportunities to extend naval capability, including by increasing reach and efficiency while reducing safety risks and environmental impact. In order to translate these opportunities into capability the vessels must be capable of compliance with applicable regulatory frameworks. This paper supports this outcome by analysing the existing applicable regulatory frameworks in Australia, identifying the unique regulatory considerations for autonomous vessels and adverse impacts of applying existing frameworks, and providing recommendations for Defence regulators to support efficient regulatory outcomes.

This paper identifies that autonomous vessels in Australia used for or in connection with a Defence purpose are subject to regulation under the same regulatory frameworks as traditional vessels. This includes under the Defence Seaworthiness Management System (DSwMS) and in some circumstances under Australian Maritime Safety Authority (AMSA) legislation. In addition, autonomous vessels are subject to State and Territory local waterways and environmental management requirements, local port requirements, and work health and safety obligations.

This paper identifies that the fundamental assumptions made by existing regulatory frameworks, for example that a human will be on board and supervising a vessel, and the fundamental differences between traditional vessels and autonomous vessels, for example their size and lifespan, gives rise to a range of regulatory considerations from a safety, environmental, and flag perspective, together with potential adverse impacts.

This paper draws on the conclusions reached regarding the current regulatory landscape for autonomous vessels, together with the experience of the authors, to put forward a series of recommendations for Defence regulators to consider in approaching and executing the regulation of autonomous vessels to ensure the opportunities presented by these vessels can be fully leveraged. These recommendations relate to (1) proactively seeking to enable test, trial and operation; (2) domestic and international collaboration; and (3) regulatory development.

Key words: Seaworthiness; Regulation; Emerging technology; Autonomous vessels

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1. Introduction

The development and use of autonomous and remotely operated vessels (autonomous vessels) is a focus area for militaries across the globe, including for the Australian Defence Force. These vessels are capable of supporting and extending existing capability, as well as establishing wholly new capabilities. The Royal Australian Navy (RAN) has recognised that "employing RAS-AI [Robotics, Autonomous Systems and Artificial Intelligence] will enable a more agile, resilient, and lethal fighting force, enhancing Navy's ability to Fight and Win at Sea." (Royal Australian Navy, 2022). In order to translate the potential offered by autonomous technology into operational outcomes, it must be capable of compliance with applicable regulatory frameworks. Inability or a high level of difficulty in understanding regulatory requirements and achieving compliance jeopardises the likelihood of successful translation of these disruptive new technologies into capability.

In an Australian defence context, autonomous vessels that are considered maritime mission systems are subject to the Defence Seaworthiness Management System (DSwMS). Understanding the regulatory landscape for autonomous vessels, the unique considerations and challenges, and identifying areas of future focus for regulatory development, is imperative. The conduct of this analysis will inform the Defence Seaworthiness Regulator (DSwR), being the steward of DSwMS, and her office, the Office of the Defence Seaworthiness Regulator (ODSwR), regarding whether regulatory reform activities are required to support the uptake of autonomous vessels within the Australian defence maritime community and what they could include. This analysis will also inform and possibly guide other defence regulators making the same assessments for their own regulatory frameworks.

This paper leverages the expertise of practitioners across the fields of regulation, flag administration, safety, and environment to analyse the current regulatory landscape for autonomous vessels used by the Australian defence maritime community, with a focus on the application of existing seaworthiness requirements. Drawing on the analysis conducted, this paper will argue that DSwMS is capable of successful application to autonomous vessels, particularly when supported by high quality guidance material, and strong, sustained engagement between DSwR and the regulated community. The paper will conclude by identifying a number of recommendations for Defence regulators to consider in approaching and executing the regulation of autonomous vessels.

2. What are autonomous vessels and why are they being used by defence forces

Autonomous and remotely operated vessels (autonomous vessels) utilise robotics, autonomous technology and artificial intelligence to operate with a spectrum of human involvement from hands on remote control through to limited or no supervision. Autonomous vessels have been in development and use since the 1970s, but rapid increases in capability and availability from approximately 2015 onwards has seen increasing use for commercial and defence purposes (Horne et al, 2023). These vessels, including both sub-surface and surface variants, are the subject of significant science and technology investment by militaries, including within Australia (Australian Government, 2024), the United States of America (Defense News, 2023) (DefenseScoop, 2024) and the United Kingdom (United Kingdom Parliament, 2023). The Royal Australian Navy (RAN) have recognised that "employing RAS-AI will enable a more agile, resilient, and lethal fighting force, enhancing Navy's ability to Fight and Win at Sea." (Royal Australian Navy, 2022).

Increased use of autonomous vessels by Defence could reduce the overall impact of maritime operations on the environment, for example by reducing emissions (CO_2, NO_2, SO_2) and pollutant discharges such as oil, fuel, sewage and garbage. (Grome, 2018) (McCarl, 2023) (Cross, 2023). Further, facilitating the use of autonomous vessels in Defence operations may accelerate Australia's transition to clean energy and contribute to its net zero greenhouse gas emissions target by 2050.[2]

In the 2020s the majority of autonomous vessels under development and use are small in nature, generally ranging from <0.1m up to 12m in length (Horne et al, 2022). This size reflects the dominant use cases, being hydrographic survey, mine counter measures and persistent surveillance, together with common understandings of existing domestic regulatory frameworks that scale regulatory requirements to specific size brackets (Horne et al, 2022). Larger autonomous vessels are in use in the United States of America (USNI News, 2023), and are expected to be integrated into the RAN in the future, including for undersea warfare (Australian Government, 2024) (Austal, 2024). **Figure 1** provides examples of autonomous vessels in use in a defence context.

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[2] *Climate Change Act 2022* (Cth) s 10(1).

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Figure 1 Compilation image of autonomous and remotely operated vessels used by Defence by Dr Rachel Horne, individual images sourced from Defence Image Gallery April 2024.

3. The regulatory landscape for autonomous vessels used in defence contexts

Autonomous vessels are regulated under the same defence and civilian regulatory frameworks as traditional crewed vessels. This means they are subject to the DSwMS, which requires the Capability Manager (CM) or their delegate to have in place a Seaworthiness Case supported by a Compliance Strategy that addresses governance and management compliance obligations (GMCOs) and activity and condition based compliance obligations (ACCOs). Vessels must also be registered on the Defence Vessel Register, which is administered by ODSwR. For autonomous vessels not included in a Seaworthiness Case and Compliance Strategy there must be an Operating and Support Intent (OSI) and Safety Case[3] in place, and the vessel must be registered on the Defence Vessel Register or equivalent.[4] DSwR has issued guidance to support the regulated community to comply with these requirements.[5]

The new Australian Naval Classification Authority (ANCA) also forms part of the DSwMS, and has recently published the Australian Naval Classification (ANC) Manual. This Manual includes the ANC Policy, the ANC Rules, and ANC Design Notes. The ANC Rules are a prescriptive materiel ruleset similar to that of a class society, and will include a specific division for remote and autonomous systems[6] (ODSwR, 2024).

In some circumstances autonomous vessels used in a defence context are also subject to regulation by the Australian Maritime Safety Authority (AMSA), as either domestic commercial vessels under the *Marine Safety (Domestic Commercial Vessel) National Law Act 2012 (Cth)* (DCV National Law Act) or as regulated Australian vessels under the *Navigation Act 2012 (Cth)* (Navigation Act). AMSA's regulation applies by default where the autonomous vessel is a "vessel", unless a carve out provision applies, for example where the vessel meets the definition of 'defence vessel' in the DCV National Law Act, or 'naval vessels' in the Navigation Act. The key Australian maritime safety frameworks are depicted in **Figure 2**.

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[3] This Safety Case must demonstrate that efforts have been made to eliminate or minimise so far as is reasonably practicable (SFARP) hazards/risks to personnel, the public and the environment, as per: *Defence Seaworthiness Management System Guidance, Making a seaworthiness case for autonomous and remotely operated vessels (autonomous vessels) which are Maritime Mission Systems in the Defence context. 2024.*

[4] Note ODSwR, the steward of the Defence Vessel Register, are working to implement a Defence Autonomous Vessel Register for non-flagged autonomous vessels, which will sit alongside the Defence Vessel Register.

[5] For more information see: Royal Australian Navy, Office of the Defence Seaworthiness Regulator, Defence Seaworthiness Management System Guidance: Making a seaworthiness case for autonomous and remotely operated vessels (autonomous vessels) which are Maritime Mission Systems in the Defence context. 2024.

[6] For more information see: Australian Naval Classification Authority | Business & Industry | Defence.

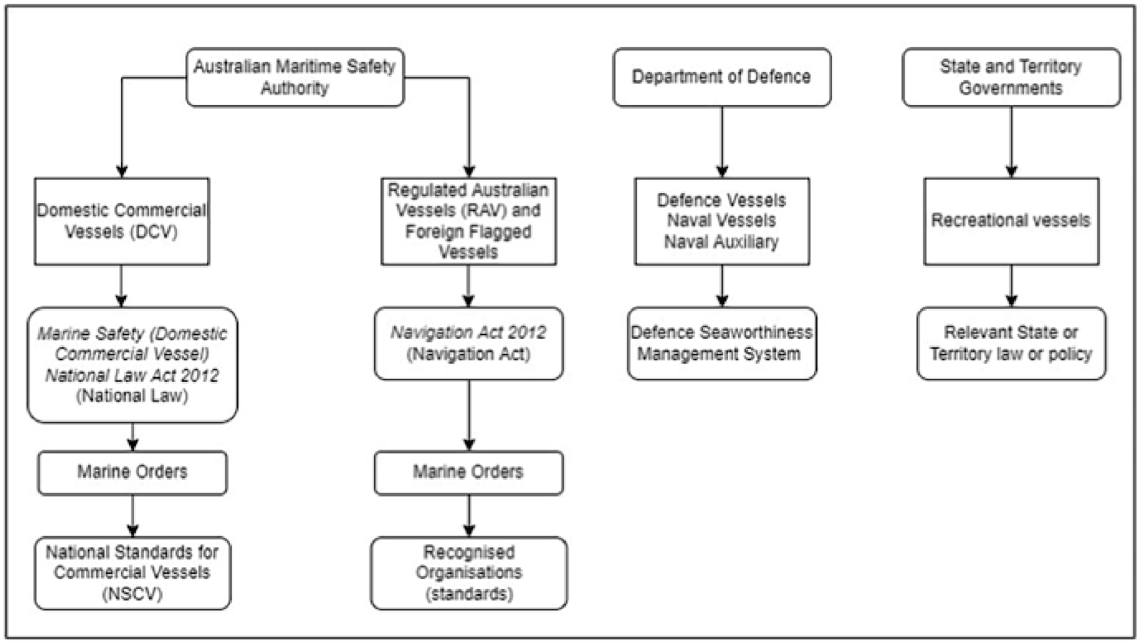

Figure 2 Four key maritime safety frameworks in Australia (Humphries et al, 2023).

a. The Defence Seaworthiness Management System (DSwMS) and how it applies

The DSwMS is a Defence-wide goals-based maritime risk management framework that applies to all maritime mission systems.[7] It provides the framework, policies and procedures that inform the actions and decisions of Defence personnel on the nature and scope of employment of mission systems, including ships, submarines, powered and non-powered vessels of any size, diving systems, unmanned underwater vehicles including remotely operated systems, and water borne drones.[8] The system is broad in its remit, regulating capability in a maritime context.

The intent of DSwMS is to support achievement of the Seaworthiness Outcome, which is defined as "to maximise the likelihood of achieving the specified operational effect for the defined tasking, where efforts have been made to eliminate or minimise so far as is reasonably practicable (SFARP), hazards/risks to personnel, the public and the environment."[9] It does this by supporting Defence to achieve operational effect by integrating hazard and risk considerations into decisions and activities across the entire Capability Life Cycle.

Notably the defence regulatory structure uses a three lines of defence model, whereby the third line directs how hazards and risks are to be managed in the context of the enterprise objectives (DSwMS); the second line provides the systems of hazard and risk control (for example through Navy's Safety Management Systems and Environmental Management Systems), and the first line conducts the core business.

DSwMS is codified in the Defence Seaworthiness Management System Manual[10], which includes volumes on system description, operations and administration; the GMCOs; the ACCOs; and independent seaworthiness management review. The core of DSwMS are the GMCOs and the ACCOs, as depicted in **Figure 3**.

The ANCA and ANC Rules support the attaining and maintaining of classification as part of achieving the Seaworthiness Outcome for new and existing vessels. The ANC Rules are a sovereign naval ruleset that combine best practice international shipping rules with Australian defence rules to comply with Australian requirements (Australian Government, 2024). The ANCA Handy Billy provides an accessible guide that explains the framework, how it applies, and the relevant processes.[11] The interface between the GMCOs, ACCOs, and ANC rules is being established collaboratively by ANCA and ODSwR, which sit side by side under the DSwR.

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[7] A maritime mission system is the element of a capability that directly performs the operational function, for example a ship or a distributed system such as a communications network.

[8] The Defence Administrative Policy ME2 – Defence seaworthiness management system, 04 December 2018.

[9] Defence Seaworthiness Management System Manual, Vol 002 Part 001, 04 December 2018.

[10] Defence Seaworthiness Management System Manual, Ed 3, 4 Dec 2018.

[11] For more information see: The Australian Naval Classification Authority Handy Billy published Feb 2024; and https://www.defence.gov.au/business-industry/industry-governance/australian-naval-classification-authority.

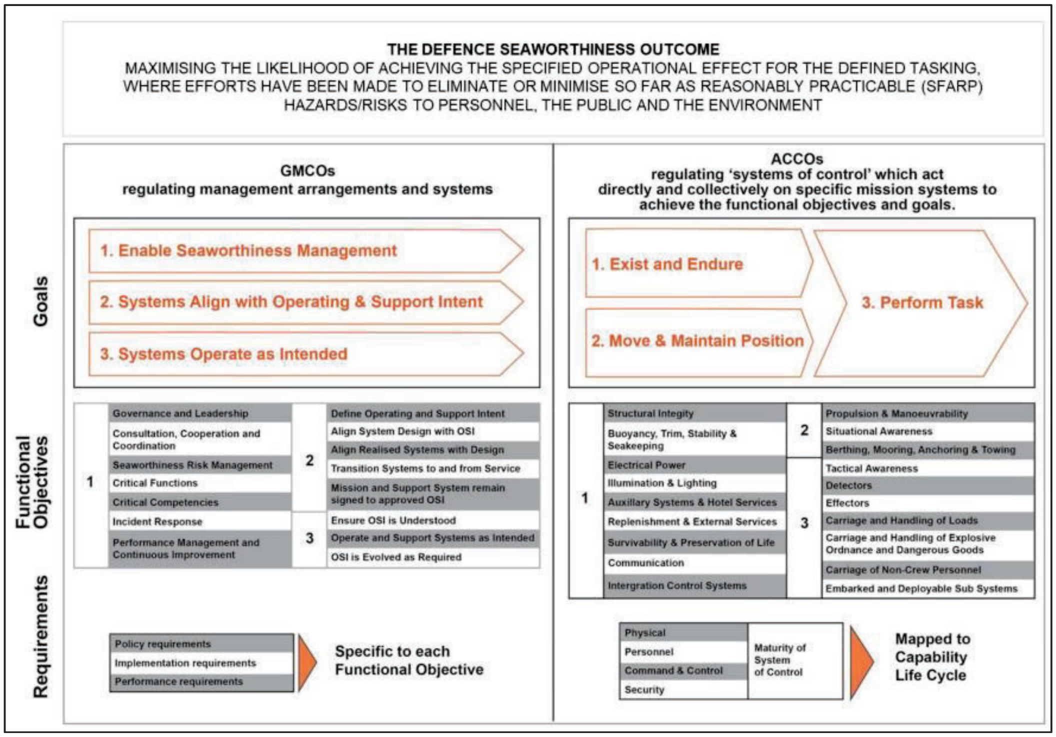

Figure 3 DSwMS Regulatory Framework

As mentioned above, the DSwMS requires each maritime mission system to be managed by the Capability Manager under a Seaworthiness Case, as depicted in **Figure 4**. This document is to be developed and managed in accordance with the Capability Manager's compliance strategy to DSwMS.[12] DSwR provides guidance on compliance with DSwMS through provision of fact sheets, case studies, training sessions, and consultation. ODSwR also conducts compliance and assurance activities to support compliance with DSwMS and achievement of the Seaworthiness Outcome.

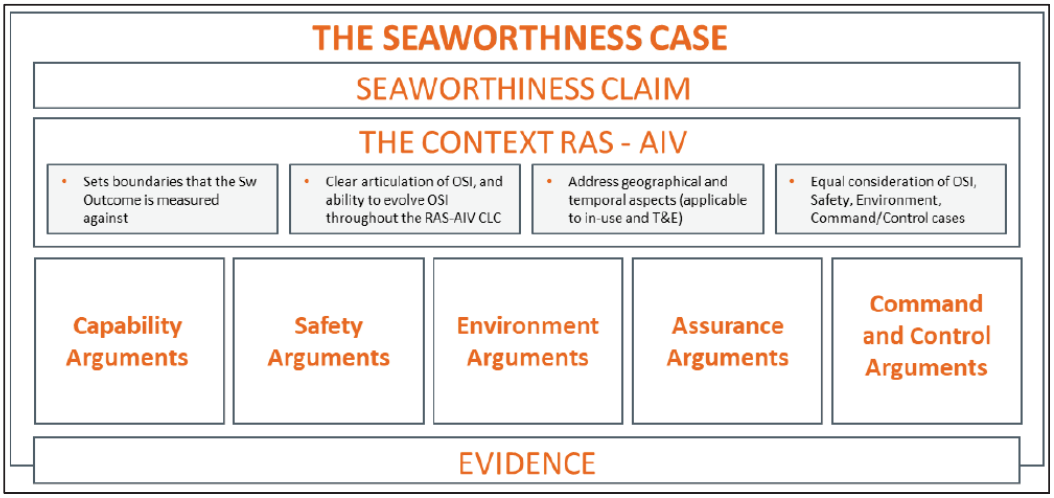

Figure 4 Structure of a Seaworthiness Case

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[12] Defence Seaworthiness Management System Manual, Vol 001 Part 00, 04 December 2018.

b. Regulatory requirements under the DCV National Law Act and Navigation Act

Autonomous vessels used in a defence context are often subject to regulation by AMSA. This is either as a domestic commercial vessel under the DCV National Law Act or as a regulated Australian vessel or foreign vessel under the Navigation Act, as per **Figure 5.**

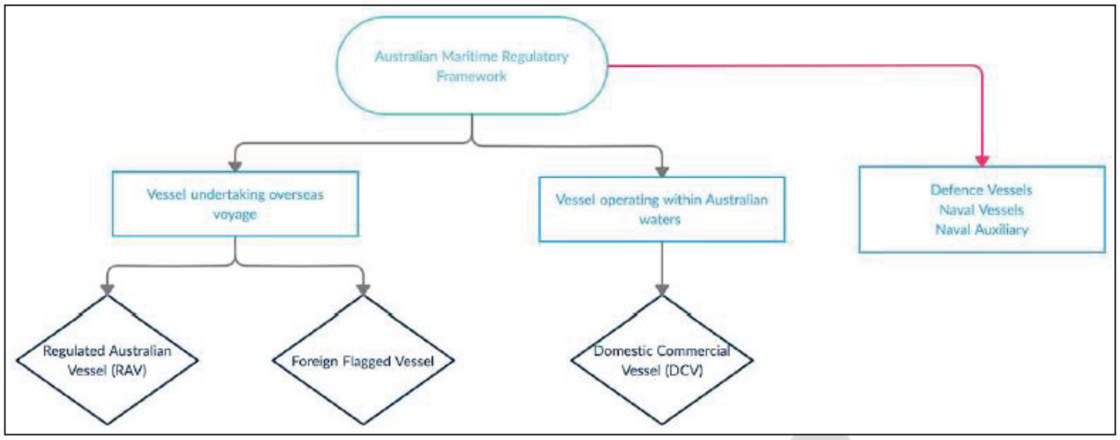

Figure 3 Categorisation of vessels in Australian maritime regulatory framework (Horne, 2024)

AMSA's regulation applies to a vessel used in connection with a commercial, governmental or research purpose unless a carve out provision applies, for example where the vessel meets the definition of 'defence vessel' in the DCV National Law Act, or 'naval vessels' in the Navigation Act.[13] The definition of 'defence vessel' requires that a vessel is:

(a) a warship or other vessel that
    (i) is operated for naval or military purposes by the Australian Defence Force or the armed forces of a foreign country; and
    (ii) is under the command of a member of the Australian Defence Force or of a member of the armed forces of the foreign country; and
    (iii) bears external marks of nationality; and
    (iv) is manned by seafarers under armed forces discipline; or
(b) a Government vessel that is used only on government non-commercial service as a naval auxiliary.

As there is no determination making power in either Act, AMSA cannot 'determine' if a vessel fits into the above definition but it can provide guidance to Defence. Only courts can determine the 'correct' interpretation of legislative provisions against specific circumstances. While it is undecided in a formal legal context whether autonomous vessels are capable of being 'defence vessels' or 'naval vessels', existing literature indicates they are (Horne, 2024). Commentary by Liivoja, Massingham and McKenzie indicate that "the command requirement does not necessitate direct oversight by a (human) commander for every decision made, but rather requires asking whether the system is fulfilling the intent of the commander." (Liivoja et al. 2022).

i. Requirements for domestic commercial vessels

Autonomous vessels that are domestic commercial vessels (DCVs) must comply with the requirements under the DCV National Law Act. Compliance requires:

- Vessels must:
  - have a Unique Vessel Identifier (UVI);
  - have a Certificate of Survey; and
  - be listed on a Certificate of Operation.
- The Master and Crew must have the required Certificates of Competency; and
- General Safety Duties must be complied with.

Flexibility mechanisms include specific and general exemptions, and equivalent means of compliance, which may be accessed to modify applicable regulatory requirements. All autonomous vessels to date have relied on exemptions to operate, noting regulatory requirements assume that humans are on board operating and supervising the vessel (Trusted Autonomous Systems, 2022).

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[13] For more explanation of AMSA's regulatory framework see R Horne, T Putland, T Roberson and C East, (2022), Body of Knowledge: Assurance and Accreditation of Autonomous Systems in Australia, Edition 1, Trusted Autonomous Systems.

ii. Requirements for regulated Australian vessels

Autonomous vessels that are regulated Australian vessels must comply with the Navigation Act, Navigation Regulation 2013 (Cth), and Marine Orders 1 – 98. International convention requirements are incorporated into these instruments, including the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL). For example, vessels must hold the required certificates, which may include:

- Certificate of class;
- Safety certificate/s and minimum safe manning certificate;
- Safety management system certificate;
- International oil pollution prevention certificate;
- International loadline certificate; and
- Maritime labour certificate.

Regulated Australian vessels over 12m in length must also be registered under the Shipping Registration Act 1981 (Cth).

The Navigation Act applies predominantly to large vessels that travel beyond the Australian Exclusive Economic Zone (EEZ) and it is not clear how this translates to small autonomous vessels. Flexibility mechanisms are limited, noting the specific international conventions under which specific requirements originate from may or may not allow a Flag State to grant an exemption from relevant requirements (Humphries et al, 2023).

c. Other regulatory requirements

All vessels, whether autonomous or not, must comply with applicable requirements arising from State or Territory legislation, such as local waterways management and environmental management requirements, together with work health and safety legislation and port-specific requirements.

4. Unique regulatory considerations for autonomous vessels under the DSwMS

There are unique regulatory considerations for autonomous vessels under both DSwMS and AMSA's regulatory framework. This paper is written in a defence context and will focus on the DSwMS. Applying the existing DSwMS framework to autonomous vessels is challenging because they are fundamentally different from crewed vessels. For example, autonomous vessels do not have humans on board to operate and supervise the vessel; instead they use sensors to perceive the operating environment and software programs to fuse and interpret data and make decisions (Horne et al, 2023) (Devitt et al, 2021). They are also often significantly smaller than crewed vessels, may be built using different materials, and may be iteratively developed with a short life span (Humphries et al, 2023) (Horne, 2021). There are also no tailored technical standards incorporated in existing Australian regulatory framework, which provide a best practice benchmark for these vessels, including from a safety and environment perspective (Horne, 2021). There is, however, a voluntary standard, the Australian Code of Practice for the Design, Manufacture, Survey and Operation of Autonomous and Remotely Operated Vessels, published by Trusted Autonomous Systems Defence Cooperative Research Centre (TAS), which may be utilised.[14] For all of these reasons, a range of unique considerations are required.

A Safety and Environment Case needs to be established as part of the Seaworthiness Case, which considers the unique risks associated with the operation of an autonomous vessel and identifies appropriate controls (ODSwR, 2024). The Safety and Environment Case contributes to achievement of the Seaworthiness Outcome by demonstrating that efforts have been made to eliminate or minimise so far as is reasonably practicable hazards/risks to personnel, the public and the environment. Specific considerations are set out below.

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[14] The Australian Code of Practice for the Design, Construction, Survey and Operation of Autonomous and Remotely Operated Vessels, Edition 1 (published April 2022 by Trusted Autonomous Systems).

a. Safety considerations

There are unique safety considerations related to the operation of autonomous vessels. For example, the utilisation of an autonomous, semi-autonomous or remote operating system reliant on sensors and real time integration of data presents unique risks. Additionally, the varying ways that autonomous vessels are built, powered, and operated also creates unique risks. The lack of an agreed best practice technical standard that identifies and considers these unique safety risks increases the need to highlight these considerations. Examples relevant considerations are set out in **Table 1** below.

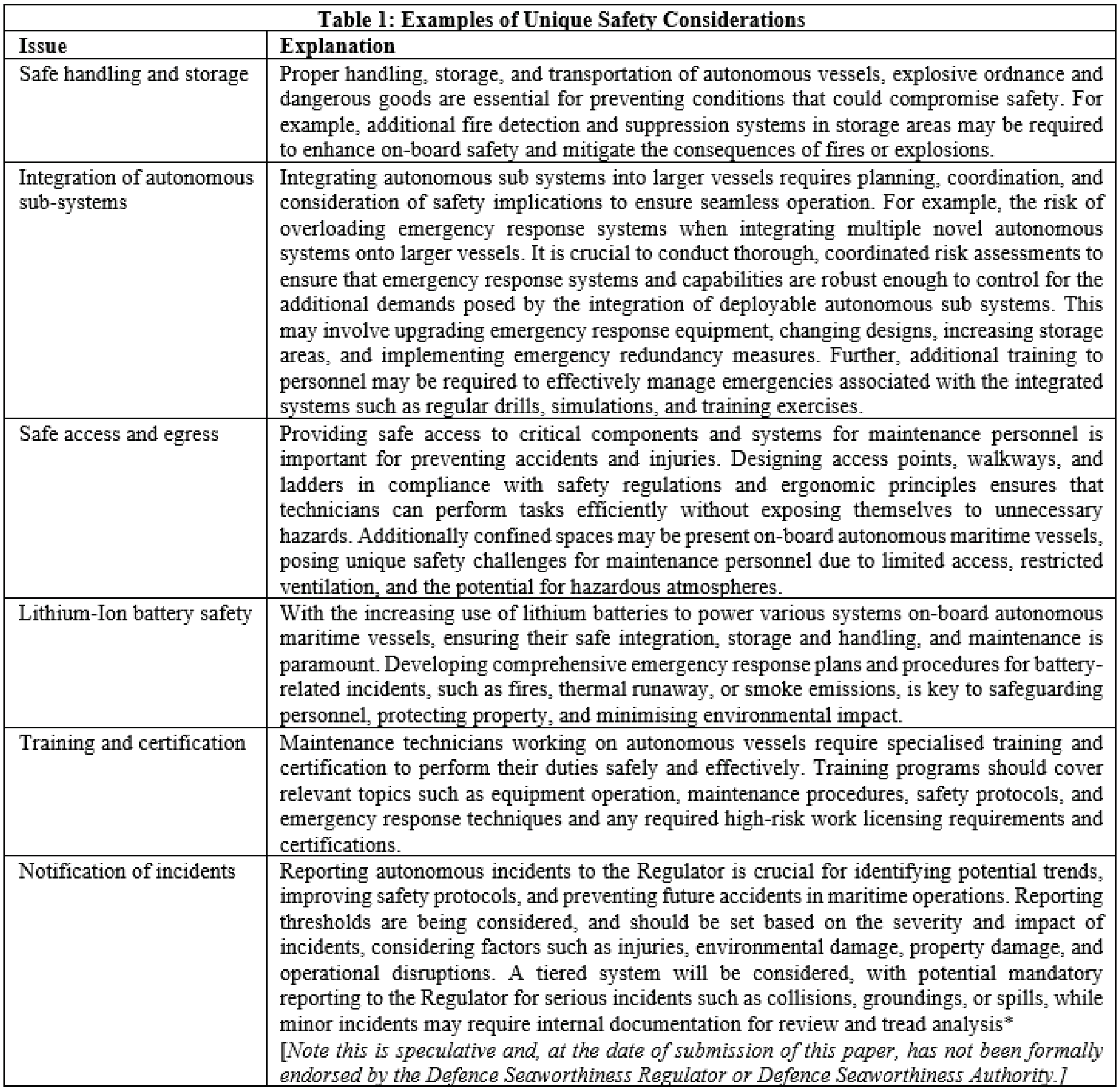

Table 1: Examples of Unique Safety Considerations

Issue	Explanation
Safe handling and storage	Proper handling, storage, and transportation of autonomous vessels, explosive ordnance and dangerous goods are essential for preventing conditions that could compromise safety. For example, additional fire detection and suppression systems in storage areas may be required to enhance on-board safety and mitigate the consequences of fires or explosions.
Integration of autonomous sub-systems	Integrating autonomous sub systems into larger vessels requires planning, coordination, and consideration of safety implications to ensure seamless operation. For example, the risk of overloading emergency response systems when integrating multiple novel autonomous systems onto larger vessels. It is crucial to conduct thorough, coordinated risk assessments to ensure that emergency response systems and capabilities are robust enough to control for the additional demands posed by the integration of deployable autonomous sub systems. This may involve upgrading emergency response equipment, changing designs, increasing storage areas, and implementing emergency redundancy measures. Further, additional training to personnel may be required to effectively manage emergencies associated with the integrated systems such as regular drills, simulations, and training exercises.
Safe access and egress	Providing safe access to critical components and systems for maintenance personnel is important for preventing accidents and injuries. Designing access points, walkways, and ladders in compliance with safety regulations and ergonomic principles ensures that technicians can perform tasks efficiently without exposing themselves to unnecessary hazards. Additionally confined spaces may be present on-board autonomous maritime vessels, posing unique safety challenges for maintenance personnel due to limited access, restricted ventilation, and the potential for hazardous atmospheres.
Lithium-Ion battery safety	With the increasing use of lithium batteries to power various systems on-board autonomous maritime vessels, ensuring their safe integration, storage and handling, and maintenance is paramount. Developing comprehensive emergency response plans and procedures for battery-related incidents, such as fires, thermal runaway, or smoke emissions, is key to safeguarding personnel, protecting property, and minimising environmental impact.
Training and certification	Maintenance technicians working on autonomous vessels require specialised training and certification to perform their duties safely and effectively. Training programs should cover relevant topics such as equipment operation, maintenance procedures, safety protocols, and emergency response techniques and any required high-risk work licensing requirements and certifications.
Notification of incidents	Reporting autonomous incidents to the Regulator is crucial for identifying potential trends, improving safety protocols, and preventing future accidents in maritime operations. Reporting thresholds are being considered, and should be set based on the severity and impact of incidents, considering factors such as injuries, environmental damage, property damage, and operational disruptions. A tiered system will be considered, with potential mandatory reporting to the Regulator for serious incidents such as collisions, groundings, or spills, while minor incidents may require internal documentation for review and tread analysis* *[Note this is speculative and, at the date of submission of this paper, has not been formally endorsed by the Defence Seaworthiness Regulator or Defence Seaworthiness Authority.]*

b. Environmental considerations

There are unique environmental considerations related to the operation of autonomous vessels, for example based on materials used for construction and payloads, their power source, the areas they operate in, the possibility they are lost and remain in the ocean, and the potential for underwater collision with marine life. Examples of specific hazards and risks are set out in **Table 2** below.

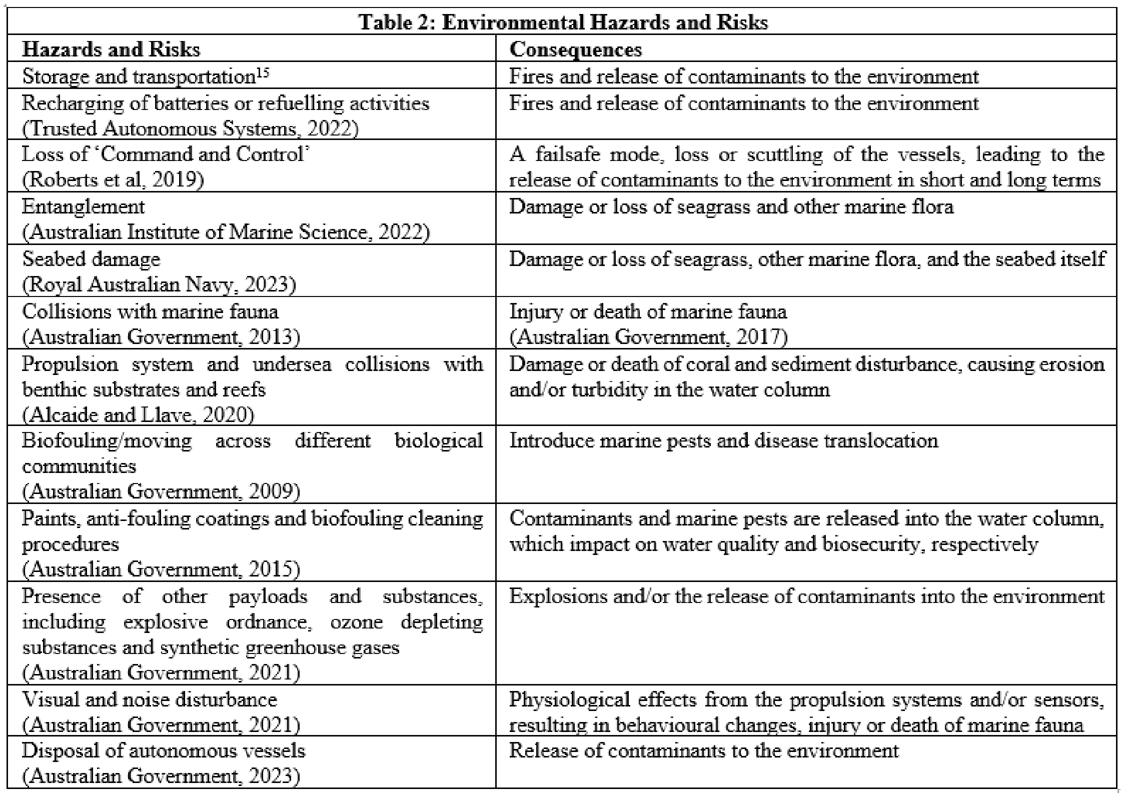

Table 2: Environmental Hazards and Risks

Hazards and Risks	**Consequences**
Storage and transportation[15]	Fires and release of contaminants to the environment
Recharging of batteries or refuelling activities (Trusted Autonomous Systems, 2022)	Fires and release of contaminants to the environment
Loss of 'Command and Control' (Roberts et al, 2019)	A failsafe mode, loss or scuttling of the vessels, leading to the release of contaminants to the environment in short and long terms
Entanglement (Australian Institute of Marine Science, 2022)	Damage or loss of seagrass and other marine flora
Seabed damage (Royal Australian Navy, 2023)	Damage or loss of seagrass, other marine flora, and the seabed itself
Collisions with marine fauna (Australian Government, 2013)	Injury or death of marine fauna (Australian Government, 2017)
Propulsion system and undersea collisions with benthic substrates and reefs (Alcaide and Llave, 2020)	Damage or death of coral and sediment disturbance, causing erosion and/or turbidity in the water column
Biofouling/moving across different biological communities (Australian Government, 2009)	Introduce marine pests and disease translocation
Paints, anti-fouling coatings and biofouling cleaning procedures (Australian Government, 2015)	Contaminants and marine pests are released into the water column, which impact on water quality and biosecurity, respectively
Presence of other payloads and substances, including explosive ordnance, ozone depleting substances and synthetic greenhouse gases (Australian Government, 2021)	Explosions and/or the release of contaminants into the environment
Visual and noise disturbance (Australian Government, 2021)	Physiological effects from the propulsion systems and/or sensors, resulting in behavioural changes, injury or death of marine fauna
Disposal of autonomous vessels (Australian Government, 2023)	Release of contaminants to the environment

The DSwMS can enable the effective management of environmental risks posed by autonomous vessels, noting management of these risks is an embedded part of the framework. Additionally, the DSwMS requires a clear understanding of the Operating and Support Intent (OSI) of the capability, accountability frameworks to manage hazards and risks, and ensuring there is risk oversight and assurance. Further, the DSwMS and its compliance obligations can provide a means to address issues associated with deployment of autonomous vessels. These issues include the lack of on-board personnel to conduct organic level preventative maintenance and defect rectification, post-incident actions that would prevent or minimise harm to the environment, and dependence on non-detached and remotely located support systems for recovery or retrieval.

Through the OSI, DSwMS requires a clear articulation and understanding of the temporal and geographical operating aspects of autonomous vessels. For example, risks (including regulatory and reputational) can vary significantly in the presence of migratory species, within protected areas, and in areas deemed to have high social, heritage, and economic values (Royal Australian Navy, 2023). These temporal and geographical variations are a fundamental aspect of existing Defence maritime environmental controls, such as within the Maritime Activities Environmental Management Plan. The temporal and geographical operating aspects are also a significant factor in deploying autonomous vessels, especially regarding command and control, maintenance, emergency response and recovery/retrieval. Additionally, risks from externalities, which are heavily influenced by temporal and geographical factors (e.g. biofouling), should also be considered (Australian Government, 2022).

c. *Flag/Defence Vessel Register considerations*

Vessels within the Defence jurisdiction, which includes vessels owned and operated by Defence and used for or in support of a Defence purpose, are registered on the Defence Vessel Register.[15] Vessels on the Defence Vessel Register which are 'warships' fly the Australian White Ensign (AWE), and all other vessels generally fly the Australian National Flag (ANF). There are currently no autonomous vessels registered on the Defence Vessel

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[15] For more information and to view the Defence Vessel Register see: https://www.defence.gov.au/business-industry/industry-governance/defence-seaworthiness-regulator/flag-administration-defence-vessel-register.

Register which fly either the ANF or AWE*.[16] Doing so would generally indicate acceptance that the vessel is either a 'warship' or a 'naval auxiliary' as defined in the United Nations Convention on the Law of the Sea (UNCLOS). Notably, for an autonomous vessel to be subject to the rights and responsibilities entailed in UNCLOS for either warships or naval auxiliaries, they must be considered capable of meeting the relevant definitions (Liivoja et al, 2022) (Horne, 2024). The key problematic elements for warships is the definitional element "under the command of an officer duly commissioned by the government of the State" and "manned by a crew which is under regular armed force discipline." This definition is based on the premise that humans are on board the vessel, as either master and crew, special personnel, or passengers (Humphries, 2023) (Horne, 2024) (Trusted Autonomous Systems, 2022). Formal legal determinations are necessary to confirm an official position on this issue, however as stated above existing literature indicates the autonomous element is not insurmountable (Liivoja et al, 2022) (Horne, 2024). This understanding would entitle an autonomous vessel to fly either the AWE or ANF, and exercise the rights and protections that affords.

d. Other considerations: Cyber risk

A major risk related to the use of autonomous vessels is their susceptibility to cyberattacks, due to their heavy reliance on sensors, automation, and integration for operation. These components may be connected to the internet and satellites. Unauthorised interference with these automated systems can be achieved in various ways, including injecting malicious software into a navigation system, infecting the vessel's primary server with ransomware, and spoofing or jamming the vessel's Global Positioning System (GPS) or Global Navigation Satellite System (GNSS) (Akpan et al, 2022). If these critical systems are infiltrated, the vessel may lose its ability to navigate. For instance, spoofed GPS signals may enable hackers to reroute a vessel without triggering an alarm or alert (Hogg and Ghosh, 2016) (Starr, 2013). Unauthorised access to data may allow hackers to modify the data, resulting in misleading navigation information (Roberts et al, 2019). Expected consequences of these incidents could include collision, grounding, environmental damage, and defection (Alcaide and Llave, 2020). These hazards and risks must be identified in a Safety and Environment Case and appropriate controls identified and implemented.

5. Potential impacts of applying existing regulatory frameworks to autonomous vessels

As described above, applying existing regulatory frameworks to autonomous vessels is challenging because they are fundamentally different from crewed vessels and they do not fit the assumptions on which the regulatory framework is based – for example that a human will always be on board, operating and supervising the vessel, and that a vessel will have a life span of 10 years or more (Horne, 2021). These assumptions mean regulatory burden, including required risk controls and survey and certification processes, and associated time and cost implications, may not be reasonably calibrated to the actual risks presented. The potential impacts and consequences of applying existing regulatory frameworks to autonomous vessels are set out in **Table 3** below.

Table 3: Impacts and Potential Consequences

Impact	**Potential consequences**
Uncertainty regarding regulatory risk tolerance, pathways and requirements	- Slower, more expensive, less ambitious technology development (Horne et al, 2023) - Underutilisation of the full capability effects and benefits (including related to safety, efficiency and environmental impact) offered by autonomous vessels (Horne, 2024) - Increased difficulty leveraging industry expertise and effort due to the project budget and schedule risk caused by regulatory uncertainty
Potential inconsistency with risk based regulatory approach	- Cost and time of regulatory compliance could be inconsistent with risks being controlled
Uncertainty regarding how to adapt current systems safety, assurance, and test and evaluation approaches	- Slower pull through of technology into service (Devitt et al, 2021) - Makes it harder to generate trust in a technology (Horne et al, 2023) (Keane et al, 2022) - Slower decision making processes in terms of bringing technology into service and deploying it
No agreed benchmark for best practice (i.e. because there are no agreed technical standards to apply)	- Jeopardises trust and increases uncertainty (Horne, 2023) - Makes it more different to leverage the lessons learned/experience of other parties, i.e. who would otherwise have contributed to the technical standard
Increased burden for both the regulator and the regulated	- Use of resources to understand how the existing framework applies, how autonomous vessels can comply, and how to update the framework to support better integration
Jeopardised social licence	- Compromised Government, community, and general stakeholder support for autonomous vessel related projects and operations, less tolerance for incidents, higher risk thresholds represented in decisions

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[16] *_At the date of submission of this paper._

As Horne et al articulate, “Because of regulation assuming human oversight, often autonomous systems are either unable to operate legally, or they are subject to very limiting processes and restrictions, which fail to address the key issues that differentiate them from traditional systems.” (Horne et al, 2023).

6. Key recommendations for Defence regulators

The analysis conducted in this paper, and the experience of ODSwR staff to date in supporting the uptake of autonomous vessels in the Australian defence enterprise, has enabled compilation of a number of key recommendations for defence regulators to consider in approaching and executing the regulation of autonomous vessels. These are set out in **Table 4** below:

Table 4: Key Recommendations for Defence Regulators

Topic	**Recommendation**
Proactively seek to enable test, trial and operation	1. Implement formal, repeatable flexibility mechanisms to enable development, test and trialling, and operation 2. Implement regulatory sandbox approaches to enable agile and iterative test and trialling (Humphries et al, 2023) 3. Ensure all approaches are scalable and flexible (Horne, 2023) 4. Elicit feedback and lessons learned from tests, trials and operations, and use it to adapt existing approaches 5. Establish the objective risk tolerance of decision makers and communicate that to relevant stakeholders, including in what circumstances that tolerance will change and the impact on decision making considerations and thresholds 6. Establish agreed objective ways to build trust in technology for different stakeholders in the capability life cycle (Horne, 2024) 7. Prioritise both short and medium term regulatory development so that technology is able to be used now, but a more tailored approach also becomes available as soon as possible 8. Publish clear guidance material identifying requirements and methods for compliance 9. Upskill the regulator workforce and associated stakeholders in autonomous technology
Domestic and international collaboration	10. Collaboration is critical and should be facilitated as a priority to enable the sharing of lessons learned and generation of new ideas. For example, in an Australian domestic context, in 2023 ODSwR established the Defence Robotic and Autonomous Systems Community of Practice, which has membership across all domains and services 11. In an international context consider establishing an International Defence Maritime Regulators Community of Practice (as advocated for by Dr Rachel Horne)
Regulatory development	12. Consider the degree of consistency required between the regulatory frameworks of Australia and its allies to facilitate interoperability 13. Consider the need to establish common language regarding autonomous systems across regulatory frameworks and domains (Horne, 2024) 14. Work with co-regulators to establish clear co-regulatory boundaries and where necessary put in place a tailored regulatory treatment to avoid delay and uncertainty for operators 15. Identify what a best practice regulatory approach looks like for the relevant regulatory context, which fits the risk tolerance of the organisation, and then work to implement it in a way that means autonomous vessels don’t have to rely on exemptions/bespoke approaches beyond the short term 16. Consider the literature regarding regulation of emerging technology, and utilise the concepts that are relevant and appropriate. For example, Horne et al proposed 10 principles to base regulatory development and implementation on: Trust-centred; Collaborative; Risk-based; Evidence-led; Facilitate experimentation; Systems-focussed; Usable; Consistent; Adaptable and Reviewable. These are intended to collectively “…provide a domain and technology agnostic basis for a regulatory framework development and implementation approach that supports the design, manufacture and operation of safe and trusted autonomous systems.” (Horne et al, 2023)

‘Learning by doing’ is one of the most successful way of identifying regulatory issues and gaps and workable short, medium and long term solutions (Humphries et al, 2023). For example, activities such as the Autonomous Warrior Exercise hosted by Warfare Innovation Navy[17], or the Trusted Autonomous Systems Maritime Showcase held at the ReefWorks test range in 2022[18], push the bounds of regulatory frameworks, build experience, and enable identification of key learnings to use to inform regulatory development.

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[17] Note Warfare Innovation Navy transitioned into Maritime Integration and Systems Branch on 13 May 24.

[18] See TAS Maritime Showcase Report (December 2022) for more information: https://tasdcrc.com.au/reflecting-on-the-tas-maritime-showcase-demonstration-september-2022/.

7. Conclusion

This paper provided an analysis of the regulatory landscape for autonomous vessels being developed and used by the Australian Defence maritime enterprise. As an emerging technology, autonomous vessels are poised to revolutionise sea warfare in the coming decades thanks to their agility, resilience, and potential for lethality. This trend is reflected in the heavy investments made by countries such as Australia, the United States of America, and the United Kingdom. In light of these developments, the analysis in the paper is timely, highly informative and significant for the regulated community, ODSwR, and other Defence regulators.

The paper analysed the existing regulatory landscape for autonomous vessels developed and used by the Defence maritime enterprise, most notably the DSwMS. The DSwMS is an important framework for ensuring safe operation of autonomous vessels and facilitating achievement of their defined tasking in the defence context. Ensuring safe operation of these vessels brings with it practical challenges. Among the challenges are the lack of humans on board the vessels and their heavy reliance on sensors, artificial intelligence, as well as information and communications technology for operation. To overcome these challenges, Capability Managers must carefully consider issues such as safety, environment impact, flag and cyber security risks. These factors are equally applicable to crewed vessels. However, the unique nature of autonomous vessels requires closer monitoring and greater management of risks and hazards. Achieving these goals necessitates a fit for purpose regulatory landscape, supported by clear guidance materials for Capability Managers, their delegated personnel, and other stakeholders.

This paper offered recommendations to better facilitate the development and use of autonomous vessels in a Defence context. These were divided into three key topics: (1) Proactively seek to enable test, trial and operation; (2) domestic and international collaboration; and (3) regulatory development. It was also noted that 'learning by doing' is one of the most successful ways of identifying regulatory issues and gaps and workable short, medium and long term solutions. The application of these recommendations is expected to improve the integration of autonomous vessels into existing regulatory frameworks, while supporting the development of fit for purpose amended or new regulatory frameworks. This outcome will support the translation of the opportunities presented by autonomous vessels into capability, enabling realisation of the RAN's predication that "employing RAS-AI will enable a more agile, resilient, and lethal fighting force, enhancing Navy's ability to Fight and Win at Sea." (Royal Australian Navy, 2022).

Reference List

Articles, Books, and Reports

Akpan, F, Bendiab, G, Shiaeles, S, Karamperidis, S, and Michaloliakos, M 2020, 'Cybersecurity Challenges in the Maritime Sector', *Network*, vol. 2, no 1, pp.126-130, DOI: 10.3390/network2010009.

Alcaide, JI & Llave, RG 2020, 'Critical Infrastructures Cybersecurity and the Maritime Sector', *Transport Research Procedia*, vol. 45, p. 552, DOI: 10.1016/j.trpro.2020.03.058.

Austal 2024, *Austal Australia Completes Sea Trials for Royal Australian Navy's Patrol Boat Autonomy Trial*, accessed 23 April 2024, <http://www.austal.com>.

Australian Government & Australian Institute of Marine Science (2022), *Marine Autonomous Systems: Environmental Impact Considerations*, Canberra.

Australian Government, Department of Agriculture, Fisheries and Forestry 2009, *National Biofouling Management Guidelines for Non-trading Vessels*, accessed 30 April 2024, <http://www.marinepests.gov.au>.

Australian Government, Department of Agriculture, Fisheries and Forestry 2015, *Anti-fouling and In-water Cleaning Guidelines*, accessed 30 April 2024, <http://www.agriculture.gov.au>.

Australian Government, Department of Climate Change, Energy, the Environment and Water 2021, *Sonar and Seismic Impacts*, accessed 30 April 2024, <http://www.dcceew.gov.au>.

Australian Government, Department of Climate Change, Energy, the Environment and Water 2023, *Sea Dumping*, accessed 30 April 2024, <http://www.dcceew.gov.au>.

Australian Government, Department of Climate Change, Energy, the Environment and Water 2021, *Ozone Protection and Synthetic Greenhouse Gas Management Legislation*, accessed 30 April 2024, <http://www.dcceew.gov.au>.

Australian Government, Department of Climate Change, Energy, the Environment and Water 2013, *National Guidance on the Management of Whale and Dolphin Incidents in Australian Waters*, accessed 30 April 2024, <http://www.dcceew.gov.au>.

Australian Government, Department of Climate Change, Energy, the Environment and Water 2017, *National Strategy for Reducing Vessel Strike on Cetaceans and Other Marine Megafauna*, accessed 30 April 2024, <http://www.dcceew.gov.au>.

Australian Government, Department of Defence, Seaworthiness: Australian Naval Classification Authority (2024), *Australian Naval Classification Authority Handy Billy*, accessed 16 May 2024, <http://drnet/dswr/ANCA/Pages/ANCA%20Handy%20Billy.aspx>.

Australian Government, Department of Defence (2024), *Australian Naval Classification Authority*, accessed 9 May 2024, <https://www.defence.gov.au/business-industry/industry-governance/australian-naval-classification-authority>.

Australian Government, Department of Defence 2024, *2024 National Defence Strategy and 2024 Integrated Investment Program*, accessed 23 April 2024, <http://www.defence.gov.au>.

Australian Government, Department of Defence 2024, *Enhanced Lethality Surface Combatant Fleet: An Independent Analysis of Navy's Surface Combatant Fleet*, accessed 13 April 2024, <http://www.defence.gov.au>.

Australian Government, Department of Defence: Office of the Defence Seaworthiness Regulator, *Fact Sheet – Background of DSwMS*, accessed 13 April 2024, <http://www.defence.gov.au>.

Cross, R 2023, 'Navigating the Future: The Promise of Autonomous Boats', assessed 12 April 2024, <http://www.unsw.edu.au>.

Devitt, S.K, Horne, R, Assaad, Z, Broad, E, Kurniawati, H, Cardier, B, Scott, A, Lazar, S, Gould, M, Adamson, C, and Karl, C, 2021. Trust and safety. *arXiv preprint arXiv:2104.06512.*

Eckstein, M, 'US Navy Aims to Field Manned-unmanned Fleet within 10 Years', 13 April 2023, accessed 15 April 2024, <http://www.defensenews.com>.

Grome, E.D., 2018. 'Spectres of the Sea: The United States Navy's Autonomous Ghost Fleet, Its Capabilities and Impacts, and the Legal Ethical Issues that Surround', *Journal of Maritime Law & Commerce*, vol. 49, no. 1, pp. 33-35 and 45-46.

Harper, J 2024, ‘Pentagon Secures $500M for First Tranche of Replicator Systems’, accessed 6 May 2024 <http//www.defensescoop.com>.

Hogg, T and Ghosh, S 2016, ‘Autonomous Merchant Vessels: Examination of Factors that Impact the Effective Implementation of Unmanned Ships’, *Australian Journal of Maritime & Ocean Affairs*, vol. 8, no. 3, p. 211.

Horne, R, 2024, ‘Regulation of Maritime Autonomous Swarms’, in H Abbas, S Ng & J Scholz (eds), Thinking Swarms, Springer (forthcoming publication 2024).

Horne, R, 2022. TAS Maritime Showcase Report, Trusted Autonomous Systems, (TAS Maritime Showcase Demo Event Report v3.pdf (tasdcrc.com.au)).

Horne, R, 2021. Autonomous and Remotely Operated Vessels 2021 to 2040. *MIAL Future Leaders White Paper. Predictions for the Australian Maritime Industry, 2040.*

Horne, R, Deane, F, Joiner, K, and Tranter, K 2023, ‘Navigating to Smoother Regulatory Waters for Australian Commercial Vessels Capable of Remote or Autonomous Operation: A Systematic Quantitative Literature Review’, *Australian Journal of Maritime & Ocean Affairs,* vol. 15, no. 4, pp. 496-517, DOI 10.1080/18366503.2022.2163549.

Horne, R, Vanderkooi, M, and Guihen, D, 2023, May. Autonomous vessel regulation in Australia: Why an Australian Code of Practice is required. Presented at *IndoPacific International Maritime Conference* Sydney.

Horne, R, Law-Walsh, C, Assaad, Z, and Joiner, K, 2023, July. Ten regulatory principles to scaffold the design, manufacture, and use of trustworthy autonomous systems, illustrated in a maritime context. In *Proceedings of the First International Symposium on Trustworthy Autonomous Systems* (pp. 1-12).

Horne, R, Putland, T, Brady, M, ‘Regulating Trusted Autonomous Systems in Australia’, accessed 1 March 2024 <http://www.arxiv.org>.

Horne, R, Putland, T, Roberson, T, and East, C 2022, *Body of Knowledge: Assurance and Accreditation of Autonomous Systems in Australia*, Edition 1, Trusted Autonomous Systems.

Humphries, F, Horne, R, Olsen, M, Dunbabin, M, Tranter, K, ‘Uncrewed autonomous marine vessels test the limits of maritime safety frameworks’, *WMU Journal of Maritime Affairs*, vol. 22, p. 317-344.

Keane, J, Joiner, K, Arulampalam, S, and Webber, R, 2022. Expediting recovery of autonomous underwater vehicles in dynamic mission environments: A system-of-systems challenge for underwater warfare. *Journal of Field Robotics*, *39*(8), pp.1323-1340.

Liivoja, R, Massingham, E, and McKenzie, S 2022, ‘The Legal Requirement for Command and the Future of Autonomous Military Platforms, *International Law Studies*, vol. 99, no. 1, p. 638.

McCarl, L.I. 2023, ‘Untethering UMVs from Vessels: Why the United States Should Construct a New Environmental Legal Scheme for Unmanned Maritime Vehicles’, *Dickson Law Review*, vol. 127, no. 2, p. 469.

Roberts, F.S., Egan, D, Nelson, C, and Whytlaw, R (2019), *Combined Cyber and Physical Attacks on the Maritime Transportation System*, Centre for Advanced Data Analysis, Rutgers University, p. 10, accessed 12 April 2024, <http://www.par.nst.gov>.

Royal Australian Navy Maritime Safety Bureau 2023, *Maritime Activities Environmental Management Plan: Procedure PS 17*, accessed 30 April 2024, <http://www.drnet/navy/MSB/Environmental/Pages/Maritime-Activities-Environmental-Management-Plan.aspx>.

Royal Australian Navy, *RASAI Strategy 2040: Warfare Innovation Navy*, accessed 17 January 2024, <http://www.navy.gov.au/media-room/publications/ras-ai-strategy-2040>.

Starr, M 2013, *Students Hijack US$80 Yacht with GPS Spoofing*, accessed 12 April 2024, <http://www.cnet.com>.

Trusted Autonomous Systems (2022), *Current Australian Regulatory Framework for Autonomous Vessels in the Maritime Domain*, accessed 15 March 2024, <http://www/tasdcrc.com.au>.

United Kingdom Parliament, House of Commons Library 2023, *Emerging and Disruptive Defence Technologies*, accessed 5 March 2024, <http://www.commonslibrary.parliament.uk/research-briefings/cbp-9184>.

USNI News 2023, *2 Navy Ghost Fleet Unmanned Ships Now in the Western Pacific*, accessed 5 March 2024, <http://www.news.usni.org>.

Legislation and Delegated Legislation

Climate Change Act 2022 (Cth).

Marine Safety (Domestic Commercial Vessel) National Law Regulation 2013 (Cth).

Navigation Act 2012 (Cth).

Navigation Regulation 2013 (Cth).

Shipping Registration Act 1981 (Cth).

International Conventions

International Convention for the Prevention of Pollution from Ships opened for signature 2 November 1973, 1340 UNTS 62 (entry into force 2 October 1983) (MARPOL), acceded by Australia 27 February 2004.

International Convention for the Safety of Life at Sea, opened for signature 1 November 1974, 1184 UNTS 278 (entry into 25 May 1980), acceded by Australia 17 November 1983.

International Convention on Load Lines, opened for signature 5 April 1966, 640 UNTS 133 (entry into force 21 July 1968) (Load Lines), entry into force for Australia, 29 October 1968.

Maritime Labour Convention opened for signature 23 February 2006, 45 ILM 792, UNTS Reg No I-51299 (entry into force 20 August 2013), ratified by Australia 21 December 2011

United Nations Convention on the Law of the Sea opened for signature 10 December 1982, 1833 UNTS 397 (entry into force 16 November 1994), ratified by Australia 5 October 1994

Quasi-Legislative Materials

Defence Seaworthiness Management System Guidance: Making a Seaworthiness Case for Autonomous and Remotely Operated Vessels (Autonomous Vessels) which are Maritime Mission Systems in the Defence Context.

Defence Seaworthiness Management System Manual <http://www.defence.gov.au>.

The Australian Code of Practice for the Design, Construction, Survey, and Operation of Autonomous and Remotely Operated Vessels' <http://www. tasdcrc.com.au>.

The Defence Administrative Policy ME2 – Defence Seaworthiness Management System.

Work Health and Safety (Managing Risks of Hazardous Chemicals in the Workplace) Code of Practice 2015.

T26 Global Combat Ship – More Than Just A Submarine Hunter

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Synopsis

The Type 26 Frigate is designed as an anti-submarine warfare platform building on the innovations of the Type 23, with a focus on hull form, machinery mounting, propeller profile, and noise-quieting electric motors. The inclusion of the Mission Bay provides rapid reconfiguration for a range of different operations, enabling the ship to host various capabilities such as autonomous underwater or aerial vehicle launchers, disaster relief stores, detainee handling facilities, military task equipment, and additional boats. The ship's flexibility and modularity enable it to respond to unidentified and evolving threats, making it a truly multi-role combat vessel. However, the adoption of modularized capability insertion comes with limitations, including compromises in growth margin and challenges in doctrine and capability development, logistics, and cost. It brings challenges related to the maturity of capabilities that could be facilitated, requiring extensive procurement and programme management. Overall, the T26 MB is a tangible representation of the Royal Navy's response to the changing global dynamic and its commitment to maintaining a versatile, adaptable, and lethal maritime force.

Keywords: Mission Bay; Capability; Modularity; Flexibility; Lethality

1. Aim

The purpose of this paper is to give the operating context of the Type 26 (T26), to outline the design intent for T26 and its Mission Bay (MB), to explain how the modularity enables greater versatility and lethality, and concludes by discussing the opportunities modularity gives for the future.

2. Strategic Context: From Type 23 to Type 26

The modern battlespace is now a complex, multi-threat environment in a mutli-polar world (Ellwood, et al., 2022, p. 6). The historical context of the Royal Navy's (RN) Anti-Submarine Warfare (ASW) frigates defending the Iceland-Faroes Gap and nothing else is an obsolete paradigm. This was becoming apparent as the replacement for the Type 23 (T23) Frigate was being designed. The replacement would need to respond to the challenges of undertaking duties beyond that of pure ASW. In 1998 the Future Surface Combatant (FSC) programme was initiated to replace the T23s which were approaching the end of their build programme. The RN needed a ship that was "*An interoperable, survivable, available and adaptable capability that is operable globally within the Maritime Battle Space to contribute to Sea Control for the Joint Force, to contribute to Maritime Force Projection and Joint Force Command and Control with the flexibility to operate across and within the range and scale of Contingent and Non-Contingent Operations.*" (Lonsdale & Lloyd, 2016, p. 34)

By March 2010 the FSC concept had evolved into the Global Combat Ship (GCS). The key change from FSC to GCS was the inclusion of the MB, a versatile integrated facility midships that allows a T26 to organically embark modularised capabilities equivalent to 10 ISO Containers[3] (Jones, 2017). Despite being designed for flexibility, the Type 26 design is still primarily an ASW platform either escorting aircraft carriers or supporting the Continuous At Sea Deterrent as the duty Towed Array Patrol Ship. It shares and develops on many of the innovations that made the T23 Frigate the "*world's quietest warship*" (Abrahamsen, 2019). This includes hull form, resilient or raft mounting of machinery, propeller profile, the ability to fully de-clutch the gearbox running on GE's "*Patented noise-quieting electric motors*" (GE Vernova, 2019) and many other features.

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[2] **Lt Mathew "Taff" Fuge** is currently serving at Defence Equipment & Support as the T26 Deputy Platform Chief Engineer and is responsible for establishing In-Service support. His last appointment was as Deputy Marine Engineer Officer of HMS GLASGOW, the first of class T26 frigate. He started his career in RN as Marine Engineering Mechanic in 2003.

[3] An intermodal container, often called ISO containers because they comply with ISO standards, is a large, standardised container designed built for intermodal freight transport. (Lewandowski, 2016)

https://doi.org/10.24868/11186

However, the need to incorporate the technology necessary to retain the RN's status as a world leader in operating quiet ships was at odds with the need to provide versatility and modularity required of the GCS concept.

This resulted in a ship design that differs from most platforms capable of embarking ISO containers, with the inclusion of a fully enclosed MB rather than a cargo deck. The fundamental part of this flexibility is the rapid reconfiguration enabled by the MB to prepare the Ship for a range of different operations. The MB enables the ship to host a range of capabilities including autonomous underwater or aerial vehicle, disaster relief stores, detainee handling facilities, military task equipment, additional boats, etc, to deliver the full range of tasks expected of a truly multi-role combatant.

As a concept, MBs are not new, with many navies already operating something similar (Bello & Segovia, 2020) (Doerry & Koenig, 2017). What makes the T26 MB unique is the level of versatility it provides. Unlike other MB designs its ability to launch and recover vessels, reconfigure its contents whilst the ship is underway, and transit additional helicopters or rotary UAVs into the hangar, brings a new dimension to this capability. This means the T26's MB enables additional war fighting capacity not previously available to frigates rather than just being a containerised cargo facility.

3. T26 Design Intent

At 149.9m in length, 20m abeam and displaying a forecast 6,900 tonnes the T26 is significantly larger and heavier than the T23 class. Despite this size increase, automation will allow the ships to operate with a smaller ship's company of only 157 rather than the T23s crew of circa 185. Additionally, the T26 will have a surge capacity of a further 50 austere bunks for embarked forces, trainees, etc... The T26 will be fitted with many of the same primary sensors and weapons as the T23 post mid-life update, including the Artisan 3D air surveillance radar, the S2087 towed array sonar, S2150 bow sonar and the Sea Ceptor variant of the Combined Anti-Missile Missile System (Jones, 2017). In an enhancement to current capabilities the 4.5" medium range gun will be upgraded to 5" and the ship will also be fitted with a silo for the Mark 41 Vertical Launch System capable of embarking a range of weapons including the American Tomahawk cruise missile and the Anglo-French Future Anti-Surface Guided Weapon System. It is propelled by a Combined Diesel Electric Or Gas Turbine (CODLOG) propulsion system comprising of 2 of GE's "*Patented noise-quieting electric motors*" (GE Vernova, 2019) and a Rolls Royce MT-30 Gas Turbine direct drive system for sprint speeds.

The first T26, HMS GLASGOW, is due to enter service with the RN in late 2026 with the final ship, HMS LONDON, due to be decommissioned in the late 2060s forming the backbone of the UK's ASW capability for the next 40+ years. The class will have the capacity to support a wide range of capability enhancements and task specific equipments over its lifespan. This includes having the flexibility to respond to yet unidentified threats which may be commonplace by the latter half of the 21st century. This is enabled through the modularisation offered by the MB which will "*deliver the opportunity to decouple the acquisition pathways of the platform and the capabilities it delivers through its operational life.*" (Parkin, 2022) During its operational life it is expected the T26 will be faced by a range of threats from conventional peer-on-peer warfare in the air, surface and subsurface domains, terrorism, piracy, smuggling, and asymmetric attacks sponsored by hostile states. To respond to these current and emerging threats, the T26 must be able to protect itself, and any high value units it may be required to escort, against an increasingly sophisticated range of conventional and advanced complex weaponry. It will be able to carry out the tasks currently expected of a T23 frigate to a higher standard with the capabilities enabled by the MB, whether deploying as a single unit or acting as an escort.

The MB will facilitate increased lethality through enabling the rapid integration of innovative technologies. "*Technology is moving faster than at any point in history - warfare has the potential to be impacted and the RN needs to be a leading force on the latest technological advances.*" (Navy X, 2024) The RN faces a step-change in the operating context of the littoral and maritime domain; the bipolar world of the cold war has come to an end and a multipolar world has emerged with asymmetric threats from state and non-state actors now rife. It is widely thought that "*high technology capabilities*" (Salisbury, 2023) will be a pivotal element in the RN's response to this changing global dynamic. The rate of change is forecast to be far beyond anything experienced since WWII and the RN will need adaptable ships to respond to the evolving threat. One option could be to design a POD with the 150kW-class Laser DEW weapon to de-risk the planned retrofit to as part of Project MIMAS; a vision to inform the RN's projected Future Air Dominance System (FADS) but sufficient power availability in the mission bay could be a limiting factor that would need to be explored. (Scott, 2023)

Occupying an area of some 300m^2 midships in the heart of 1 deck, the T26 MB is one of the RN's responses to this call. At 20m wide, it occupies the entire breadth of the ship's layout and is connected to the hangar immediately aft. (Jones, 2017) It has access to sea on both sides through two hydraulically powered doors and is fitted with an integrated Mission Bay Handling System (MBHS). This is an integrated overhead crane capable of embarking and moving ISO containers within the MB in 3 planes of motion and able to move/rotate with 6 degrees of freedom; enabling it to launch and recover boats and uncrewed vehicles. The MB will be able to house new and novel weapons systems in self-contained ISO containers. This means that when new threats are identified, such as that from Uncrewed Air Vehicles (UAVs), bespoke weapons systems can be developed ashore and embarked rapidly into the Ship. This will significantly reduce the time taken to embody new capabilities from months or even years, to days or even hours. Examples of potential containerised capabilities are shown below in figure 1:

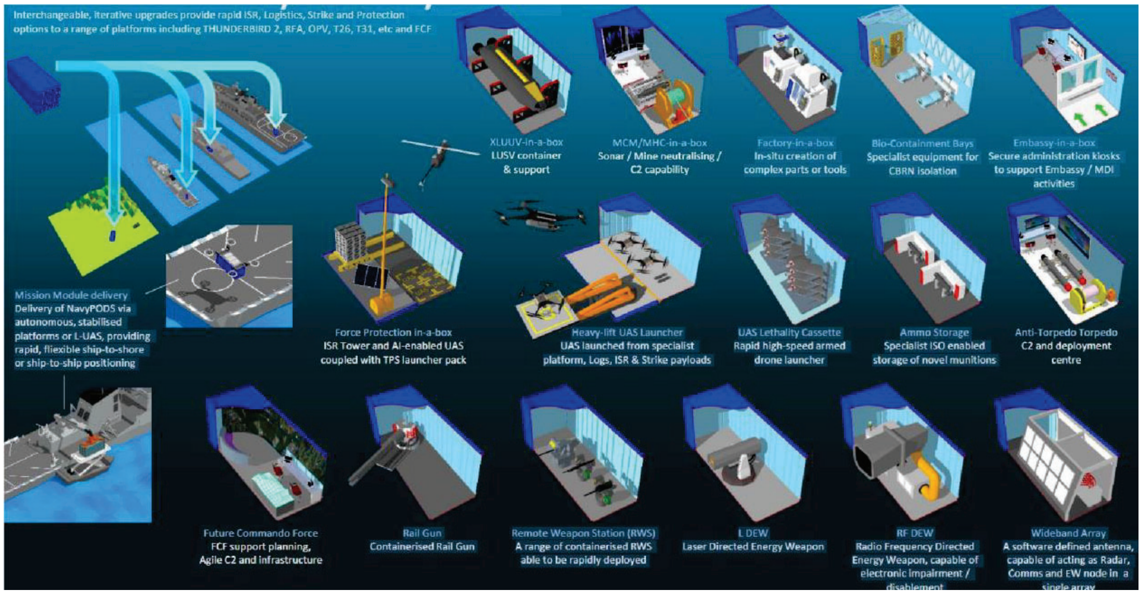

Figure 1: MB Module Concepts (Parkin, 2022, p. 32) © Crown Copyright 2022

4. Benefits Of The T26 Mission Bay

The immediately apparent advantage of the MB is the ability to rapidly embark new capabilities to best tailor the ship to each mission. A range of capabilities have begun to be containerised and the RN can also rely on existing containerised facilities. This includes Humanitarian Aid and Disaster Relief Stores, Role 3 medical facilities in a box, small ships support capability, additional containerised austere accommodation, additional containerised auxiliaries such as Chilled Water Plants or cold rooms and even a holding facility for captured personnel/detainees. This already gives flexibility in tailoring a ship to meet the specific requirements of the operation or tasking it is undertaking, as well as the ability to embark additional resilience against Operational Defects.

As well as the dynamic nature of capabilities fitted within a T26, the MB will be an integral part of the RN's future autonomous vehicle capability. Whilst most RN platforms will be able to deploy UAVs, there are a limited number of platforms that will be able to operate Uncrewed Surface Vehicles or Underwater Under-water Vehicles (UUVs), particularly in high threat areas. The complexity of integrating a remote operated vessel into a warship's order of battle cannot be overstated. It is a problem with which navies around the world are grappling. The T26 MB will be a paradigm shift in their integration. Not only can it launch and recover them organically it can change between uncrewed mission systems in a matter of hours, disembarking UAVs and embarking USVs or UUVs in the same day. The RN's most recent Maritime Operating Concept stressed the importance of uncrewed platforms working in tandem with conventionally crewed and remotely crewed systems: "*Greater uncrewing, combined with a distributed force, will continue to demand highly trained and technically skilled people to provide the necessary support which underpins availability and force support*." (Parkin, 2022)

The modular MB design does not come at zero cost. With the requirement to retain more than 150 tonnes of topweight to enable up to 10 ISO containers of up to 15 tonnes each, compromises have had to be made. The main compromise is the reduction in growth margin and as a result there is very limited stability margin left to consume through life, despite the weight of the Ship. Whilst the MB enables the rapid insertion of discrete, modularised capabilities, that has come at the cost of the ability to fit additional capability as part of the Ship's permanent outfit, particularly if those new capabilities are heavy or high up within the ship.

Secondly, and arguably more importantly the adoption of modularised capability insertion is only viable if there are modules to embark. This requires a paradigm shift in doctrine at the concept phase of the CADMID/T life cycle. Future operational and capability requirements must be geared towards making best use of the MB capability. This requires not only that the mission modules be developed but that all the Defence Lines Of Development are considered for this capability to be revolutionary and to deliver its full potential. The support and storage facilities, the off-ship maintenance, the training, etc… all need to be considered if the MB is to be a success. All this clearly has associated cost on top of the reported £1.31 Billion per platform. Many of the more innovative options are only at the Concept/Assessment phases of the CADMID/T[4] cycle. Looking at existing missions that T26 could be tasked to undertake based on the existing operating profile for T23s, the capability enhancement offered by the MB has been assessed for maturity using a RYAG scale. Green represents capabilities already in service, Yellow represents COTS capabilities that are tested and ready to begin integration trials on RN platforms, Amber represents capabilities which are in the Design phase of the CADMID/T Cycle and Red represents capabilities in the Concept phase of the CADMID/T Cycle. It is important to stress that this assessment is of the maturity of the capabilities that could be housed in the MB to enhance operational effectiveness. It is not an assessment of how effective the T26 will be at completing the tasks/operations.

Counter Narcotics or Anti-Piracy piracy operations, such as those undertaken in the Caribbean and Horn of Africa, are assessed as green with only UAVs and Captured Persons Handling Facilities not yet fully established as in service capabilities. The Future Tactical Uncrewed Air System project has concluded that the Schiebel S100 Camcopter is the preferred system to enter service as PEREGRINE. It is due to enter service on HMS LANCASTER in late 2024 (Claridge, et al., 2023). Likewise Humanitarian Aid and Disaster Relief operations and Littoral Strike operations in the form of SF insertion or Amphibious Raiding are also assessed as green with FTUAS/Peregrine being an optional capability.

Deterrence and Mercantile Marine Escort Duties in the Arabian Gulf/Gulf of Oman region in support of Op Kipion are assessed as yellow driven by the immaturity of the DragonFire counter UAV capability. In April 2024 it was announced that DragonFire will enter service in 2027 on an RN vessel (Shapps, 2024), however a containerised solution has not yet been procured. With the full ORBAT of the RN's autonomous underwater capability is yet to be defined, the assessment of the enhancement to the Towed Array Patrol Ship Duty is also yellow. Whilst the RN has already procured 3 x Remus 100 UUVs, this capability is assessed as amber as it has only been trialled for use in a mine warfare context (DSTL, 2024). The RN has also contracted for a Very Large Uncrewed Underwater Vehicle (VLUUV) called Cetus which is currently at the assessment phase of the

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[4] The CADMID/T cycle is the project lifecycle model used by all branches of the Ministry of Defence (MOD): The Concept, Assessment, Demonstration, Manufacture, In-Service and Disposal/Transfer (CADMID/T) cycle. (Parkin, 2022)

CADMID/T Cycle and as such is assessed as Red. The MB maturity assessment for each of the operations currently undertaken by T23s is graphically presented below in figure 2:

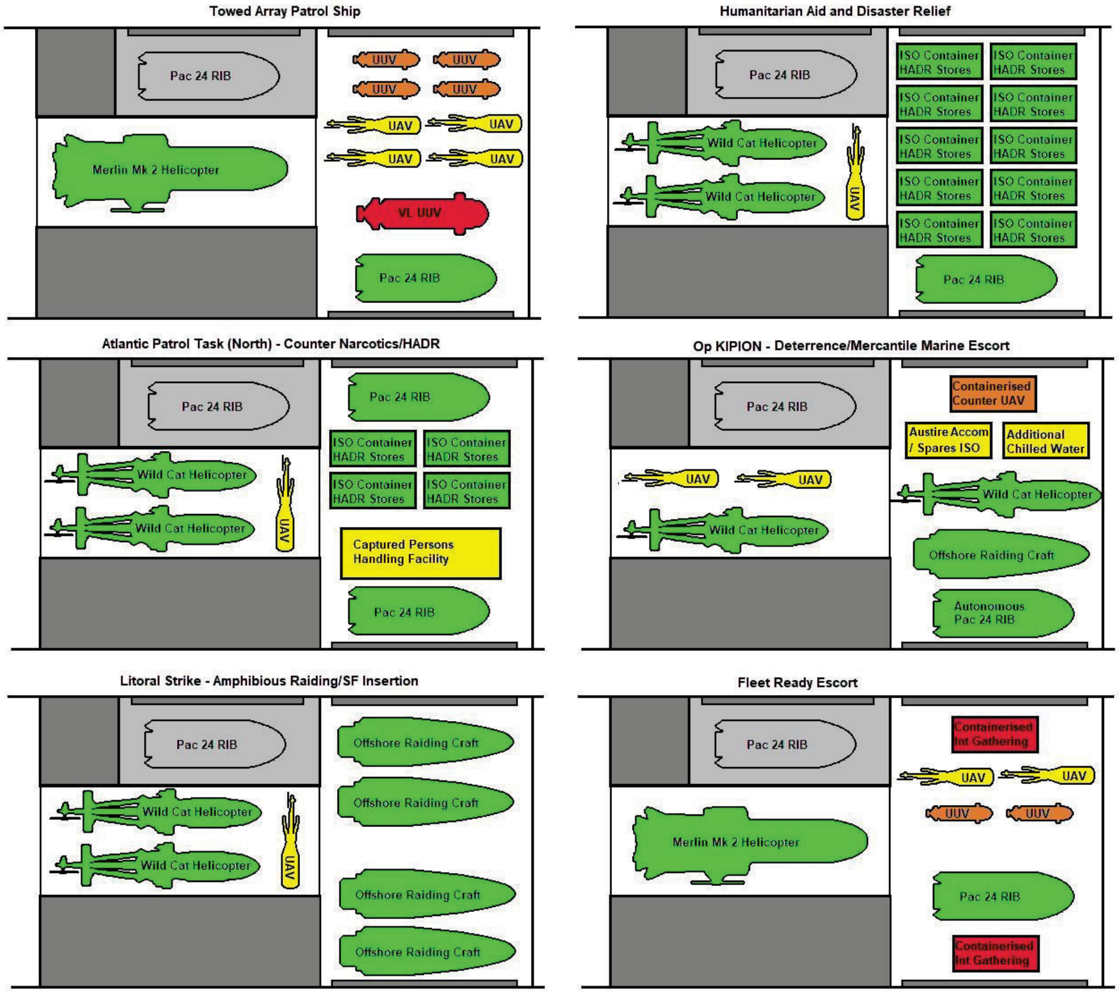

Figure 2: Graphical representation of maturity levels of capabilities likely to be carried in the MB by operational tasking.

There is, therefore, extensive procurement required - CETUS VL UUV, DragonFire Counter UAV, Remus UUV and Peregrine UAV - for the full lethality of the MB to be realised. Each of these capabilities has a programme in place and it is likely that they will deliver this as a stand-alone system before T26 reaches its Initial Operating Capability (IOC) currently forecast for 2028. (Webb, 2024)

5. MB Handling System Operation

Whilst at its core the MB concept itself is simple: Store Containerised Capabilities onboard (Parkin, 2022) the capability of the MB can only be fully realised with an organic means to embark, disembark, and re-configure modules, which is the capability provided by the MB Handling System (MBHS). The means to move modules in, out and around the MB, turns an empty space into a force multiplying asset.

The MBHS primary purpose is to launch and recover boats, USVs and UUVs from either side of the ship whist underway in sea conditions up to sea state 4. It must also be able to safely lift items varying in shape, dimension and weight from any of the nominated tie down locations up to the boundaries of the MB. The MBHS must also be able to embark containers and other capabilities from the dock side to avoid the requirement to rely on dock-side facilities. As well as launch and recovery of and vessels or autonomous vehicles, the MBHS must be able to transfer the craft between its storage and launch positions and, if necessary, move it to a different location within the MB. The MBHS must be able to lift items up-to 15 tonnes in weight including crewed systems or capabilities up-to 10 tonnes in weight. It will be compatible with NATO standard ISO containers as well as equipment that may not be compatible with ISO twist-lock connectors. However, whilst containerising capabilities is the preferred solution it is understood that this may not always be possible. Rolls-Royce Canada, in Ontario was chosen as the preferred supplier in 2014 because of their extensive record and expertise developing and building load lifting equipment for the commercial marine sector. The full contract for production of the MBHS for all three ships in Batch 1 was placed in 2018. In total across 3 nations there are expected to be at least 29 ships operating the MBHS; in addition to the 15 Canadian vessels, there will be 8 RN ships and 6 Australian vessels. (Jones, 2017)

The flexibility and adaptability of the platform through the MB comes with it's challenges. The MBHS is a complex mechanical and electrical system of systems which includes the hydraulically operated MB doors and the emergency generator back-up to enable launch of a PAC 24 sea boat in the event of a total loss of electrical supplies. This is due to the MBHS secondary duty as the launch and recovery method for the starboard sea boat. While the maintenance and defect repair of the individual components and systems is captured as part of the RN's core career training, the safe operation of the system is unique to T26 and a challenging and expensive requirement. Notwithstanding this, a factory environment does not replicate the lived experience of an operating ship, such as pitch and roll conditions and the challenges of embarking and disembarking containers through the MB doors which are not an integrated part of the test facility. Therefore, generation of Standard Operating Procedures and team training may result in utilisation of the onboard system in the First of Class platform. While this appears a sensible and practical solution, operating a complex system such as the MBHS during build will inevitably result in conflictions and possible delays in the build programme.

The MBHS itself is mounted across the width of the MB compartment deckhead on twin I-Beam rails. The complete carriage assembly is then suspended from the rails via 8 roller truck assemblies. This allows the carriage assembly to be moved across all aspects of the MB, allowing for different configurations as required. The height of the compartment and dimensions of the carriage assembly do not allow for loads to be moved over other loads. The assembly is split into upper and lower carriage systems. The upper carriage facilitates slewing activities via a slew ring and chain drives and the lower carriage facilitates the booming activities via boom and luffing cylinders. (Morrow, 2018)

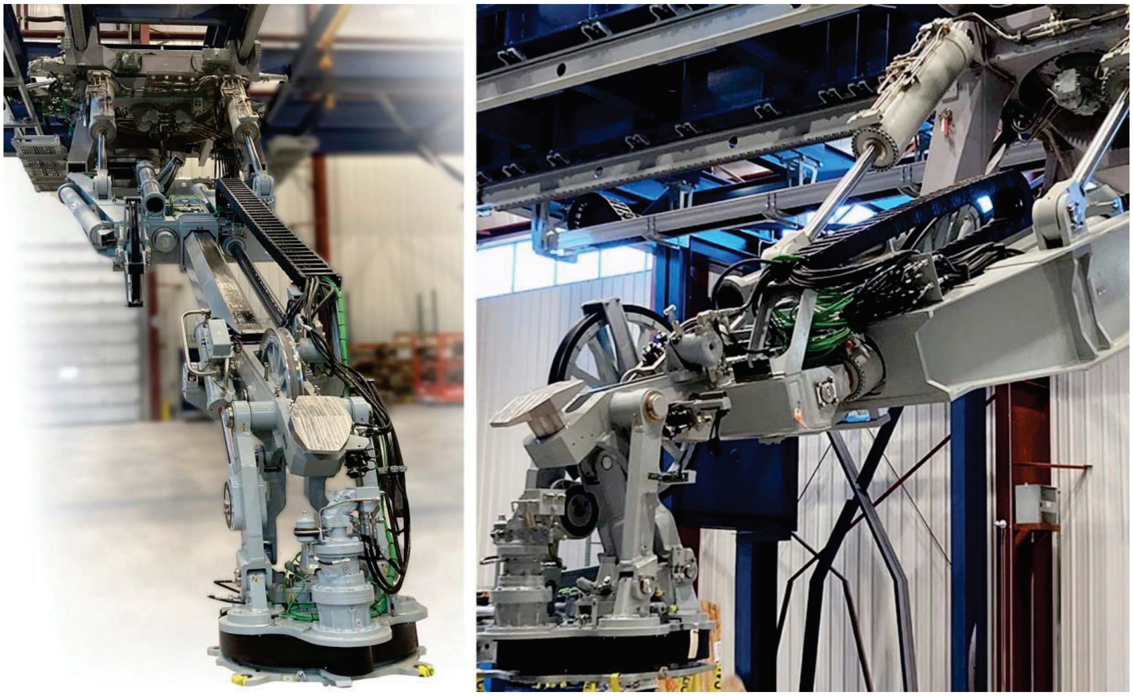

Figure 3a: The first MBHS assembly to be manufactured by Rolls Royce. Extended (left) and retracted (right). (Morrow, 2018) © Rolls-Royce plc 2024

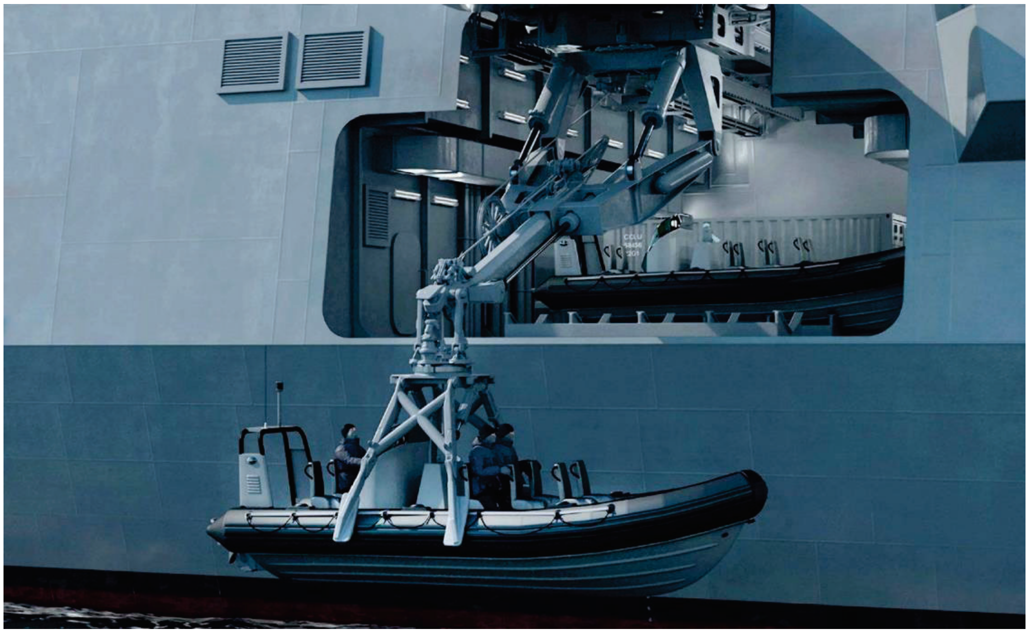

Figure 3b: Mission Bay Handling System Boat Assembly (Morrow, 2018) © Rolls-Royce plc 2024

6. Stability and Loading

As with all vessels, maintaining good stability is paramount in ensuring both hull and crew safety and largely attributed to weight and weight movement. The stability considerations are greatly increased in T26 when considering the embarkation and disembarkation of containers totalling 150 tonnes.

"*A further risk to be considered in the ship building area is the platform structural integrity and balance effects of large MBs.*" (Parkin, 2022, p. 19)

Early on, redundancy in "margins" is considered to allow for growth and future upgrade. Margins are defined as contingency allowances on systems and structure used to manage the impact of uncertainties and to accommodate for through life change. Failure to provide sufficient margin could lead to platforms being unable to accommodate future change, upgrade or refit and ultimately unable to go to sea. Margins are instantiated through physical characteristics like size, weight, and system capacity, margins cost money, and compete for these parameters with the baseline warfighting capability of the ship at delivery (Catton, 2022). It is important that margins are controlled effectively to support the capability requirements through to Out of Service Date (OSD).

At the Initial Preliminary Design Review, it was reported that the Design and Build Margin associated with weight had been completely utilised due to a revised steel weight estimate, together with other equipment weight increases. A weight optimisation activity was initiated with the aim of recovering sufficient Design and Build Margin to take the vessel design and build to OSD. Through a combination of weight reduction initiatives, such as pipework optimisation and Urea concentration increase, together with a re-assessment of critical design limits, revised Design and Build margins were established (Table 1).

Description	**Margin**
Hull and Superstructure	6.2%
Armour	6.2%
Propulsion	7.13%
Electrical	8.35
Control and Communications	7.7%
Auxiliary Systems	8.6%
Outfit and Furnishings	9.6%
Armament	6.4%
Operating Fluids	10%

Effective Wholeship DBM	**455tonne**

Table 1: Revised T26 Design and Build Margins

Many considerations are made during the design phase for potential growth and upgrades that will affect margins, known as Installation Provision Made In-design (IPMd). This will account for all margins (including weight), which will allow for a faster, more efficient fit that will not require in-depth analysis as they have already been factored. The MB containers are included in the IPMd and has accounted for a total capacity of 150 tonnes of containers or equipment. The maximum allowable weight of a single FEU is 15 tonnes (Morrow, 2018)

The In-Service Growth Margin (IGM) is defined as an allowance for unattributable growth to the platform throughout its in-service life and is applicable to the weight and Vertical Centre of Gravity (VCG) of the platform. The IGM is managed by modelling the weight and VCG using growth rates and known design changes. The modelling will be verified for each build model by conducting incline tests in accordance with the Maritime Acquisition Publication on "Stability of Surface Ships". Changes in VCG can occur for two main reasons; an addition of weight high up in the ship or a reduction in weight low down which results in an increase in the VCG. The second is inaccurate assessments of initial VCG or changes in the vertical location of moveable weight items giving a decrease in VCG. Given the relatively low effective wholeship DBM of 455tonnes, the margin will need to be managed carefully by the platform Chief Engineer through life, prioritising upgrades as necessary and ensuring the acceptable limits of VCG are not compromised as a result. This could result in the capacity of the MB being reduced to 8 or even fewer ISO containers.

Consideration could be made towards utilising the allocated container loading provision (150 tonnes) through the IPMD as potential growth margin for platform capability. The MB containers can be embarked, disembarked and repositioned relatively easily using a stability model to calculate the effect. The onboard ballast system that is designed with the MB as an area of significant stability implication, can then be used to ensure the platform remains within allowable limits. The decision to utilise the MB margin as Wholeship DBM would come with greater affect. Any change proposal would need to follow the lengthy full acceptance routine which would include a feasibility study, Installation Solution (IS) and generation of an Engineering Guidance Pack. It would also necessitate significant re-evaluation of the stability profile to account for the potential removal of the 150 tonnes of top weight accommodated by the MB contents and addition of weight at other points across the ship. This could include docking for inclining experiments, at relatively significant cost to the MOD but more importantly take platform availability away.

7. Conclusion

The inclusion of the MB provides rapid reconfiguration for a range of different operations, enabling the ship to host various capabilities such as autonomous underwater or aerial vehicle launchers, disaster relief stores, detainee handling facilities, military task equipment, and additional boats. The ship's flexibility and modularity enable it to respond to unidentified and evolving threats, making it a truly multi-role combat vessel. However, the adoption of modularized capability insertion comes with limitations, including compromises in growth margin and challenges in doctrine and capability development, logistics, and cost. It brings challenges related to the maturity of capabilities that could be housed in it, requiring extensive procurement and programme management. Overall, the T26 MB is a tangible representation of the RN's response to the changing global dynamic and its commitment to maintaining a versatile, adaptable, and lethal maritime force.

References

Abrahamsen, K., 2019. Design of Quiet Ships. *The Journal of Ocean Technology,* October, 14(3), pp. 54-61.

Bello, L. & Segovia, C., 2020. *Evolution and Present of Modularity in Warships.* Santa Monica, California, s.n., pp. 201-210.

Catton, L., 2022. *Nav Archs (You Gotta) Fight For Your Right (To Margins)!.* Durban, SA, s.n., p. 15. Claridge, R., Hadley, L., Evans, D. & Morris, T., 2023. DE&S procures Royal Navy's new 'eye in the sky'. *DESIDER - AN INSIDE LOOK INTO LIFE AT DEFENCE EQUIPMENT & SUPPORT*, 10 MArch, Issue 175, p. 24.

Doerry, N. & Koenig, P., 2017. *Modularity and Adaptability in Future U.S. Navy Ship Design.* Hamburg,, Germany, s.n.
DSTL, 2024. *Dstl and DASA research underpins Royal Navy maritime autonomy.* [Online]

Available at: https://www.gov.uk/government/news/dstl-and-dasa-research-underpins-royal-navy-maritimeautonomy

Ellwood, T. M. et al., 2022. *The Integrated Review, Defence in a Competitive Age and the Defence and Security Industrial Strategy,* Westminster, UK: House of Commons.

GE Vernova, 2019. *Global Combat Ship Ultra-Quiet Hybrid Electric ASW Frigate,* Stafford, UK: GE.

Jones, K., 2017. *Global Cobat Ship.* [Online]
Available at: https://www.baesystems.com/en-uk/product/global-combat-ship

Lewandowski, K., 2016. Growth in the Size of Unit Loads and Shipping Containers from Antique to WWI. *Packaging Technology and Science,* 29(8-9), pp. 451-478.

Lonsdale, J. & Lloyd, K., 2016. *Ministry of Defence Departmental Overview 2015-16,* Westminster, UK: National Audit Office External Relations.

Morrow, B., 2018. *Rolls Royce.* [Online]
Available at: https://www.rolls-royce.com/products-and-services/defence/naval/naval-handlingsystems/mission-bay-handling-system.aspx [Accessed 07 May 2024].

Navy Lookout, 2023. *Refining the requirements for the Type 26 frigate mission bay.* [Online]
Available at: https://www.navylookout.com/refining-the-requirements-for-the-type-26-frigate-mission-bay/

Navy X, 2024. *Technology and Equipment.* [Online]
Available at: https://www.royalnavy.mod.uk/news-and-latest-activity/features/innovation

Parkin, J., 2022. *Maritime Modularity Concept,* Portsmouth, UK: Navy Graphics. Parkin,

J., 2022. *Maritime Operating Context,* Portsmouth, UK: Navy Graphics.

Salisbury, E., 2023. *The future Royal Navy needs more than technology.* [Online]
Available at: https://www.navylookout.com/the-future-royal-navy-needs-more-than-technology/

Scott, R., 2023. *UK's New DEW Roadmap Includes Maritime Laser Weapon.* [Online]
Available at: https://www.navalnews.com/event-news/dsei-2023/2023/09/uks-new-dew-roadmap-includesmaritime-laser-weapon/#prettyPhoto [Accessed 10 May 2024].

Shapps, G., 2024. *New procurement rules help rapid fitting of military laser to Royal Navy ships.* [Online].

Webb, F., 2024. *Royal Navy: MoD reveal when brand new Type 26 frigates will enter service as HMS Glasgow work continues.* [Online]
Available at: https://www.portsmouth.co.uk/news/defence/mod-reveals-when-royal-navy-type-26-ships-willenter-service-4522988

Glossary of terms

T26	Type 26
MB	Mission Bay
RN	Royal Navy
ASW	Anti-Submarine Warfare
T23	Type 23
FSC	Future Surface Combatant
GCS	Global Combat Ship
ISO	International Standardisation Organisation
GE	General Electric
PCE	Platform Chief Engineer
DPCE	Deputy Platform Chief Engineer
UAV	Unmanned Aerial Vehicle
CODLOG	Combined Diesel Electric or Gas Turbine
PODS	Persistent Operational Deployment Systems
FADS	Future Air Dominance System

LDEW	Laser Directed Energy Weapon
MBHS	Mission Bay Handling System
CADMID/T	Concept Assessment Development Manufacture In-Service Disposal / Transfer
COTS	Commercial Of The Shelf
RYAG	Red Yellow Amber Green
ORBAT	Order of Battle
DSTL	Defence Science and Technology Laboratory
IOC	Initial Operating Capability
NATO	North Atlantic Treaty Organisation
PAC 24	Pacific 24
OSD	Out of Service Date
DBM	Design Build Margin
IPMD	Installation Provision Made in Design
FEU	Forty foot Equivalent Unit
IGM	In-service Growth Margin
VCG	Vertical Centre of Gravity

Radical Warship Concepts – Testing and Acceptance

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Synopsis

This paper examines the shape of future naval fleets and how they could contain radical new warship platform concepts including multi-hulls with hydrofoils able to sprint at high speed to respond to an emerging crisis. The lean, mean and green radical concept discussed is a Small Waterplane Area Nonohull (SWAN) with nine connected hulls. Propulsion arrangements are enabled by the electric ship concept, arranged for survivability in the modular multi-hull arrangement. The paper addresses the drivers for moving from evolution to revolution in warship design and how, when faced with radical new concepts, we can test, and accept them using modelling and simulation.

Keywords: disaster relief; electric propulsion; hydrofoils; hyper-modular; ISO container; small waterplane area nonohull (SWAN).

1. Introduction

At the Royal Institution of Naval Architects (RINA) Warship conference in 2015 the author, presented a historical review of naval fleets and the step changes and evolutions through history in a paper called "The Shape of Fleets to Come". That paper was developed into a forward-looking view presented at the RINA Warship conference in June 2024, which explored radical ship concepts and how they might be tested. This paper resulted from discussions with marine engineers on whether both disciplines needed to follow a radical approach.

2. The Challenge

Warships have not generally been required to carry heavy loads, but with the advent of asymmetric threats and the need for multi-role platforms to counter the rapidly changing nature of threats, a different approach is needed. The theme of the RINA Warship conference in 2019 was multi-role vessels and several papers, including that of David Andrews, further inspired this concept. Since then, there has been much development of containerised solutions and we are now in an era of offboard systems, in particular drones. Previous research by the author reviewed the success of modularity, looking back to the Danish STANFLEX concept and others. Modularity is very much with us today, and the common module of choice is an International Standards Organisation (ISO) shipping container, normally in the 20-foot robust variant. Current warfare in the Black Sea, Red Sea and Eastern Mediterranean requires much larger capacity for missiles, munitions, and the delivery of logistics. There is also a pressing need to respond urgently to rapidly developing crises. This drives a need for new types of platforms optimised for offboard systems, modular weapons, adaptability for multiple missions and the ability to sprint into action, whilst also being able to loiter for long periods in areas of strategic interest as a deterrent. Today there is a need to deliver all the following:

- Large numbers of defensive missiles
- Vast quantities of ammunition for artillery and deployed land forces
- Clean water and food for displaced civilians
- Medical and humanitarian aid
- Intelligence, surveillance, reconnaissance, and information operations
- Armour, vehicles and heavy military equipment and troops to an unprepared shore
- Offboard autonomous systems in the air, surface, and underwater domains

There is also a pressing need to deal with non-combatant evacuations and to render assistance to climate emergencies that are occurring more frequently around the globe. A lean, lithe frigate or destroyer just can't carry the payload required to really help. This paper explores a family of extremely modular ships, how they

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[1] **Author's Biography**

Matthew Hood holds the current position of Head of Practice at Nova Systems in the UK, responsible for expanding capability in support of defence systems. The Author's experience includes the Royal Corps of Naval Constructors for design, acceptance, and support of warships, auxiliaries, and submarines. He has also spent many years supporting aircraft, rail systems and C4ISTAR systems.

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might be powered and what we would need to do to test and accept such radical new platforms into service with global navies.

3. Modern Conflict

What innovative technologies are needed to respond to the challenges of modern conflict? How will we overcome swarms of small, cheap drones in the air, on the surface and under the surface? There has been a step change in the threat environment, particularly in the volume of attacks against ships. We have not been fighting a warship-on-warship war since arguably 1941. Today we need to respond and strike quickly, with the most appropriate effect, which may be missiles, drones, troops, or humanitarian aid.

Nick Childs writing on "*Britain's Future Navy*" (2012) looks at the balance of the fleet (Ch 10). Discussing the Royal Fleet Auxiliary (RFA) Bay Class Landing Ships Dock Auxiliary he identifies "*They have huge amounts of space to carry equipment and stores. They lack a helicopter hangar, but that could be added. Some critics say they are critically short on power. They are not pretty, but they are certainly imposing, due largely to an astonishing tower block of superstructure*". The dock ship is extremely versatile and suits modern warfare with offboard systems very well. However, they need to move much faster in response to rapidly changing situations. Protected space at sea is a highly valued commodity in modern warships.

A surface combatant needs to take the fight to the enemy, a combat radius of 100nm from the ship is needed, with range from base of more than 1000nm to deliver effect. That 'effect' will probably be offboard drones that loiter and react when instructed. A single warship is no longer the fighting unit, it is an operating base for offboard systems, (see the UK Defence Drone Strategy, 2023). A more unified approach across services and allied forces is demanded. War now has many more shades of sub-threshold conflict. Lawrence Freedman in his book ('*The Future of War – A History*' 2017), concludes with his view that "*War therefore has a future. It can make an appearance wherever there is a combination of an intensive dispute and available forms of violence*".

The concept presented is one of operating bases or mother ships rather than a complex fully integrated warship. Existing and operating safely within the ocean environment will remain the primary challenge for any ship, explained beautifully by Helen Czerski in her book ("*Blue Machine – How the Ocean Shapes our World*" 2023).

4. SWAN Concept

In 2015, inspired by work in Navy Command Headquarters, the author developed a concept referred to obliquely in his 2015 paper. So, what is a SWAN? A *Small Waterplane Area Nonohull*. That is nine hulls connected together. Each is a separate unit that can be designed, built, maintained, and potentially operated separately. This is a combination of a Small Waterplane Area Twin Hull (SWATH), a trimaran, a hydrofoil, and a Surface Effect Ship (SES), a schematic layout is shown in figure 1 with functions described in Table 1.

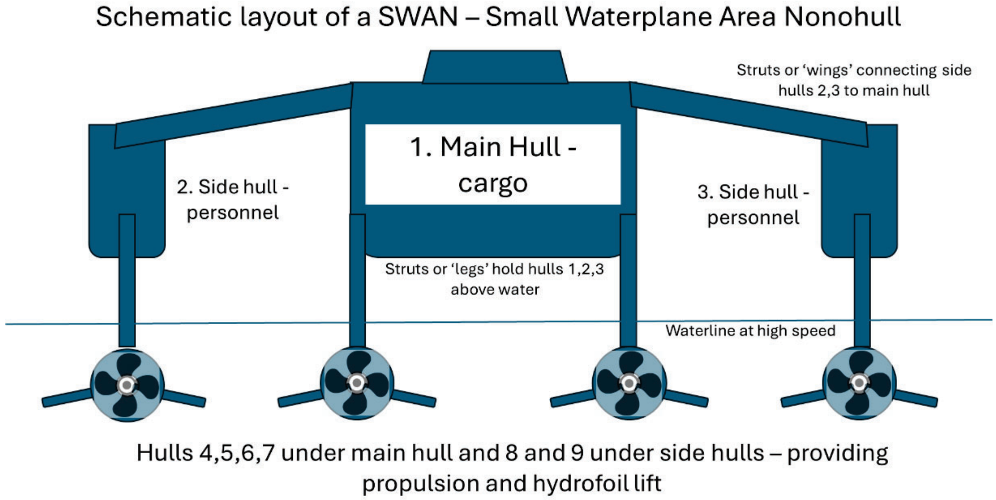
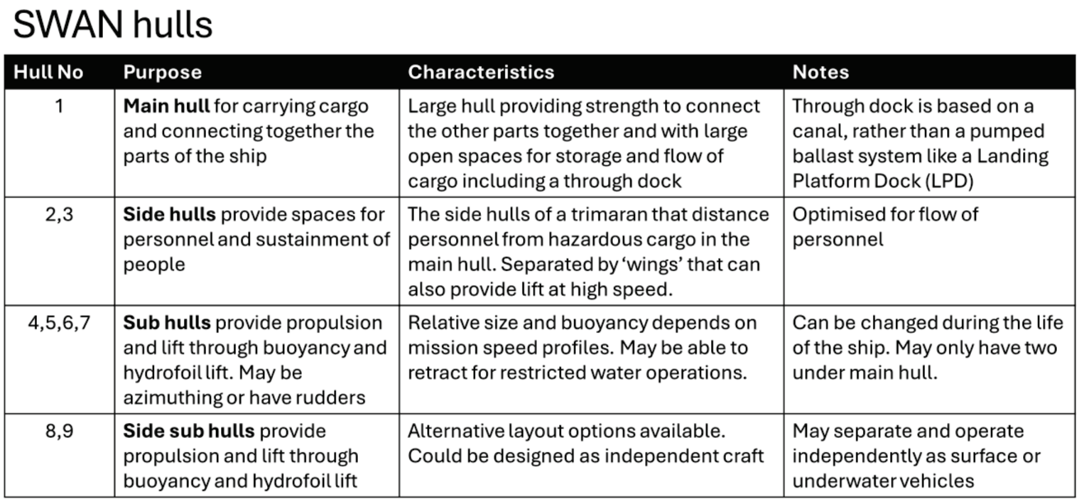


Figure 1. Schematic layout (section view) of the nine hulls of a Small Waterplane Area Nonohull



SWAN hulls

Hull No	Purpose	Characteristics	Notes
1	**Main hull** for carrying cargo and connecting together the parts of the ship	Large hull providing strength to connect the other parts together and with large open spaces for storage and flow of cargo including a through dock	Through dock is based on a canal, rather than a pumped ballast system like a Landing Platform Dock (LPD)
2,3	**Side hulls** provide spaces for personnel and sustainment of people	The side hulls of a trimaran that distance personnel from hazardous cargo in the main hull. Separated by 'wings' that can also provide lift at high speed.	Optimised for flow of personnel
4,5,6,7	**Sub hulls** provide propulsion and lift through buoyancy and hydrofoil lift. May be azimuthing or have rudders	Relative size and buoyancy depends on mission speed profiles. May be able to retract for restricted water operations.	Can be changed during the life of the ship. May only have two under main hull.
8,9	**Side sub hulls** provide propulsion and lift through buoyancy and hydrofoil lift	Alternative layout options available. Could be designed as independent craft	May separate and operate independently as surface or underwater vehicles

Table 1. Hull purpose and modes of operation

At low or zero speed hulls 1,2 and 3 are floating. These are partially supported by buoyancy from the sub surface hulls 4-9. Once forward speed commences with propulsion from the sub surface hulls the hydrofoils provide lift, raising the floating hulls above the water. At high-speed aerodynamic lift also contributes.

Sprint capability is the key requirement for this design concept. The need to respond to an incident quickly over long distances, potentially trans-oceanic, is the primary driver. This drives the need for foiling clear of the top of the waves. The need for speed in a warship is an ancient characteristic that has been reduced today due to cost and the introduction of missiles and aircraft. However, lean, mean ships with sprint capabilities allow a nation to respond rapidly to incidents to gain military advantage or save lives. Responding within 12 or 24 hours saves lives of those injured, if the ship doesn't arrive for three to five days there will be many more casualties and disease will have set in. Speed can also help avoid trouble and evade threats or prevent an adversary from establishing a secure base. To pursue this concept, you must want to respond quickly to emerging incidents. Whether for your own benefit or others.

This concept requires high power density, well proven in gas turbines, as fitted to warships and high-speed craft. Massive power will be required making use of large gas turbines providing collectively more than a hundred megawatts to achieve the sprint speeds. Hybrid configurations of propulsion and storage enable concepts that include electric and diesel propulsion and use of other fuels. In hydrofoil mode these craft will move at 40 – 60 knots extending their radius of response to 960-1440nm in a day.

Loiter and offload are other key features of this concept. The ability to load and offload at sea and operate as an amphibious ship enables a huge range of mission types. With the rise of autonomous offboard systems this has become much more important. These SWAN ships are designed to load and offload surface and underwater vehicles. The key to this operation is a through dock, or canal in the centre of the main hull. The general principle is to onload small craft, at the bow and offload at the stern. This allows craft to be gathered with a low forward speed of the ship. Offload at the stern provides protection from waves and shields the daughter craft from hostile enemy action. The canal will vary in size across the family of SWAN ships. Around 3m wide in the smallest increasing to around 8m wide to take a Landing Craft Utility sized craft.

Segregation for survivability is a key feature of this SWAN concept. Moving the propulsion motors into separate hulls (large pods) and having many of them enables survivability through replication of propulsive power. The primary benefit is to build separate hulls for people and cargo. Each hull should be able to survive independently and operate to some extent if disconnected. Modular design will also enable swapping or cannibalisation of modules between hulls and between different craft in the SWAN family.

A family of SWANs is covered in this concept with different sizes, see figure 2. Different configurations can be achieved with the same construction modules. The smallest craft, dubbed the Cygnet, should fit into the larger craft with 8m wide docks. Lengths of craft are selectable and the sub hulls providing buoyancy and power might be changed through life. For example, to explore new propulsion motors or propulsors.

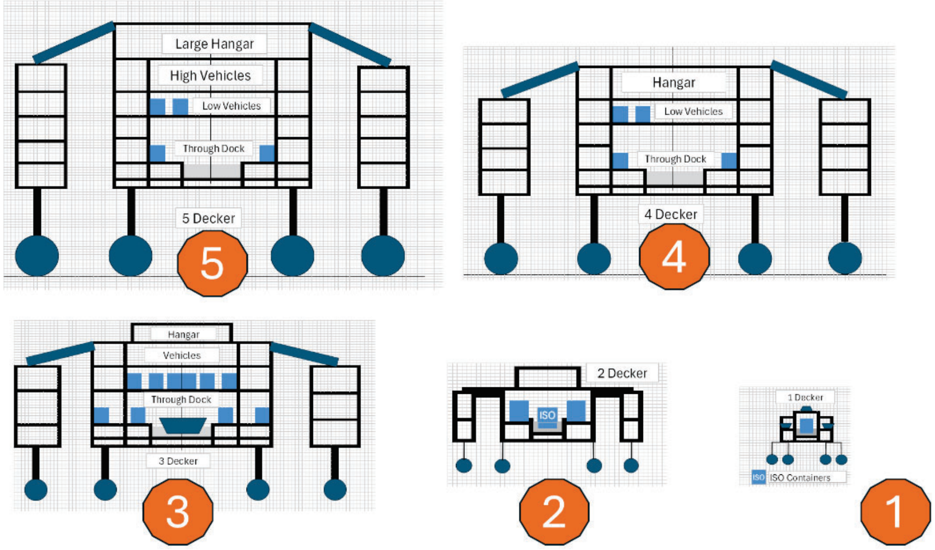


Figure 2. Family of SWAN concept craft, the small 1 Decker is the cygnet in the family

Cygnet – the one deck craft. This small craft is designed to carry up to three 20-foot ISO containers in barges (possibly inflatable), vehicles, or uncrewed craft, that fit within the through dock. It also carries 2 boats and is intended for a mission crew of 8 persons with two operators. This is conceived as a 24m long by 8m wide craft that can fit inside the dock of the larger craft in the family. Renders of the early concept are shown in figures 3 and 4. The main hull acts as an aerofoil to provide additional aerodynamic lift during high-speed transit.

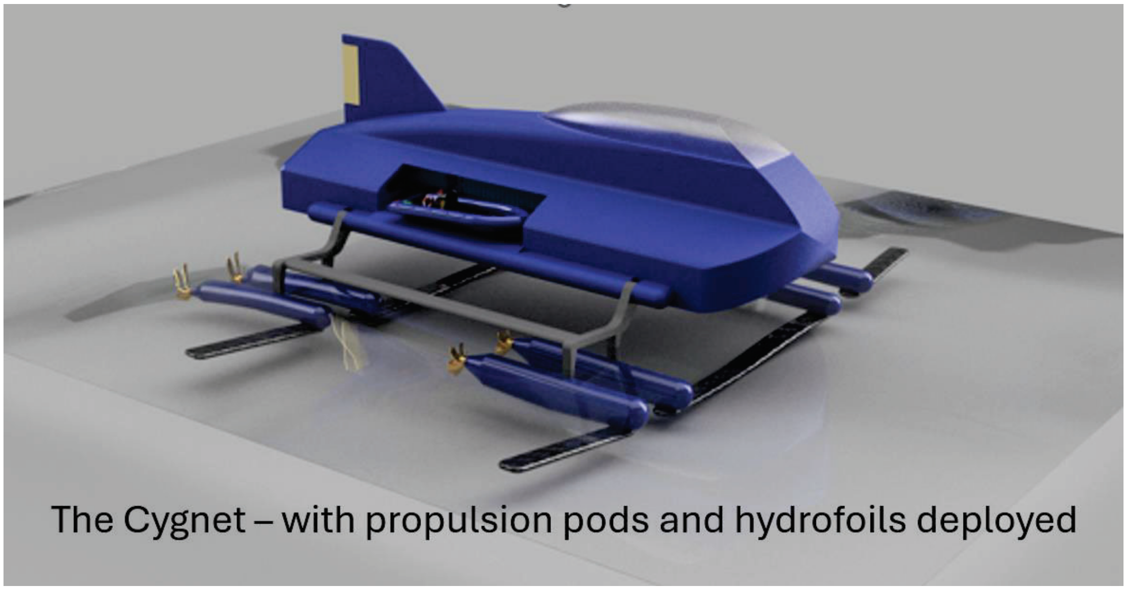


Figure 3. 1-Decker Cygnet render showing pods and foils deployed and sea boats. This craft is 24m long.

Hyper-modular construction is intended across this family of craft. Wherever possible the systems and equipment are to be included in ISO containers and ‘plugged in’ to the craft. This includes the following:

- Mission modules
- Propulsion prime movers
- Some electrical generation and possibly storage
- Water making and wastewater treatment
- Refrigeration and stores

- HVAC equipment and controls
- Firefighting systems including mist or fog systems
- Computing and communications
- Secondary accommodation for passengers
- Medical facilities so that they can be donated ashore

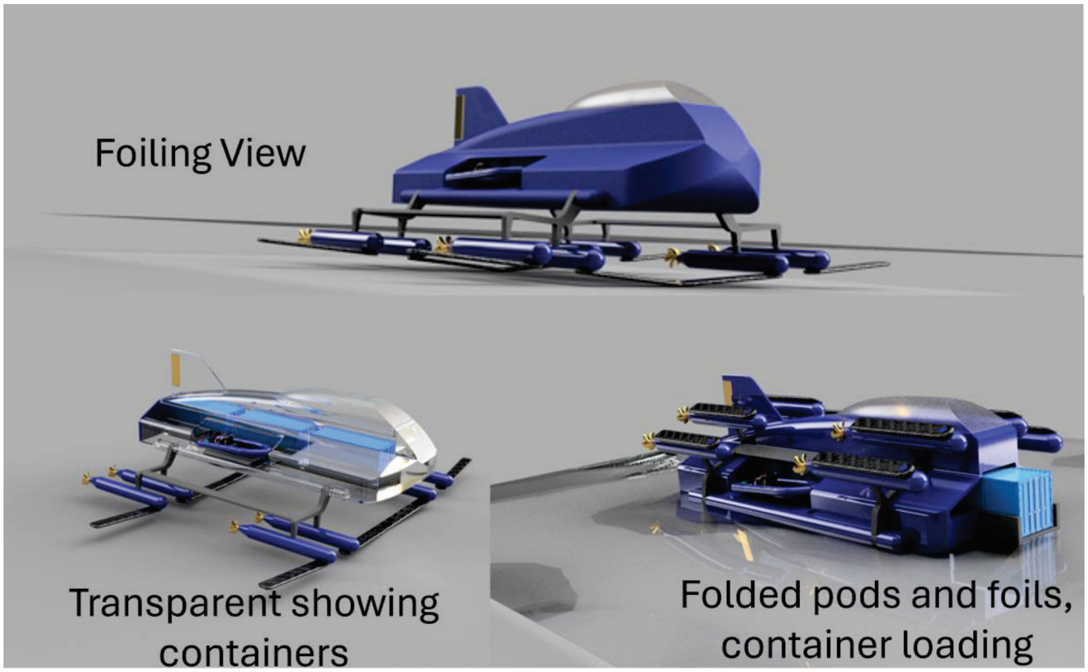


Figure 4. Renders of Cygnet craft showing different aspects including stowage of three 20' ISO containers

Modules will be able to be swapped during life and even during operations. Consequently, there is a need to move loaded ISO containers at sea. Containers will be able to be moved around the ship, not just as cargo but as operational systems. Interfaces for containers placed around the ship will allow exchange.

Hybrid composite construction is intended to achieve the light weight. Recently developed materials including fire-resistant structural foams and carbon fibre with fire retardant resins enable new approaches. Standard external module sizes for the sandwich panels are intended with selectable sandwich cores for different parts of the ship, for example acoustic or thermal insulation, or ceramic armour.

Included within the thickness of the hybrid composite panels are ducts for electrical cabling and pipework. Deck panels will incorporate scuppers and drains and deckhead panels will have air extraction for ventilation, lighting, smoke and heat detection and firefighting spray systems built into the structure. Computer controllers will be built into the structural panels. The data gathered is used for maintenance based on actual panel use.

Evolution through life is a key objective for this concept. By separating the hulls, designing for modular construction, and incorporating many systems and equipment into containers these craft will be able to adapt. All mission systems will be modular and carried, rather than integrated. These ships will be able to carry and operate containerised UAVs and weapon systems from the upper deck.

6. Propulsion Configuration

This SWAN concept requires a flexible propulsion system, with commonality of modules across the family. Generation of electricity needs to occur in the main hull and side hulls above water. Gas turbines to achieve sprint speeds will be placed in modules high in the ship to allow large air flows. Loiter speeds and hotel loads will need smaller generators, probably diesels, also in ISO modules. Different fuels might be used for sprint and loiter to enable greener operations. The sub hulls provide propulsion thrust through electric motors in the hulls underwater.

Electric ship principles are used. This is intended to be a Direct Current (DC) architecture with multiple prime movers as generators with at least one in each of the above water hulls. The approach of generation as alternating current (AC) current with immediate rectification to DC for storage, distribution, and powering electric motors is proposed. This approach overcomes the challenges of synchronization of AC phases between circuits in each hull.

Rotating machines such as motor generators or flywheels are proposed for energy storage and to maintain spinning reserve. These machines offer the opportunity to absorb spikes in power demand and generation from multiple prime movers of different sizes. This approach resulted in discussions with colleagues, and a reminder that this problem was solved before using synchronous-self-shifting (SSS) clutches. Hendry in his paper "*Application & Experience of the SSS (Synchro-Self-Shifting) Clutch for High Speed Gas Turbine Marine Propulsion Systems*" (2018) reviews propulsion arrangements in high-speed craft since the 1960s and how some were successful whilst others remained experimental. SSS clutches have now become a fit and forget item for the Royal Navy following careful selection.

The electricity produced and used by the different machines enables segregation for redundancy with different systems, potentially at different voltages in each hull. Digital DC propulsion motors in the pods can be fed with high voltage whilst other circuits and systems operate at lower voltages.

Flywheels enable smoothing and storage of energy, peak lopping of demand and potential use as gyroscopic stabilisers for these high-speed craft, or as drivers for a stabilisation system. This architecture avoids the need for additional running engines to maintain 'spinning reserve' as it is provided by the rotating machines.

Sustained sprint requires continuous high power for long periods and immediate consumption of generated electricity. However, in other modes of operation the electricity can be stored in batteries and/or capacitors for use at loiter speeds and alongside. The expectation is that these ships will spend most of their lives loitering, so efficient loiter operation will help to reduce greenhouse gas emissions.

7. Modelling And Simulation

This concept will go nowhere unless we can digitally model and simulate the solutions. The mathematics of the design must balance across:

- Mass and Lift
- Thrust and Drag
- Energy for endurance and speed
- Strength and deflections

Digital Engineering and Model Based Systems Engineering is used widely and forms the basis for examining radical concepts and testing them before the designs firm up. Systems can be modelled at different stages of the lifecycle, in particular developing requirements, conducting verification and validation and operational test and evaluation. A digital approach to design, acceptance and testing supported by digital modelling and simulation is needed through life. Three-dimensional computer aided design (CAD) enables a substantial amount of modelling and finite element analysis for stress, vibration, thermal loads, flows and other factors as part of the native tools as each component is designed. More integrated Product Lifecycle Management systems enable connection of product models with mathematical and physics models to test a design in purely digital format as the design develops.

8. Testing and Acceptance

The hull structures and systems modules can be tested separately, and systems integration facilities constructed ashore, distributed at different locations. By using a digital integration architecture via exchange of data messages the systems can be tested before they are brought together as a ship. The physical and communications interface being the ISO container interface that includes data interfaces. The propulsion system proposed is constructed from proven components in an unproven configuration so can be tested in a modular manner before combining to system level within each hull. Replication across multiple hulls also saves testing time.

Propulsion and electrical systems and digital controllers will need thorough testing and acceptance in offsite facilities, again replicating systems in multiple hulls saves effort. Facilities proving the generation configuration of connected machines will need to be collocated, but the motors, connected by DC do not have to be proven together with the power generation system. With a data interfacing approach, rather than tight integration between systems, it will be possible to test systems across wide area networks.

Aircraft and air systems use an extremely thorough, but more risk-based, approach to certification and acceptance. This radical platform type will certainly require a prototype of at least the smallest craft. That in turn can provide acceptance evidence to support the larger members of the family. It is normal for air platforms to enter service with limited operating envelopes that expand through life. The same approach is proposed here with constrained speed, power, payload, and weather limitations applied early in the lifecycle. The Bow Tie approach to safety is recommended for a more risk-based approach (as opposed to a design code approach), as used by the Military Airworthiness Authority, which enables duty holders to understand the residual safety risks that they are accountable for.

Sensors and weapons testing can be divorced from the life of the ship. Cooperative use of sensors and weapons across allied nations must be a key goal. These ships could carry novel weapons. The ability to separate crew from hazardous cargo and weapons, and the use of the huge electrical capacity for sprint creates opportunities for these craft to operate extremely powerful weapons systems.

9. Safety And Regulation

High-speed foiling is beyond the capability of human controllers. These platforms require multiple automated systems for stability, ‘flight control’, power distribution, and many other aspects. Operations will be automated wherever practicable, and oversight, diagnosis and analytics of operational data will be carried out ashore. First line maintenance aboard will be reduced by a deliberate approach to ‘repair by exchange’ of modules.

Each module will require its own lifecycle, type approval, maintenance checks and inspections for this concept to work. A data-driven approach to product lifecycle management is essential. Different parties are likely to maintain responsibility for different modules, some may be operated on a service basis with ownership remaining with an OEM or leasing agent, using ‘power by the hour’.

Ship safety will be based around the IMO High-Speed Craft Code (2008) with warship extensions for carrying munitions and higher survivability with the intent of complying with Naval Ship Rules. However, it is evident that this concept cannot comply directly with the current Lloyds Register Naval Ships Rules. Materials selection within the hybrid composites and fire protection will be critical. Blast radii from hazards, in particular munitions, is mitigated by the arrangement of the multiple hulls. High speed reduces vulnerability to attack by some threats but creates other hazards. The ISO containers for weapons systems will need be constructed as magazines.

The safety case for operation of armed and unarmed offboard systems in all environments will require particular care. The use of Ship Vehicle Operating Limits based on Ship Helicopter Operating Limits (SHOL) is something that is developing for drones and is being explored by my colleagues with very advanced modelling and simulation. Complications are added by remote operation of weapons from ashore under some circumstances.

To take this radical approach requires a cautious approach to regulators. A pressing need for new warship types exists and an approach that avoids acquisitions of twenty years and a billion pounds is needed. By designing an ecosystem for multi-national, multi-role, multi-type, multi-supplier solutions this concept addresses those challenges.

10. Conclusions and Further Research

This paper provides a deliberate challenge to current warship design. The thesis that a radical design concept requires a radical approach to test, evaluation, and acceptance may be flawed. Including well proven components and sub-systems could mitigate risks. INEC exists to promote advances in naval engineering and sharing of experiences between navies. This concept offers an approach that pushes boundaries and is aimed at multi-national collaborations at module, hull and ship level.

This concept is the author’s research rather than a company sponsored project, the opinions expressed are not those of my employer. Over 10,000 people a year are killed by natural disasters and whilst these ships can’t save those who are killed by the initial event, navies can and do help to save the lives of those who are injured, trapped, displaced, or left without clean water, shelter, or functioning infrastructure. There is a pressing need for internationally managed ‘peaceships’ as well as next generation warships. Further research into this need for high-speed sprint capability over long distances to respond to incidents is needed.

These ships speak to the deterrent effect of being able to rapidly respond and to surprise a hostile entity. The most significant warlike feature of these ships is "*surprise*". Others will never know what these ships are capable of because they can be filled with non-descript boxes that can be deployed to other units, to locations ashore and could contain a myriad of different capabilities. As these ships evolve through their lives the modularity will enable them to keep up with the pace of technology and respond to different issues that threaten our sea lines of communication and our interests around the globe. They could also adapt to oceanographic changes that will driver wider climate change and political tension, resource competition, displacement of people, and war. These SWAN ships with hyper-modularity are arguably *lean, mean and green*, with the exception of the vital need to sprint into action to respond to an unfolding crisis and to save lives.

The author invites further discussion on this concept and a collaborative approach with warship designers, builders, and maintainers to stimulate further research and co-development of this concept. Equipment suitable for modular application is also sought together with implementation of the developing NATO standards for ISO container interfaces. Any sources of research funding to assist with high-speed responses for humanitarian aid and disaster relief are also welcomed.

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References

ANDREWS, D, 'The Multi Role Combatant – Jack of All trades, Master of None', Warship 2019: Multi-Role Vessels, RINA, June 2019.

BALLANTYNE, IAIN, 'Strike from the Sea', Pen and Sword Books, ISBN 1-84415-059-3, 2004.

CHILDS, NICK, 'Britain's Future Navy', Pen and Sword Books, ISBN 978-1-84884-291-5, 2012.

CZERSKI, HELEN, 'Blue Machine – How the Ocean Shapes Our World', Penguin Random House, ISBN 978-1-9117-0910-7, 2023.

FREEDMAN, LAWRENCE, 'The Future of War – A History', Penguin Random House, ISBN 978-1-846-14749-4, 2017.

HENDRY, M L, 'Application & Experience of the SSS (Synchro-Self-Shifting) Clutch for High Speed Gas Turbine Marine Propulsion Systems, Proceedings of ASME Turbo Expo, Oslo, June 2018.

HOOD, M W, 'The Shape of Fleets to Come', Warship 2015: Future Surface Vessels, RINA, June 2015.

HOOD, M W, 'Radical Warship Platform Concepts – Testing and Acceptance', Warship 2024, RINA, June 2024.

International Maritime Organisation, '2000 HSC Code – International Code of Safety for High-Speed Craft, ISBN 987-92-801-4240-2, 2008 edition.

UK Ministry of Defence, 'Defence Drone Strategy – the UK's Approach to Defence Uncrewed Systems', UK Ministry of Defence, 22 February 2024 Defence Drone Strategy - the UK's approach to Defence Uncrewed Systems - GOV.UK (www.gov.uk) .

A triple-network-layer method for designing high resilience system architectures

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Synopsis

Complex multi-domain engineering systems are at the heart of modern warfare. The very nature of complexity means that the interactions between elements of such systems can lead to unforeseen consequences that are difficult to understand and predict. This is particularly true when there are varied types of disruption that can take place, such as component failure or deliberate attacks. The ability to analyse and assess how complex systems recover from disruption is critical for understanding resilience, especially as automated control design aspects are increasing. This paper proposes a triple-layer network methodology that is based on the physical, functional, and control layers of a complex system. The number of controllers and connections between controllers and functional nodes are varied for different design options, and resilience is evaluated. By identifying the control design features that have the greatest influence on resilience, the preferred design option can be chosen, ensuring that resilience meets the design objectives in the early stages with only the necessary redundancy elements. The method is suggested to be integrated into the overall process of designing high resilience monitored and controlled system architectures ultimately allowing to design for recoverability

Keywords: resilience, recoverability multi-layer network analysis, early-stage system architecture design, control systems.

1. Introduction background

1.1. Research motivation

The complexity and interconnectedness of modern engineering systems are caused by their increasing size, the amount of data they manage, and the introduction of new and more sophisticated technologies, such as automation and platform management with their increased monitoring and control elements. This has made engineering systems more vulnerable to expected and unexpected disruptions during their lifecycle. INCOSE (2023) defined the purpose of the system architecture process as “to generate system architecture alternatives, select one or more alternatives(s) that address stakeholder concerns and system requirements, and express this in consistent views and models”. In this way, system architecture process is an appropriate process to address resilience concerns and the resilience requirements, therefore, having appropriate system architecture method to address resilience is valuable.

1.2. Resilience

The resilience concept seeks to address the ever-changing vulnerability of engineering systems, necessitating the design and development of resilience systems. Resilience is defined by (Haimes 2009) as the “ability of a system to withstand a major disruption within acceptable degradation parameters and to recover with a suitable time and reasonable costs and risks”. A typical resilience curve is shown in Figure 1 displaying the system performance plotted against time prior, during and post disruption.

Resilience is impacted by the topology of the system, thus the interconnectivity of the constituent components of the system (Bertoni et al. 2021). Similarly, (Office of the Assistant Secretary of Defense for Homeland Defense and Global Security 2015) specifies resilience as an inherent property of a system architecture, recommending that it should be analysed and defined during the system architecture process alongside other design variables. Redundancy in the system architecture is an important aspect of designing a resilient system.

Author’s Biography

Giota Paparistodimou works as a Model Based Systems Engineer with BAE Systems. She is a Chartered Engineer, has completed a PhD in System Engineering and has a number of academic publications in the area. She has worked internationally, as a newbuilding ship Classification Surveyor in South Korea, Project Engineer in Brazil and Norway, and as a Principal System Engineer in the UK. Philip Knight is a Senior Lecturer in Mathematics at the University of Strathclyde. His primary research interests are in applied linear algebra, encompassing a wide range of topics in network analysis. He has written a number of highly cited papers on matrix algorithms and is co-author of the well-regarded textbook "A First Course in Network Theory". Malcolm Robb is a Research and Technology Engineering Manager for BAE Systems’ Future Business and Technology Team. He has worked for BAE Systems for twenty-six years on a wide variety of warship designs and projects. Malcolm holds a PhD in composite materials. Gail Hughes, a Chartered Engineer, is a Principal Research and Technology System Engineer and has a PhD in control system design.

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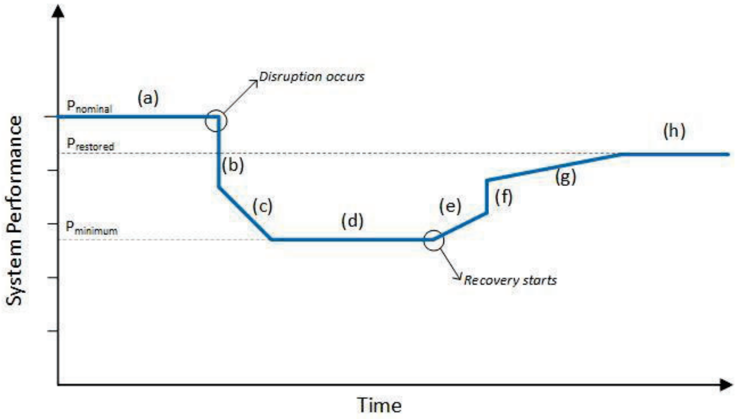
Redundancy improves recovery capabilities by creating different routes that aid in preserving system performance when disruptions take place (Yodo and Wang 2016). (Paparistodimou et al. 2020) in a structural viewpoint stated design for redundancy involves “architectural (components and their connections) options in the instantiated system architecture that are capable of satisfying the same function”.

Meanwhile, (Wied et al. 2020) mentions that the difference between a resilience and a predictive approach is that the first prepares, monitors, responds, rebounds, whereas the second forecasts, assesses, plans and prevents. Particularly, resilience relates to the ability to respond (Hollnagel et al. 2011).

Facets of resilience are related to the system's ability to monitor its operations, anticipate potential failures, and respond to such failures (Yodo and Wang 2016).



(a) Normal operation phase, system operates at nominal operation performance ($P_{nominal}$).
(b) Immediate degraded state.
(c) Subsequent degrading state
(d) Resulting disrupted state, system operates at minimum disrupted performance ($P_{minimum}$).
(e) Recovery improved state.
(f) Resulting recovered state.
(g) Repairing state
(h) Final stable state, system operates at stable restored performance ($P_{restored}$).

Figure 1: Generic resilience curve

1.3. Monitor and control systems relationship with resilience

Today's complex engineering systems have extensive monitoring and control over the behaviour of their constituent components, which adds to the complexity of modern systems as the number of components and intertwined interactions grows. A high level of monitoring and control helps to manage the system's behaviour better under normal conditions, as well as detect degradation behaviour before it becomes completely incapacitated, allowing control systems to initiate and complete the recovery pathway. Monitoring and control architecture supports complex systems' resilience behaviour by detecting early signs of degraded behaviour and facilitating quick and intelligent corrective actions to recover system performance to normal. As a result, monitoring and control are essential for enabling the resilience recovery path, but they can also increase system vulnerability in the event that they are unable to support the system's recovery.

In this way, monitoring and control have become key parts of complex systems, but also have become great causes of vulnerabilities, as failures of sensors or controllers are becoming key causes for loss of total system functionality. Thus, when sensors or controllers fail, the entire system's resilience suffers. The recent cases of sensor failures that contributed to total system failure demonstrate the inherent interdependence between designing resilient systems and resilient of monitoring and control architectures. According to (Yoo et al. 2020) sensors cause problems and downtime in various aerospace engineering systems and have even contributed to plane crashes. These are key characteristics in the automated system making it even more important that they be studied early and in-depth.

Control systems increase the size and therefore the complexity of systems, and have a key involvement in initiating recovery in modern systems, particularly those that are automated. As a result, selecting the control system design that initiates recovery by designing the right connectivity between control and redundant nodes in a system is a significant consideration that has a direct impact on the system's resilience. System architecture methods and tools that focus on the control-redundancy-resilience requirements are needed because performing such analysis is not a simple task.

1.4. Research gap and aim

Network science approaches have been proposed in naval ship engineering literature to analyse vulnerability of ship distributed systems (Rigterink 2014, de Vos and Stapersma 2018, Paparistodimou et al. 2018, Brownlow et al. 2021). However, these existing methods do not offer a method that focusses on a dynamic analysis upon the resilience of the interwoven physical, functional, and control layers of a ship distributed system.

The aim of the paper is to support the system architectures process by creating a method that models the physical, functional, and control layers of systems together, facilitates the generation of options for system architectures, and provides a resilience assessment calculation. The results of the proposed method can help guide decisions about resilience, functional redundancy, and control architecture design during the system architecture process. The following Section 2 details the proposed method and illustrates the concept in Figure 2.

2. Methodology

The method proposed in the paper employs a triple layer network (physical, functional, and control). The physical layer represents the spatial system architecture, with disruption occurring at the physical layer and the consequences extending to the functional layer. The functional layer represents the functional flows and includes standby redundancy nodes, which are designed to recover in the event of a disruption. The control layer represents the control nodes. Standby redundant nodes initiate recovery only when they receive control node instructions via the network connectivity. A resilience metric is proposed for evaluating resilience at the functional layer. In the methodology presented herein, the experiments focus on the controlling aspects of the system. The function of a control node is to trigger the start-up of standby redundant nodes at the functional layer. The method enables the variation of the number of control nodes; their connectivity to the standby redundancy nodes enables the experimentation to identify improved resilient design solutions. Questions to be investigated include the placement of controllers and the interlinking of controllers and standby systems to optimise a measure of resilience subject to constraints on the level of redundancy. The resilience of the network is assessed by simulating disruptions at the functional layer in an exhaustive fashion. Post disruption control nodes trigger the start-up of standby redundant nodes at the functional layer. The resilience of the different control design options is assessed based on a resilience metric that measures if the required performance (specified by the user in terms of components whose function is essential) is satisfied post disruption. The methodology identifies control layouts at an early stage of the design process that can offer benefits for resilient behaviour.

2.1. Methodology Stages

Figure 1 illustrates the triple layer modelling approach with a simplistic example to aid the understanding of the methodology.

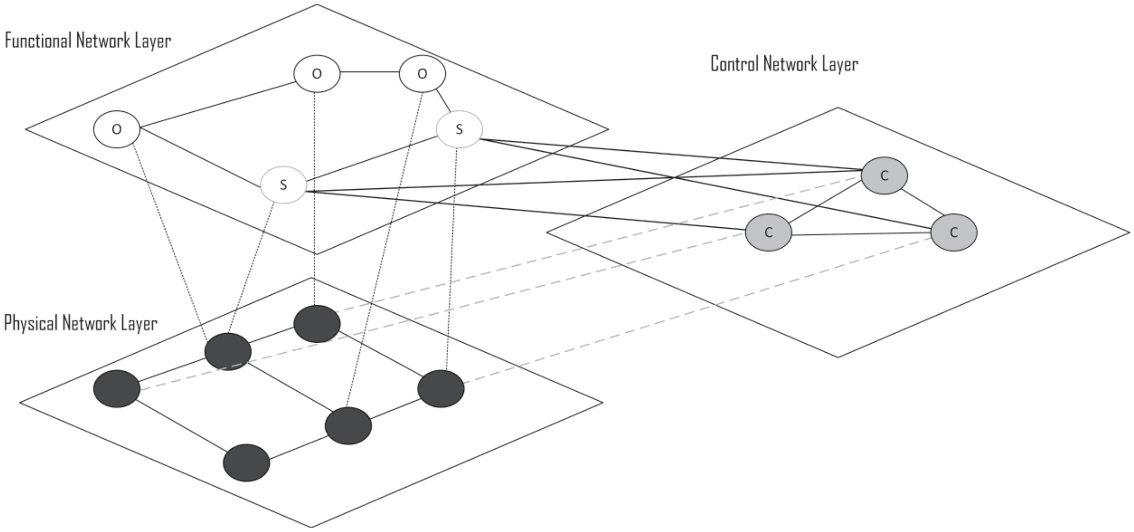


Figure 2: Triple layer modelling approach

The nodes in the functional network layer annotated with letter S indicate the standby redundant components, and the nodes annotated with the letter O show the operational components prior to disruption. The nodes annotated with the letter C in control network layer represent controllers. Table 1 presents an overview of the stages of the methodology which are implemented in MATLAB software environment.

Table 1: Methodology stages overview

	METHODOLOGY STAGE	**EXPLANATION**	**INPUTS/OUTPUT**
1	Definition of the functional network layer	Representing the functional elements and their links; a common approach to model system architectural functionality is using Design Structure Matrix. (Eppinger and Browning 2012, Paparistodimou et al. 2017).	***Input*** a. Number of functional elements. b. Interconnectivity of elements c. Construct Design Structure Matrix. d. Definition of standby redundant and operational functional elements. e. Definition of source and sink elements. f. Essential dependencies between sinks and sources for satisfactory and normal performance.
	Definition of the physical network layer	Representing the spatial dimensional layer as a grid network	***Input*** Number of potential sites in each dimension under consideration.
3	Definition of the control network layer	Representing the controllers as a network layer	***Input*** Total number of controllers (nc).
4	Definition of the standby links between control network layer and functional network layer	Representing the standby links between controllers and standby components ➢ Default Option is to assign standby links from standby components to their physically nearest controller(s). ➢ When increasing the standby links for a standby component the tool selects the additional standby link from the next physically nearest controller.	***Input*** Number of standby links between each standby component in the functional layer to each controller (s_{nc}) at the control layer.
5	Definition of the links between control network layer and physical layer.	Representing the location (as connectivity) of controllers on physical network. ➢ The controllers represent the centre of areas within the ship that a particular controller is controlling. ➢ Default strategy is to place controller physically near the neighbourhood of the standby redundant components they control.	***Input*** Physical locations for each of the controllers according to deck/zone.
6	Simulation of physical disruptions	Simulating disruption by removing the disrupted nodes (functional components and controller) and any associated edges of that node. ➢ Default controller disruption approach: the tool removes an increasing number of controllers from 1 to n_c, and measures the effect on resilience, producing the resilience curves.	***Input*** Number of components to disrupt in the functional layer in a combinatorial exhaustive approach, which means, for example for two components every possible combination of two components is disrupted in the functional network.
7	Simulation of recovery	Simulating recovery by a default approach that is a controller starts up standby redundancy post disruption.	***Output***
8	Calculation of resilience	Calculating resilience by a measurement measured based on the proportion of disruptive events for which performance is restored within an acceptable time. ➢ The proposed resilience metric measures performance in terms of level connectivity between sources and sinks previously defined by Paparistodimou et al. (2020a).	***Output***

2.2. Assumptions

A number of assumptions and simplifications are adopted to develop the proposed methodology. It is assumed that all controllers are linked to sensors receiving real time information. Sensors are not modelled in the methodology, but it is assumed that each physical node has a sensor attached to it. In addition, it is assumed that each controller receives timely information from sensors, and that controllers are immediately activated on receipt of a message from a sensor.

3. Case Study & Results

The case study presented herein models the power and propulsion systems of a generic naval ship with the addition of controllers (Figure 3) and is based on a medium redundancy technical system architecture as previously presented in Paparistodimou et al. (2020b). In Figure 3 components illustrated in black colour (annotated in white) show standby components and the standby links from controllers to standby components are annotated in grey colour. The number of controllers and number of standby links are the two design variables that are investigated in the case study.

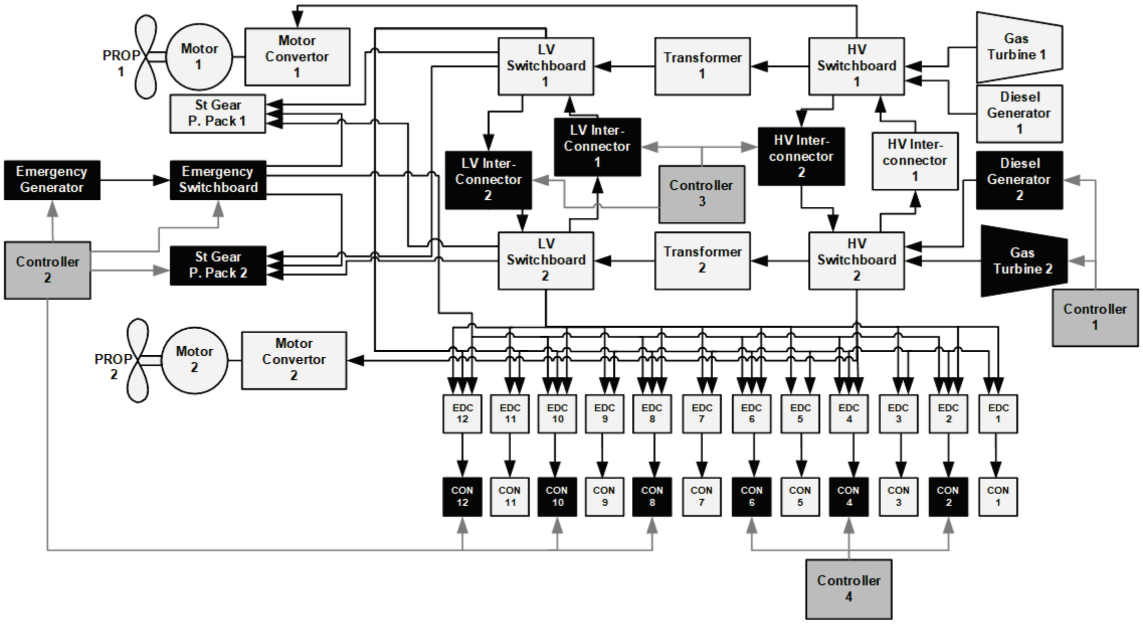


Figure 3: Generic power and propulsion system architecture (design option 1) adapted from Paparistodimou et al. (2020b)

In Figure 3 the generic power and propulsion system architecture design (design option 1) is varied systematically to create various design options based on Design of Experiment approach. The number of controllers is defined as Variable 1 and the standby connectivity between controllers and standby redundant components is defined as Variable 2 as shown in Table 2.

Table 2: Definition of Variable 1 & 2

Transformer	**Value 1**	**Value 2**	**Value 3**
Variable 1: Number of Controllers(n_c)	4	6	8
Variable 2: Standby links (s_{nc})	1	2	3

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Based on the above definition of control system architecture variables, the following nine design options are devised. The resilience for each design option presented in Table 3 was calculated based on the resilience metric under combinatory physical disruptions. The resilience measure is an average of the resilience score as 1, 2, 3…n_c controllers are removed after the system suffers 3 components disruption (all combinations of components disruption are considered). The controllers are removed in several different patterns to give a better picture of what's happening.

Table 3: List of Generated Design Options

Transformer	**Variable 1**	**Variable 2**	**Resilience metric**
Design Option 1	$n_c = 4$	$s_{nc} = 1$	0.5196
Design Option 2	$n_c = 4$	$s_{nc} = 2$	0.6545
Design Option 3	$n_c = 4$	$s_{nc} = 3$	0.7266
Design Option 4	$n_c = 6$	$s_{nc} = 1$	0.5494
Design Option 5	$n_c = 6$	$s_{nc} = 2$	0.6732
Design Option 6	$n_c = 6$	$s_{nc} = 3$	0.7357
Design Option 7	$n_c = 8$	$s_{nc} = 1$	0.5573
Design Option 8	$n_c = 8$	$s_{nc} = 2$	0.6795
Design Option 9	$n_c = 8$	$s_{nc} = 3$	0.7417

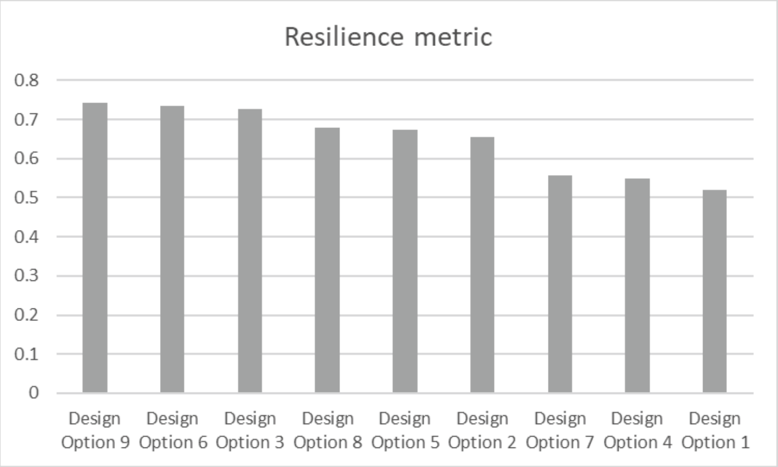

Figure 4: Resilience metric results for design option 1-9

Design option 9 in Figure 4 is shown to be the most resilient option which is as expected as it has the highest number of controllers and interconnections between controllers and standby components. Similarly, the least resilient option occurs with the least numbers of controllers and minimal connectivity. There is a difference in the effect on resilience between increasing the number of controllers and increasing the standby links. For example, the resilience between options 3, 6, 9 does not increase significantly even though the number of controllers increased, whereas the resilience of options 7, 8, 9 increases more notably with increase in the number of standby links between controllers and standby redundancy. Furthermore, while options 3 ($n_c = 4$, $s_{nc} = 3$) and 5 ($n_c = 6$, $s_{nc} = 2$) have exactly the same total number of links between controllers and components (3*4=6*2=12) there is a marked difference in resilience. Option 3, that has minimum number of controllers combined with maximum level of standby links, outperformed Option 5, that has the higher number of controllers with medium level of connectivity between standby redundant and controllers.

To illustrate these differences, Main Effects and Interaction Plots of Means were produced using Minitab, shown in Figure 5 and Figure 6 below.

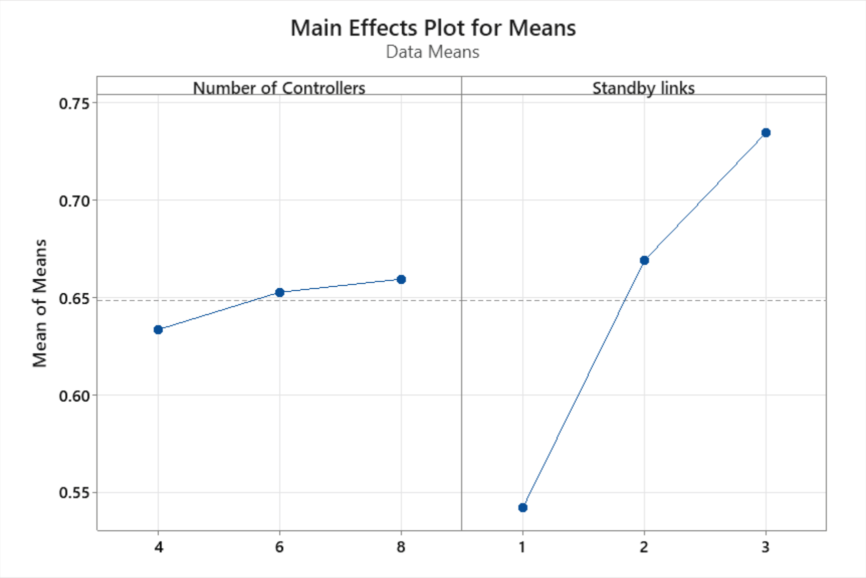

Figure 5: Main Effect Plots for Means

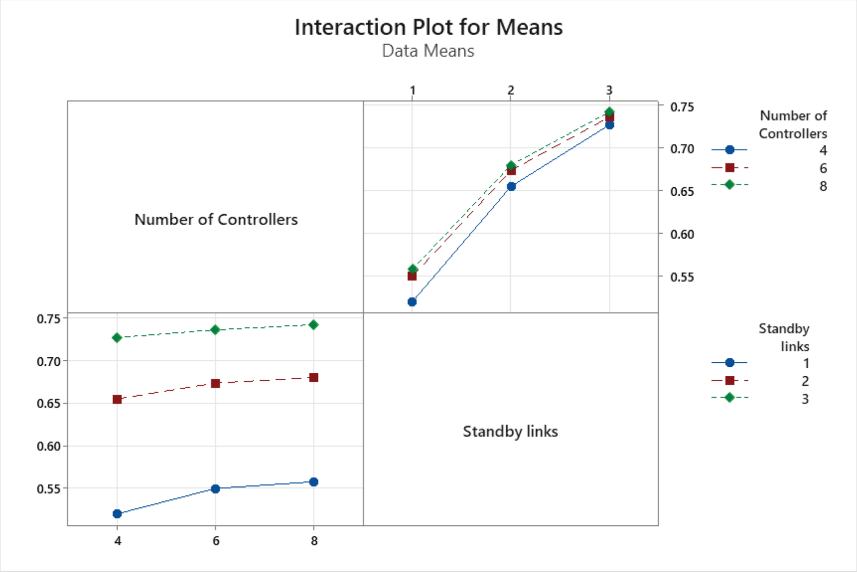

Figure 6: Interaction Plot for Means

In summary, the resilience results show that the level of interconnectivity between controllers and standby redundancy has a greater impact than the number of controllers. Such findings can provide useful insights during the early stages of design, when key design decisions are made, such as determining the number of control components and the number of standby connections between controllers and standby redundant components. This method is centred on the standby linkage, which is an important enabler of the post-disruption recovery process because it allows for reconfiguration, and thus improves system resilience.

Designing redundancy in system architecture centres on which parts to denote as redundant, the amount of redundancy at the component and interconnection, and the type of redundancy. Such redundancy decisions are made alongside other design considerations (Chen and Crilly 2014). The proposed method aids system engineering discussions by providing quantitative indicators for identifying design approaches that will provide the most benefit in terms of redundancy at the lowest possible cost, as well as avoiding incorporating designs that will provide no significant benefit in terms of resilience.

The proposed methodology is suggested for use during the early design decision phase, before detailed information is available. The findings are limited to the system architecture under investigation and are not intended for generalisation. It is expected that any design options developed early on based on the method's results will be thoroughly examined using a multi- physics analysis approach.

4. Conclusions & Future Research

The paper describes a method for assessing resilience in the early stages of design by modelling the complex system using a triple-layer network approach. The method considers the physical, functional, and control aspects of the system. This paper applied the method to a generic naval system power and propulsion case study, with control elements included. The case study presented experiments with different numbers of controllers and levels of connectivity between controllers and standby redundant components. The goal was to examine how the control aspect influences the system's resilience. The findings revealed that increasing connectivity between controllers and standby redundancy had a greater impact on resilience than increasing the number of controllers.

The method is intended to help at the very early stages of design, when important decisions are made, but detailed analysis tools are not available. The results of applying the method can help designers choose systems that meet the design objectives without introducing ineffective additional redundancy and the associated costs.

The case study presented in this paper is simple but provides early evidence that the multilayer design approach can give a speedy indication of the benefits of different design option approaches. The study suggests that there is value in exploring further how best to arrange the controllers in the design, both in terms of their interconnections and also in terms of how the controllers are associated with each individual standby component. In this study, the assignment was performed on the basis of physical location of the various components, however it is possible to explore other approaches.

Future research will focus on combining resilience optimisation strategies on multiple levels, such as within the functional and/or controller layer, and simultaneously positioning components in these two layers with reference to the physical layer. This will allow for the identification of optimal multilayer architecture patterns at a very early stage of design. Another potential future direction is to improve resilience metrics to capture different stages of the recovery process while also incorporating various reconfiguration approaches.

5. References

Bertoni, V.B., Saurin, T.A., Fogliatto, F.S., Falegnami, A., and Patriarca, R., 2021. Monitor, anticipate, respond, and learn: Developing and interpreting a multilayer social network of resilience abilities. Safety Science, 136 (October 2020), 105148.

Brownlow, L.C., Goodrum, C.J., Sypniewski, M.J., Coller, J.A., and Singer, D.J., 2021. A multilayer network approach to vulnerability assessment for early-stage naval ship design programs. Ocean Engineering, 225, 108731.

Bertoni, V.B., Saurin, T.A., Fogliatto, F.S., Falegnami, A., and Patriarca, R., 2021. Monitor, anticipate, respond, and learn: Developing and interpreting a multilayer social network of resilience abilities. Safety Science, 136 (October 2020), 105148.

Brownlow, L.C., Goodrum, C.J., Sypniewski, M.J., Coller, J.A., and Singer, D.J., 2021. A multilayer network approach to vulnerability assessment for early-stage naval ship design programs. Ocean Engineering, 225, 108731.

Chen, C.C. and Crilly, N., 2014. Modularity, redundancy and degeneracy: Cross-domain perspectives on key design principles. In: 8th Annual IEEE International Systems Conference, SysCon 2014 - Proceedings. IEEE, 546–553.

Eppinger, S.D. and Browning, T.R., 2012. Design Structure Matrix Methods and Applications. Cambridge, MA, USA: MIT Press.

Estrada, E. and Knight, P., 2015. A First Course in Network Theory, 272.

Haimes, Y.Y., 2009. On the definition of resilience in systems. Risk Analysis.

Haley, B., 2014. Evaluating complex engineered systems using complex network representations.

Hollnagel, Erik, Pariès, J., Woods, D., and Wreathall, J., 2011. Resilience engineering in practice: A guidebook. Resilience Engineering in Practice: A Guidebook. Ashgate Gower.

INCOSE ed., 2023. INCOSE systems engineering handbook. John Wiley & Sons.

Office of the Assistant Secretary of Defense for Homeland Defense and Global Security, 2015. Space Domain Mission Assurance: A Resilience Taxonomy White Paper. Federation of American Scientists, (September), 1–10.

Paparistodimou, G., Duffy, A., Knight, P., Whitfield, I., Robb, M., and Voong, C., 2018. Network-based metrics for assessment of naval distributed system architectures.

Paparistodimou, G., Duffy, A., Voong, C., and Robb, M., 2017. System Architectures Assessment Based On Network Metrics. In: 19th International Dependency and Structure Modeling Conference, DSM. Aalto University Design Factory, Finland.

Paparistodimou, G., Duffy, A., Whitfield, R.I., Knight, P., and Robb, M., 2020a. A network tool to analyse and improve robustness of system architectures. Design Science, 6, e8.

Paparistodimou, G., Duffy, A., Whitfield, R.I., Knight, P., and Robb, M., 2020b. A network science-based assessment methodology for robust modular system architectures during early conceptual design. Journal of Engineering Design, 31 (4), 179–218.

Rigterink, D., 2014. Methods for Analyzing Early Stage Naval Distributed Systems Designs, Employing Simplex, Multislice, and Multiplex Networks. The University of Michigan.

de Vos, P. and Stapersma, D., 2018. Automatic topology generation for early design of on-board energy distribution systems. Ocean Engineering, 170 (February), 55–73.

Wied, M., Oehmen, J., and Welo, T., 2020. Conceptualizing resilience in engineering systems: An analysis of the literature. Systems Engineering, 23 (1), 3–13.

Yodo, N. and Wang, P., 2016. Engineering resilience quantification and system design implications: A literature survey. Journal of Mechanical Design, 138 (11).

Yoo, M., Kim, T., Yoon, J.T., Kim, Y., Kim, S., and Youn, B.D., 2020. A resilience measure formulation that considers sensor faults. Reliability Engineering and System Safety, 199 (September 2017), 106393.

Rationalising safety cases for naval systems

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Synopsis

As naval systems become more complex, it is increasingly challenging to provide assurance that they can be operated safely. Safety cases need to be cost-effective to produce, yet robust in delivering a well-founded argument for the safety of the overall capability system. There is the potential to spend disproportionate effort demonstrating the safety of relatively simple, well-understood equipment; while not necessarily applying enough effort to understand how system elements function together to deliver a safe overall system. Increasingly, naval capabilities are assembled as a system-of-systems, bringing together a mix of bespoke, off-the-shelf and legacy elements, including both onboard and offboard systems. Such complex systems need a systems engineering approach to system safety. This paper examines some of the work underway to help rationalise and streamline management of safety cases for complex systems, including IEC 63187, the international standard currently being drafted for systems engineering, system safety and complex systems in defence applications; and Def Stan 02-904, the new UK Defence Standard on Surface Ship Safety Critical Items.

Keywords: Systems engineering; System safety; Safety-critical items; Standardization; Safety cases

1. Introduction

1.1. The problem with safety cases

To gain assurance that the systems it procures will be safe, the UK Ministry of Defence (MOD) has for many years required the production of a safety case (Inge, 2007). A safety case is defined as ‘a structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a product, service or system is safe for a given application in a given environment’ (MOD, 2023a). This argument changes through the system life cycle: starting as a case that it will be feasible to make a capability safe, then that the product delivering the capability is designed and manufactured in a way that will make it safe to operate, then that it is maintained in a state where this is so, and actually operated safely. A safety case is documented in a series of safety case reports, which summarise the arguments and evidence at a moment in time and document progress towards implementing the safety strategy. However, there is considerable flexibility on exactly what is required to constitute an acceptable safety case, in terms of its format, structure, and level of rigour. This flexibility allows an appropriate approach to be tailored to each project but introduces an ambiguity about the requirement that can lead to inefficiency.

Military systems are often very complex, both in a technological and a managerial sense. Naval platforms are often physically large, with a multitude of subsystems that can themselves be complex engineered artefacts, such as weapon systems or sensor suites. While some of these subsystems may be developed as part of the platform design or in parallel projects, in many cases they are developed separately. Some may be commodity parts or off-the-shelf designs that are already in-service elsewhere, others may be legacy equipment cross-decked from other platforms. And with ships in service for decades, they are likely to be fitted with new subsystems in the future, which may not have been considered at the time they were built.

Authors’ Biographies

James Inge leads the Ships domain Safety and Environmental Protection Team in Defence Equipment & Support. He is a past chair of the MOD Safety and Environmental Standards Review Committee and is currently part of IEC SC65A Working Group 18, developing the new system safety standard for defence, IEC 63187.

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All too often though, safety cases are written as a set of bolt-on documentation for an existing product. In many cases, the authors are consultants who do not work directly for the Original Equipment Manufacturer (OEM) or integrator. There may be good reasons for this: suppliers may not be familiar with the safety case regime; some manufacturers may no longer exist for legacy systems. However, this can mean the authors are given little access to information about the design or the context of use and the safety case report becomes detached from the engineering processes or the operation of the system; it may reflect neither the good safety engineering that might have been done by the designer, nor the true hazards seen in operation. Without having clear links between safety arguments at different levels of the systems hierarchy, it can be hard to understand what attributes of a sub-system make it safe – which can make it hard to replace if an alternative with identical form, fit and function is not available. Conversely, we may be unaware of latent safety problems, if it is not clear what role a sub-system was supposed to play in the safety case of the higher-level system.

In the past, the safety case approach has sometimes been criticised as producing ‘impenetrable tomes’ (SDF, 2022), or obscure documents of bureaucratic length (Haddon-Cave, 2009). One frequently finds lengthy safety case reports for minor equipment that pose very little hazard, while all too often, accident investigations for more complex systems find issues that had been overlooked in the safety case. To paraphrase Tony Hoare, it is difficult to make a safety case that is so simple that there are *obviously* no deficiencies; it is far easier to make it so complicated that there are no *obvious* deficiencies (Hoare, 1981). There is a risk that a considerable amount of time, effort and expense is spent creating and maintaining safety cases that do not do much to improve safety.

The challenge is to avoid on the one hand producing reams of paperwork that add little value, and on the other hand giving superficial treatment to important safety issues. In the past, there was a perception that every item of equipment the MOD purchased required its own exhaustive safety case. The current Defence Maritime Regulations, DSA02-DMR, now recommend that the safety case is ‘developed proportionate to the perceived level of safety risk’ (MOD, 2024). Producing a ‘proportionate’ safety case means finding the happy medium between the extremes of being recklessly scant and paralyzingly comprehensive. But how should this best be achieved?

1.2. The structured argument approach

A common approach to producing a safety case is to use a structured argument. In this context, a structured argument is one in which makes a high-level claim and breaks it down into a hierarchy of sub-arguments that are eventually supported by evidence. This may be presented as structured text, or graphically to make it easier to understand the relationships between elements of the argument. Two graphical notations often used for this purpose are the Goal Structuring Notation (GSN) (ACWG, 2021), and Claims, Argument and Evidence (CAE) (Adelard, 2024). Typically, the top-level argument is a statement such as ‘the [system] is acceptably safe for its [context of use]’, with appropriate explanations to describe the scope of what is meant by the [system] and the [context of use]. In GSN, this is known as a ‘goal’, since the goal of the safety effort is to ensure that the statement is true. In CAE, it is a ‘claim’, which expresses the conclusion that the rest of the argument is expected to support. The goal/claim is then broken down into sub-goals/claims, until the argument is defined clearly enough that the lowest-level goals can be satisfied by tangible pieces of evidence (‘solutions’ in GSN terms). At a basic level, GSN and CAE are similar, but GSN includes additional elements to help explain the context, assumptions, justifications and strategies underpinning complex arguments.

GSN also includes features for modularising safety arguments, which can be helpful for complex systems. MOD policy in Joint Service Publication JSP 815 (MOD, 2023b) and DSA02-DMR requires the safety case to be endorsed by a representative of the operator: either the Senior Responsible Owner (SRO) of the programme acquiring a system, or the Duty Holder or other Accountable Person responsible for operating it once in service. For a complex system such as a warship, it is not practical to expect the operator to sign off separate safety cases for each component system element. Component-level safety cases need to be integrated into an overall safety argument for the system. Modular safety cases in GSN provide a mechanism to do this: an ‘away goal’ in a platform safety case may be supported by the argument presented in a separate safety case module, e.g. the safety case for a sub-system.

Safety is an emergent property resulting from interactions between all the elements of a complex system. While the principle of ‘platform primacy’ suggests that the safety case for a naval platform should incorporate arguments for the safety of its component elements, it is not sufficient just to claim that the platform is safe because its components are safe. We also need to argue about the way that sub-systems are integrated: how they work together to deliver safety functions, and how they avoid interfering with each other in a hazardous manner. This means that there will normally need to be multiple touchpoints between a platform-level safety argument and its supporting sub-system safety arguments.

GSN allows interfaces between modules to be defined by ‘contracts’. These describe the links between the away goals that require support, their relevant context and justifications, and the goals, context and justifications in other module(s) that provide the supporting argument (ACWG, 2021). As well as making it clear how different safety argument modules support each other, formally describing these interfaces can make it easier to swap modules, e.g. by facilitating analysis of whether the safety case for a new sub-system still supports the safety case for the platform in the same way as its predecessor.

Structured arguments presented using notations such as GSN and CAE can be useful to help clearly set out the safety argument. At the start of a project they make it easier to see what evidence will need to be generated to argue that a PSS is safe; later they can help identify the impact if the system changes or the validity of evidence is brought into question. And breaking structured arguments into modules can help manage complexity by abstracting the detailed arguments about subsystems. However, to be effective and efficient, we must choose a good argument structure that is proportionate to the risk involved.

2. Efficient arguments for maritime safety

2.1. Choosing the argument structure

Depending on the stage of the project and the purpose of the safety case report, it may be appropriate to break the top-level argument for safety of a product, service or system into two sub-goals: that the PSS is ‘safe to operate’, and that it is ‘operated safely’. Within the MOD, this neatly breaks the argument into the parts managed by the acquisition organisation (normally Defence Equipment & Support or the Submarine Delivery Agency), and the parts managed by the system operator, for instance the Royal Navy.

Below the top level of the safety argument, one needs to choose an appropriate strategy to make a compelling argument that the system is safe. One strategy is to argue about the effectiveness of the Risk Control Systems (RCS) that control the risk posed by the product, service or system as part of a Safety and Environmental Management System (SEMS). In DSA02-DMR, the Defence Maritime Regulator recommends adopting appropriate risk control systems from Table 1.

Table 1. DSA02-DMR Risk Control Systems (MOD, 2024).

RCS	Description
a)	Safety and Environmental Management System documented using Organisation and Arrangements Statements and Safety and Environmental Management Plans
b)	Certification and Certification Strategy
c)	Integration of Safe Design and Construction
d)	Maintenance of the Ship and Equipment
e)	Management of Change; Maintenance of Conditions
f)	Documentation
g)	Crewing Levels, Competence and Training
h)	Incident Reporting and Analysis
i)	Emergency Preparedness
j)	Safe and Environmentally Compliant Operating Envelope
k)	Live Health, Safety and/or Environmental Case and the Health, Safety and/or Environmental Case Report, Summaries and Statements
l)	Requirements Management
m)	Verification of Internal Assurance (1st Party Assurance and 2nd Party Assurance)

Unfortunately, such an approach can be inefficient, especially for relatively simple pieces of equipment. The risk control systems used in DSA02-DMR are based on work that was originally intended to give assurance about the end-to-end safety process across organisations within a complex enterprise (Inge and Costello, 2008). With sufficient interpretation (DSA02-DMR does not expand beyond the descriptions in Table 1), each risk control system can be relevant to a safety case, but the set is not optimised for this purpose. This can lead to a temptation to write a similar amount for each one, rather than focus on those that are most important, or to fill in the space even where a theme is not relevant. The set of risk control systems in DSA02-DMR acts more as a list of relevant topics than a structure for a compelling argument.

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An alternative argument strategy, illustrated in GSN at Figure 1, has been used for some while for Type Airworthiness Safety Assessments (TASA) in the Air domain in DE&S and can also be adapted for the Maritime environment. The top-level goal that a Product, Service or System (PSS) is acceptably safe, G0, is broken into four sub-goals. Guidance in the DE&S Air Engineers' Toolkit breaks these sub-goals down to a further level of detail, with the requirements varying between commodities and more complex systems.

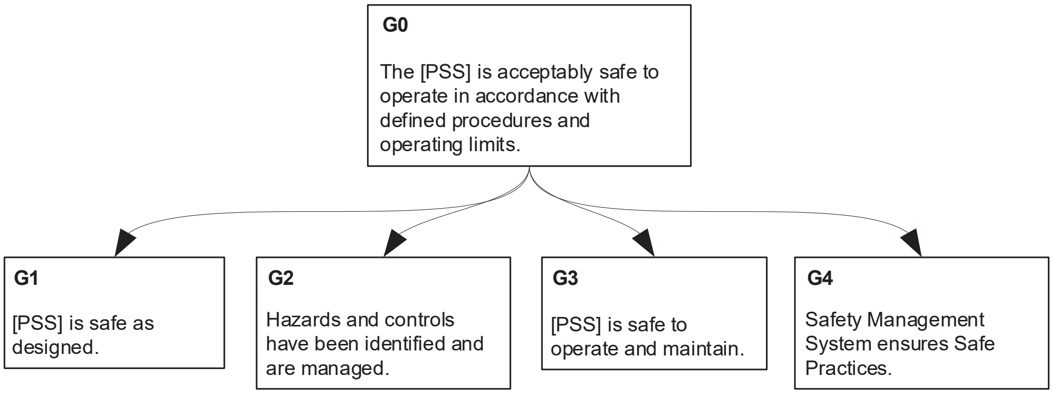

Figure 1. Four-pillar safety argument, based on Air Engineers' Toolkit TASA model.

Under G1, arguments are made that the designer or supplier has conducted a suitable safety process themself, certification standards are met, the design has been tested in a representative environment for its intended use, and is kept under proper configuration control. G2 argues that an effective risk analysis process has been put into effect. G3 makes the claim that the user has been provided with the information necessary to safely use the product, service or system (via documentation, training, emergency arrangements, etc. as appropriate). G4 makes a process-based argument that management processes are in place to review and update the safety case, and to ensure compliance with relevant standards, legislation, regulation and policy. The goals in Figure 1 overlap the topics covered by the risk control systems at Table 1, but do not correspond directly to them. Some risk control systems, such as 'Documentation', impact multiple goals, while others like 'Certification and Certification Strategy' are more specific to one area of the argument.

Beneath the four sub-goals, one must decide how to expand the argument in a way that is proportionate to the circumstances in question. This must consider the complexity of the product, service or system under consideration and its interfaces with the wider system it operates in, as well as the magnitude of the hazard and consequent need for reassurance about safety. The argument must also be tailored to the stage of the system in its product life cycle. Early in the acquisition phase, the argument will focus more on G1, checking that it is designed or selected appropriately. As the system comes into service, the argument shifts more to G2 and G3, checking that safety arrangements are in place and are operating effectively.

2.2. Arguments for low risk / low complexity equipment

JSP 815 guides that for some equipment, a safety case approach may not be proportionate, if the complexity and level of risk involved is sufficiently low (MOD, 2023b). This might apply to equipment where no specific hazard or contribution to safety is identified. Some kind of safety assessment is still required, but it can be argued it would be proportionate to do this at the level of groups of related equipment, rather than individual items, and to base the assessment more on the management processes involved than technical analysis of a Product, Service or System (PSS). Such a safety argument could be developed along the lines of Table 2 (shown in tabular format for brevity – graphical notation could also be used).

Table 2. Skeleton safety argument for low risk/low complexity items with negligible safety impact.

Goal	Supporting lines of argument	Examples of potential supporting evidence
G1	The appropriate standards for the PSS are well understood, and there is evidence of compliance.	CE/UKCA marking, Original Equipment Manufacturer (OEM) endorsement of spare part.
G2	The PSS is not known to be safety-related, and no specific hazards have been identified.	Declaration by Suitably Qualified and Experienced Personnel (SQEP) holding appropriate safety delegation.
G3	There is no requirement for specific operating or maintenance information to ensure safety.	
G4	Systems are in place to select competent suppliers, manage product quality, review ongoing suitability.	Safety Management System documentation. In-service defect or incident reports.

The bulk of a safety case based around Table 2 would be focused on Goal 4, arguing that the acquisition organisation and operators had appropriate processes in place. The only item-specific parts of the case would be the list of items to which it applied and the records that the SQEP delegated person had assessed that this style of argument was indeed appropriate to those items. This approach of using the skeleton argument from Table 2 to create a generic safety case applicable to a list of items would only be appropriate for the lowest-risk and complexity items. Once items are known to have a safety impact, more specific information is required to justify their safety, as shown in Table 3.

Table 3. Skeleton safety argument for low risk/low complexity items.

Goal	Supporting lines of argument	Examples of potential supporting evidence
G1	Appropriate standards for the PSS have been selected and complied with.	Declaration by SQEP delegation-holder that chosen standards are appropriate for the application. Manufacturers' declaration of conformance. Type approval certificates. Test/survey results and certification. List of hazardous materials.
G2	All identified hazards have been controlled via adherence to the appropriate standards, or supply of appropriate safety information.	Declaration by SQEP delegation-holder.
G3	Appropriate safety information is included in training, manuals, operating limitations, etc.	References to the relevant documents.
G4	Systems are in place to select competent suppliers, manage product quality, review ongoing suitability.	Safety Management System documentation. In-service defect or incident reports. Audit reports.

The skeleton argument outlined at Table 3 may be appropriate where the product, service or system is known to have a safety impact, but that impact is well controlled by existing standards and processes. It is not sufficient to use a generic safety argument as described previously, but it may be proportionate to apply a template argument to groups of similar systems and populate it with references to specific evidence for each item. This saves the effort of generating a new argument from scratch for each item. To further reduce duplicated effort, the Safety Management System argument at G4 can be referred to as a safety argument module and re-used between groups of different system types.

There is a risk here: the safety case approach has been criticised for a tendency towards confirmation bias, or assuming that the top-level goal is true without critically analysing the safety argument (Haddon-Cave 2009; Leveson, 2011). When using a template safety case, it is vital to populate it with details that are relevant to the system in question and are verified to be true. For instance, it is not sufficient to just say that a hazard is controlled by 'documentation'; it needs to be clear which documents are being referred to, and that those documents actually hold the relevant details for that system. Similarly, when basing a safety argument on the existence of a documented Safety Management System, there needs to be evidence that the procedures in that management system were actually applied to the product in question.

2.3. Safety Critical Items approach

As system elements become more complex and have more interactions with higher-level and peer systems, it becomes harder to support the goals that 'the system is safe as designed' and the 'hazards and controls are identified and mitigated' (G1 and G2 in Figure 1). Platform and system-level concerns often start to dominate, and safety becomes more dependent on integration aspects rather than individual system element designs. Addressing these integration issues can be a management challenge, and if there is insufficient delineation between local hazards to personnel and hazards with platform-level effects, it is easy to focus effort on the wrong issues.

With *Def Stan 02-904 – Surface Ships Safety Critical Items* (MOD, 2023c)*,* the MOD is starting to adopt an approach for naval ships that is already in use for submarines and in the offshore oil and gas industry. For certain system elements that are designated as 'Safety Critical Items', i.e. those that are essential to the platform 'safe to operate' argument, Def Stan 02-904 requires the associated safety functions and performance standards to be identified. A verification scheme is then to be established to ensure that performance standards are – and continue to be – achieved. This means that the G1 safety argument for a sub-system can focus on whether the performance standards are met and safety functions delivered, without making a risk-based argument about each hazard. This supports clearer articulation of the overall platform safe to operate argument, while avoiding forcing the person with safety responsibility for the sub-system to try to make decisions about risk without knowing the full context. Local risks can still be addressed in the G2 argument, but in most cases will not form the most important part of the overall argument.

Def Stan 02-904 provides a definition of 'Safety Critical Items' that allows such items to be identified. Essentially, the scope of 'Safety Critical Items' comprises those items that provide mitigation against, or whose failure could cause or substantially contribute to, a loss of multiple lives associated with a Key Hazard Area, failure of life support systems for divers, or platform-level effects that could lead to severe damage or loss of the platform. Ideally, the safety functions performed by a Safety Critical Item and the associated performance standards would be known in advance of choosing a design. In the future, this may become more usual: the NATO ANEP-77 Naval Ship Code is expected to be updated to include a definition of 'essential safety function' which would align well to the concepts in Def Stan 02-904. Where this is not the case (e.g. when considering the safety case for operating or replacing a legacy system), it may be necessary to reverse-engineer the safety functions by examining the system design and the hazards involved, to identify those items that could lead to the type of losses described above, and to determine what role they might play in an accident sequence.

2.4. Complex Systems approach – IEC 63187

The Safety Critical Items approach described above is expected to be useful at the level of acquiring individual systems elements. It allows for some negotiation between the equipment level and the platform level, to agree what safety functions will be performed, and whether hazards will be mitigated at the platform or equipment level. However, when dealing with platforms built from complex systems, or themselves incorporated in higher-level capabilities, a more encompassing approach is needed.

The International Electrotechnical Commission (IEC) is currently developing a standard for the defence sector that addresses safety from a systems engineering viewpoint. *IEC 63187 – Systems engineering – System safety – Complex systems and defence programmes* will be based on ISO/IEC/IEEE 15288, the systems engineering life cycle standard (ISO, 2023). It takes the approach of augmenting the ISO/IEC/IEEE 15288 processes used to manage complex systems, to make them appropriate for safety-critical systems (Ricque et al. 2022, Inge et al., 2023). While many safety standards are designed primarily to be applied internally by an organisation (e.g. IEC 61508 (IEC, 2010), or between an acquisition organisation and a prime supplier (e.g. Def Stan 00-056 (MOD, 2023a)), IEC 63187 is being written for more complex supply chains, where multiple stakeholders will supply different system elements at different levels in the systems hierarchy.

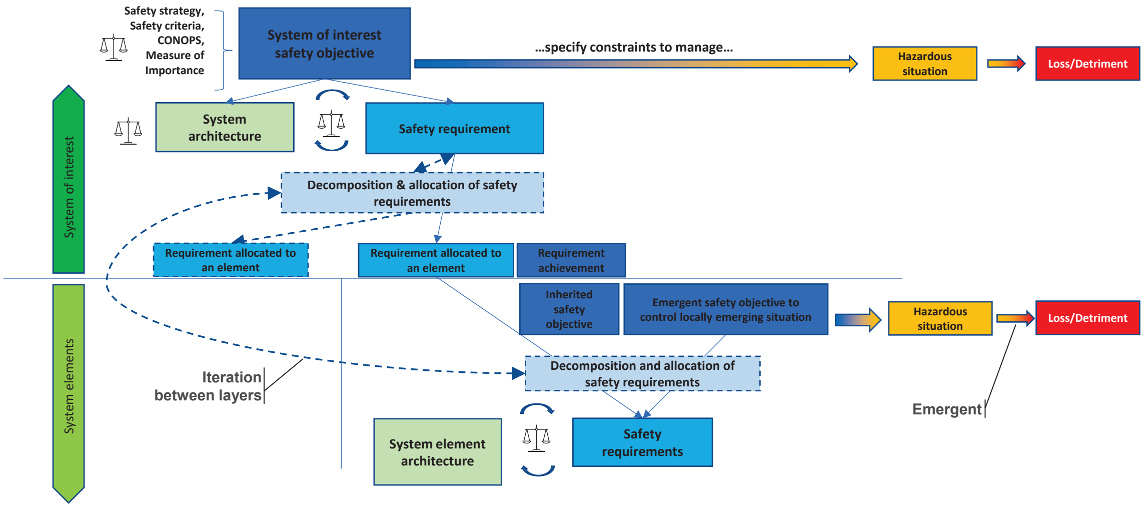

Figure 2. Cascade of safety objectives and requirements in IEC 63187 (Inge et al., 2023)

The new standard provides a framework for flowing safety objectives and corresponding requirements up and down the systems hierarchy (Figure 2). It has mechanisms to allow high-level platform safety objectives to flow down to system elements, and for objectives to be escalated to address interaction issues or hazards introduced by system elements that cannot be managed within the individual element. It also accounts for different elements being developed according to different life cycles and at different periods in time, e.g. legacy or commercial-off-the-shelf equipment being incorporated into a bespoke new capability.

Applying a framework like IEC 63187 at the architectural level on major programmes will help set clear requirements at the system element level, which will then feed into the safety functions and performance standards required for Safety Critical Items. In the future, this should make the Safety Critical Item approach described in section 2.3 easier to implement and more effective, by making it easier to see how individual sub-systems or equipment contribute to an overall platform or capability safety case, and what they have to do to be safe.

Conclusions

Haddon-Cave emphasised Cullen's view that 'safety cases were intended to be an aid to thinking about risk, not an end in themselves' (Haddon-Cave, 2009). Competent safety engineers are currently a limited resource across industry and the MOD. To make best use of this resource, and to have the best chance of improving safety, we must focus our safety case efforts on the most important parts of the safety argument, where there is the greatest opportunity to reduce risk. This paper has presented practical opportunities to reduce the effort spent on producing safety cases for low risk, low complexity items. It has also explained how structured arguments and modular safety cases can focus safety case production effort, and introduced work on two new standards, Def Stan 02-904 and IEC 63187, that will facilitate this for more complex systems.

References

ACWG, 2021. *GSN Community Standard Version 3*. York: Safety Critical Systems Club, Assurance Case Working Group No. SCSC–141C.

Adelard, 2024. Claims, Arguments and Evidence (CAE).

Haddon-Cave QC, C., 2009. *The Nimrod Review: An independent review into the broader issues surrounding the loss of the RAF Nimrod MR2 Aircraft XV230 in Afghanistan in 2006*. London: The Stationary Office.

Hoare, C.A.R., 1981. The emperor's old clothes. *Commun. ACM*, 24 (2), 75–83.

IEC, 2010. *IEC 61508 – Functional safety of electrical/electronic/programmable electronic safety-related systems*. International Electrotechnical Commission.

IEC, 2023. *ISO/IEC/IEEE 15288 – System and Software Engineering – System life cycle processes*.

International Electrotechnical Commission.

Inge, J., Potiron, K., Williams, P., and Ricque, B., 2023. IEC 63187: Engineering Safety into Complex Defense Systems. *In*: *Safety in an Agile Environment: The International Systems Safety Conference 2023*. Portland OR, USA: International System Safety Society.

Inge, J.R., 2007. The safety case, its development and use in the United Kingdom. *In*: *Proc. 25th International System Safety Conference*. Baltimore MD, USA: International System Safety Society, 725–730.

Inge, J.R. and Costello, G.T., 2008. End-to-end reviews: A new approach to providing assurance that a complex organisation is effectively managing safety. *In*: *Proc. 26th International System Safety Conference*. Vancouver BC, Canada: International System Safety Society.

Leveson, N., 2011. The use of safety cases in certification and regulation. *J. syst. saf. (Online)*, 47 (6).

MOD, 2023a. *Def Stan 00-056 – Safety management requirements for defence systems – Part 1: Requirements*. Glasgow: Ministry of Defence, Defence Standard No. 00-056 Part 1 Issue 8.

MOD, 2023b. *JSP 815 – Defence Safety Management System*. London: Ministry of Defence, Joint Service Publication No. 815.

MOD, 2023c. *Def Stan 02-904 – Surface Ships Safety Critical Items*. Glasgow: Ministry of Defence, Defence Standard No. 02–904.

MOD, 2024. *DSA02-DMR – Defence maritime regulations for health, safety and environmental protection*. London: Ministry of Defence, Defence Regulation No. DSA02–DMR.

Ricque, B., Joguet, B., Brindejonc, V., Semeneri, N., and Potiron, K., 2022. IEC 63187 : intégrer la sûreté de fonctionnement au sein de l'ingénierie système. *In*: *Congrès Lambda Mu 23 " Innovations et maîtrise des risques pour un avenir durable " - 23e Congrès de Maîtrise des Risques et de Sûreté de Fonctionnement*. Paris Saclay, France: Institut pour la Maîtrise des Risques.

SDF, 2022. *Peer review of safety cases*. Nuclear Industry Safety Directors Forum.

Widening the Net of the Future Air Dominance System

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Synopsis

As aerial weapon systems continue to advance in capability, the ability to detect and neutralise such threats quickly and efficiently is becoming increasingly important. Advanced airborne threats, such as sea-skimming missiles and low-flying aircraft, are becoming more difficult to detect with current radar technology. Meanwhile cheap, 'swarming' attack drones threaten to overwhelm air defence systems through sheer force of numbers. The proposed Future Air Dominance System aims to utilise a *system of systems* approach, with anti-air systems remaining a critical component to dealing with these emerging threats. Capabilities are split across multiple 'nodes' within the system to provide protection over a wide area. This presents an opportunity for a radar picket ship to form one or more such nodes. A platform operating on the periphery of the task group's radar detection range can detect and neutralise airborne threats before the rest of the task group can be targeted. The use of existing platforms in a radar picket role presents an immediate means of widening radar detection range. However, the increased danger and risk associated with radar picket role's up-threat position means that a purpose-built radar picket platform may be considered as more acceptable and cost effective. This paper discusses the role of a radar picket and how such as role may be fulfilled in the future naval battlespace, considering factors such as radar technology, crewing and armament.

Keywords: Naval; Future; Radar Picket; Future Air Dominance System; Airborne Early Warning

1. Introduction

The recent Red Sea Crisis has highlighted the continued requirement for anti-air systems as well as maritime protection roles. Aerial weapons including one-way attack drones, cruise missiles and ballistic missiles have been launched against shipping lanes. HMS Diamond, operating as part of a wider taskforce, has destroyed these threats with both Sea Viper missiles and the ship's guns (Navy Lookout, 2024). The Type 45 destroyer – of which HMS Diamond is one of six – is the Royal Navy's current anti-air warfare (AAW) capability. The current out-of-service date for the Type 45s is 2038 and by this point the successive class should be in service (HC DEB, 2024).

The Type 45 planned replacement, the Type 83, is expected to operate as one part of the Future Air Dominance System (FADS) which will utilise a *system of systems* approach to detect and neutralise threats. As threats increase in capability, they will need to be detected, and neutralised, at ever greater ranges. To achieve this FADS aims to utilise multiple, disaggregated sensors and effectors.

How to increase the range of detection is not a new problem. Radar picket ships saw service in WW2, the Falklands, and the Gulf where they were used to provide early warning of incoming threats. What is new is the size of the net now required to achieve aerial dominance. This paper will explore the potential options required to expand this system using current technology and development.

Author's Biography

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2. Widening the Net

2.1. Increasing Radar Coverage

Radar is a technology that is limited by line of sight, so there is always a necessity to increase overall coverage beyond the radar horizon. Just as in the past, any ability to provide early warning to a major asset increases the time within which reactions can be made. Furthermore, modern-day threats still include sea skimming missiles and low flying aircraft which are both becoming more advanced. Additionally, there is likely to be an increased use of swarming one-way attack drones flying relatively low and targeting maritime assets. Any amount of early warning is a benefit to the task group and in future conflicts a radar picket role will be highly beneficial.

The radar picket role involves increasing radar detection range to detect airborne threats earlier and has historically been performed by ground-based stations, submarines, naval vessels, or aircraft.

The primary function of FADS will be force protection over a wide area, primarily centred around a carrier strike group (CSG). As a system of systems, FADS will be made up of multiple nodes. Whilst many of the nodes will have offensive capabilities, radar coverage is limited to where these assets are located. Through the use of additional nodes in FADS, this radar coverage can be expanded.

In order to increase radar coverage, a platform performing a picket role must operate on the periphery of the task group's radar detection range. With the aim being to detect incoming airborne threats, a picket ship would be best situated in the anticipated direction of such threats. Such a position, described as 'up-threat', inherently comes with increased risk to the platform from airborne, surface and submarine adversaries due to its isolated position.

2.2. Airborne Platform Host

Airborne Early Warning (AEW) is currently provided to the Royal Navy by Merlin helicopters fitted with a Crowsnest system. While this system is currently operational, there is an intention to replace the use of a crewed helicopter with an uncrewed system by about 2030 (Navy Lookout, 2022). AEW provides a highly effective air and surface surveillance and detection capability due to its ability to host a radar at height, vastly increasing the lines of sight. AEWs are capable of vastly widening the FADS net in comparison to surface ship radar capabilities.

Figure 1 - Merlin Crowsnest with Radar Dome Lowered (Royal Navy, 2021)

The downside to AEW systems – crewed or uncrewed – is that their endurance is likely measured in hours, rather than days or weeks. Therefore, around-the-clock monitoring is likely to be difficult, due to the number of vehicles required. Airborne systems could also be considered to be highly vulnerable, especially as AEW systems are required to fly high to increase radar coverage but at the same time this allows them to be detected easier. Furthermore, not every task group that FADS is protecting will have an aircraft carrier with the capacity to host multiple AEW systems.

2.3. Naval Platform Host

Hosting the early warning radar function on a naval platform as opposed to an airborne platform has the potential to significantly increase the availability of the system. Requiring less energy to maintain position, and with higher capacity for weight and outfit, a naval platform has the potential for a much greater endurance than that of its airborne counterpart.

A naval platform can provide increased radar coverage for a task group for extended periods of time depending on its size and requirements. For example, a smaller craft may be able to remain at sea for multiple days, whereas larger vessels, such as frigates or destroyers, may remain at sea for several weeks at a time without replenishment.

Moving towards a naval platform would typically limits the altitude of the radar system, losing a key advantage of airborne hosts such as AEW and UAVs. At sea level, the radar system will detect low-flying airborne threats at much shorter ranges than an AEW system due to the curvature of the earth. Whilst high altitude airborne threats such as ballistic and cruise missiles may still be easily detected, low-flying threats such as sea-skimming missiles operate in a blind spot for low altitude radar systems. As such, radar systems should be placed as high as practically possible, whilst avoiding other obstructions and minimising interference from other emitters. The main restrictions on the height of the radar is vessel stability. Higher radars will also increase the vessel's own radar cross section.

Conventional ships, such as frigates and destroyers, are able to house large, capable, radar systems. For example, the RN Type 45 destroyer is outfitted with a SAMPSON multi-function radar positioned at almost 40m above sea level, bringing the radar horizon to around 22.6 km – without considering refraction. Larger and taller radar systems, in addition to the increased size and weight of their respective masts, raise the centre gravity of the whole platform, negatively impacting stability. Radar size and height restrictions may be overcome by other vessel characteristics, such as utilising different hull forms – like a trimaran – to compensate for the impacts on stability.

3. Using an Existing Ship

3.1. Benefits to using Existing Platforms

With a fixed surveillance radar a naval platform may fulfil the high availability required by the radar picket role, which may also be supplemented with a hosted AEW system of its own. Whilst a radar picket ship may be a bespoke vessel, the use of an existing RN platform to fulfil the role of a picket ship should first be considered.

Existing naval platforms such as frigates and destroyers already host capable AAW radar technology. Operating such a vessel as a picket ship within FADS would meet the requirement for increased AAW capability without requiring a new vessel to be designed and manufactured. Furthermore, the vessel would remain sufficiently capable outside of FADS without the need for retrofit.

3.2. Specialist AAW Platform – A Destroyer

The RN already operates specialist AAW platforms, namely the Type 45 destroyer, and its successor, the Type 83 destroyer, is currently in development. Such platforms have the capability to easily fulfil the role of a picket ship. However, an argument can be made that the high capability of these platforms is in fact excessive and undesirable for a radar picket platform.

The Type 45 destroyer is equipped with an advanced multi-function radar system, which can track multiple airborne threats simultaneously and perform fire control functions for onboard weapon systems. The ability to neutralise airborne threats after detection is desirable capability for a radar picket, as it may therefore defend itself and the rest of task group for which it is providing an early warning.

However, operating such a platform as a radar picket would involve accepting the increased risk associated with the up-threat position. A significant component of this risk would involve the high crew complement of such a platform – 190 personnel, up to potentially 285. Furthermore, when operating as a radar picket, other platform capabilities would likely be underutilised or be less effective due to the ship's position away from the rest of the task group. This includes the use of the ship's helicopter, an embarked military force, and land attack weaponry. Therefore, it can be argued that the radar picket role should also have limits on crew complement and platform capability in order to keep the consequences of losing a vessel as low as possible.

The Type 83 destroyer currently in development is intended to play a key role in FADS. Whilst it can be assumed that the size of crew complement may be lower than that of its predecessor, publicly released concepts for the Type 83 indicate that it may carry a significant weapons payload with advanced sensors. Such a large payload capacity would likely well exceed the requirements needed in the radar picket role.

Operating such an advanced AAW platform as a radar picket puts at risk a highly capable vessel and an unnecessarily large number of crew. Losing such an asset would be unacceptable politically and therefore these advanced platforms would be best deployed in the manner in which they were intended to be as opposed to as a radar picket.

3.3. General Purpose Warship

A general-purpose frigate (GPF) is more preferential to fulfil the picket role than a specialised destroyer such as the Type 83. A GPF will still have a capable radar that allows the radar coverage to be extended, without using up a much more specialist craft. Furthermore, it continues to have capability outside the picket role.

A GPF is likely to be cheaper than a purpose-built AAW destroyer and have equipment that is more acceptable to be lost, however there is still an increased risk to the platform when operating in a picket role. Whether or not it is acceptable to operate a large, crewed asset in such a way would be determined by operational needs at the time, but with limited hulls, any attrition of major surface combatants would likely be undesirable.

4. A New Design - Bespoke Picket Ship

4.1. Sensor Outfit

A bespoke design of picket ship could take several forms which balance cost and capability. Surveillance radar systems range from 2D medium range radars through to highly capable 3D multi-function radars. Airborne threat detection is a primary requirement for the picket role and therefore the choice of surveillance radar presents an important decision.

More capable radar systems typically have a greater impact on the overall design of the ship, the main factors for which include increasing system weight, space, and power requirements. Furthermore, radar mast height plays an important role in a radar system's effectiveness and is particularly relevant in cases where an advanced 3D medium or multi-function radar system has been selected. The selection of a lower-capability radar system may be justified by the decision to deploy a larger number of vessels and fulfil the picket role of increased radar coverage through quantity.

A bespoke picket vessel does not necessarily have to rely solely on standard, mast-mounted, radar systems. Secondary means of increasing radar coverage include deployable UAVs, AEW systems and tethered airborne radar systems. Whilst the operation of such systems can be disrupted by adverse weather conditions, airborne surveillance systems can significantly increase the radar horizon as a result of the high altitudes that can be reached.

Tethered airborne radar systems potentially offer a greater radar horizon whilst maintaining higher endurances and availability than UAV and helicopter-mounted AEW systems. Such systems have seen extensive use in ISR operations by the United States Coast Guard (USCG) and United States Army. A notable example includes Raytheon's Joint Land Attack Cruise Missile Defense Elevated Netted Sensor System (JLENS), which tracked long range surface-to-air missiles as its primary function (Horitski, 2016). The altitude, flight endurance and payload weight of an aerostat typically scales with its size, with larger aerostats carrying payloads of up to 1,600kg, having endurances of up to one month, and potentially increasing radar horizon to up to 250km.

Figure 2 - Carlson Tide with TCOM Sea Based Aerostat (TCOM, 2014)

Hosting aerostat surveillance systems from naval platforms has been demonstrated in the past with the U.S. Army's Tide-class Small Aerostat Surveillance Ships (SASS) and the USCG Mobile Aerostat Platform, which saw use from the early 1980s until retirement in 1994 (Lobner, 2023). These programmes demonstrated that aerostats could be deployed from slow-speed naval platforms to detect low-flying aircraft at long distances, but were ultimately terminated due to adverse weather limitations and carrier ship availability. If these limitations were to be overcome with modern technology, a tethered aerostat radar system may have use onboard a radar picket platform.

4.2. Uncrewed Platform

The use of an uncrewed platform to fulfil the requirements of a picket ship presents an attractive solution as the lack of crew allows for a smaller platform with reduced defensive capability and other secondary platform functions. With currently available technology, a complete lack of crew is only feasible on smaller platforms.

Autonomous systems contribute to the platform's complexity and upfront cost. Therefore, a smaller platform should consider eliminating unnecessary capabilities whilst utilising autonomy where necessary to minimise vessel complexity. Furthermore, maintenance, damage control and warfare operations are limited without the versatility offered by a well-trained and experienced crew. As such, an uncrewed solution will drive the design towards low-complexity, cheaper solutions.

It may be possible to field multiple autonomous vessels to collectively fulfil the picket ship role within FADS. By using less capable radars on the design to lower the cost, the reduction in capability may be offset by fielding an increased number of vessels. Minimising platform costs and removing the crew will allow for each vessel to become more expendable, a desirable feature for a vessel required to be up-threat and subject to an increased chance of enemy attack.

As mentioned previously, with current technology, complete autonomy is currently limited to smaller, less complex, vessels. Whilst on larger platforms autonomy may be applied to more generic marine systems, such as those associated with manoeuvring, military-specific systems still require a minimum number of crew. Weapons and damage control systems are perhaps the most significant systems that will currently struggle with automation and drive the need for a minimum level of crewing. Furthermore, a radar picket's up-threat position requires a minimum level of defensive weapon capability to increase survivability.

4.3. Crewed Picket Ship Platform

In order to become a viable option, a picket ship should mitigate against the risk of loss. This can be achieved by increasing the capability of the design so that it may defend itself, or through the use of multiple nodes to increase resilience in the whole FADS task force. Cost versus capability is the big driver.

A more survivable platform comes through the use of a crew: damage control is possible to extend a platform's life after action, more advanced weaponry can be included as this can now be maintained and operated, and maintenance can be conducted extending potential endurance. This likely means that a crewed picket ship will be larger than its uncrewed counterpart due to the increased space needs of a crew including accommodation, dining, medical and other facilities. Having a survivable platform is a much more crucial feature when hosting a crew.

By having advanced weaponry, the survivability of the platform is vastly increased, as well as providing an option to counter threats to the CSG earlier than the CSG could. Several Tactical Mk41 VLS cells could provide great flexibility to the platforms CONOPS. For example, Sea Ceptor missiles (Common Anti-Air Modular Missile) or their future equivalents can be quad-packed for a point defence and local defence capability. A Mk 41 VLS can also accommodate Aster 15 and Aster 30 missiles, as well as American SM-2 missiles for longer range targets. This increase in survivability comes with a large increase in cost, not just from the silos and missiles, but also the accompanying equipment necessary to operate a complex weapons system. Furthermore, such weapon systems lead to a larger crew requirement. Simpler self-defence weaponry, such as CIWS, may be better placed on a picket ship. These will be cheaper, have smaller crew requirements and will be better placed to be remotely operated from an external position. Weaponry could also include counter-UAS systems such as DragonFire; major threats would then be countered by other FADS nodes, with simpler targets being attended to by the picket ship.

Overall, the capability of the picket ship needs to be carefully balanced with its cost to ensure that a high value unit, such as a GPF, is not simply replaced with another unit of equal value.

5. Potential Options

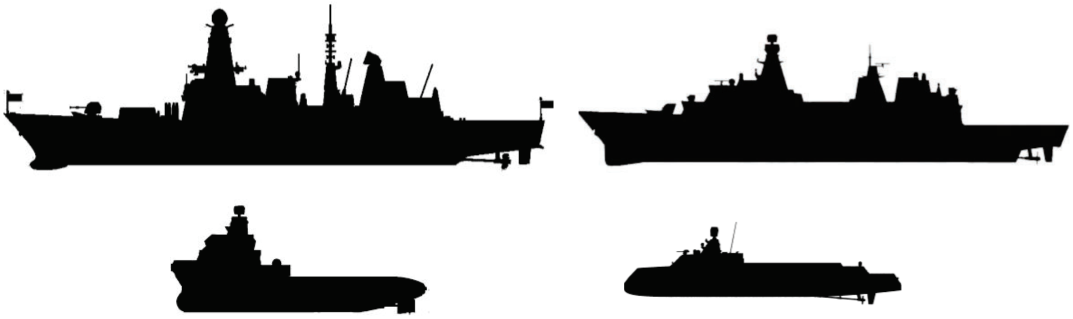

Figure 3 - Potential Options for a FADS Picket Ship

The four potential options discussed in this paper are as follows:

- A specialised, capable AAW destroyer with an advanced radar and significant weapon arsenal – the Type 83 destroyer. A destroyer, whilst being the most capable ship in the list, is likely to only be built in small numbers and could be overly complex for a picket role.
- A general purpose frigate – for example, a Type 31 – which provides a much more rounded (but significant) capability more suited for the role of a picket. However, this still results in putting a major crewed warship in an up-threat position.
- Multiple cheap, uncrewed picket ships, capable of extending radar horizon with minimal additional capability. Uncrewed vessels remove the crew from immediate danger whilst extending coverage. Multiple ships creates resilience in the system. However, the platforms would be largely limited to surveillance roles.
- A simple, low-cost, lean-crewed picket ship – with additional capability to its uncrewed counterpart but simple enough that the consequences of loss are limited. A purpose-built platform provides a more optimised design for use in the picket role whilst also providing the option to perform other tasks. Furthermore, this design could function as a test bed for transition from lean-crewed to fully autonomous operations.

Although the preferred option of a low-cost lean-crewed picket ship constitutes a new design, the wider RN may benefit from having another type of warship in its fleet to provide a diversified capability. A simpler warship will diversify what can be achieved.

6. Further Design Considerations

The choice of surveillance radar system is an important consideration due to its cost and its impact on the overall design of the radar picket platform.

At a minimum, the purpose-built radar picket platform will require a fixed mast-mounted surveillance radar. A 3D medium range surveillance radar, such as the Type 997 Artisan radar system, offers a suitable level of capability to meet this requirement. This fixed radar system may then be complemented with an airborne means of radar detection to reduce the blind spot created by the radar horizon. Either a tethered airborne radar system or a more traditional AEW system should be considered.

As with the fixed radar system, the choice of airborne surveillance system will also impact the overall design of the platform. The most obvious impact of these systems is perhaps the space required above deck. Both tethered and AEW systems would require a sizable amount of deck space for use as either a mooring station or flight deck.

In the case that the platform is to operate independently with a more traditional AEW system, a hangar space would be necessary to protect and maintain helicopters or UAVs between deployments. Alongside adequate flight deck and hangar spaces, internal space for airborne operations planning and flight crews would also be required.

A tethered radar system has different, albeit slightly similar, effects on the rest of the platform. The system's mooring station would need to be located at the aft of the vessel so that the aerostat, which may take up a considerable volume and length once inflated. The platform will require a control and data processing centre, a suitable winch system and sufficient power capacity to deploy, operate and retrieve the airborne radar system.

The purpose-built radar picket platform should be equipped with self-defence weaponry including counter-UAS systems, such as DragonFire, and CIWS. Vertical launch system silos will be sacrificed to reduce the complexity of the platform, major threats will therefore have to be dealt with by other nodes in FADS. The possibility of designing the purpose-built platform ‘for but not with’ particular weapon systems should be considered, as doing so would allow for defensive capability to be tailored to a given adversary’s level of weapons technology. For example, during peace time weapons outfit can be reduced to minimise crew requirement and platform cost.

7. Conclusion

Airborne threats continue to develop through multiple avenues, including both advanced missile technology and cheap, low-tech, swarming drones, which operate at low altitudes to evade radar detection until as late as possible. The RN’s FADS system will control air space over a wide area surrounding a CSG using multiple systems and nodes. Historically used to extend radar coverage, radar pickets are ideal nodes within FADS. Operating up-threat of the CSG, a radar picket will detect incoming airborne threats, providing early warning and neutralising threats where possible. The radar picket will specialise in maintaining an increased radar horizon to ensure low-flying airborne threats are detected as early as possible.

The RN currently operates the Crowsnest system to perform AEW. Whilst AEW may be used as part of FADS, current AEW systems have limited endurance that makes constant operation difficult. Operating a naval platform as a radar picket has potential to provide increased radar coverage more efficiently and for longer periods of time.

The role of radar picket ship could be fulfilled by either an existing RN platform or a bespoke radar picket ship. Specialised, highly capable assets such as the Type 83 could be seen as overly complex for the picket role and would present too great of a risk when operated as a radar picket. General purpose frigates are more suited towards the radar picket role, however they still require the commitment of an asset that could be used more efficiently in other roles.

A fleet of uncrewed drones, relying on cheaper radar systems to increase coverage through quantity over quality offers another potential option. However, such a system would likely be limited to surveillance roles and be vulnerable to less advanced enemy weapons.

A purpose-built radar picket platform presents a means of optimising the role of radar picket. A lean-crewed platform that focuses on radar capability could successfully perform the radar picket role whilst reducing its associated risk. Such a platform would host a capable fixed radar system, whilst also maintaining an airborne radar system to increase detection of low flying threats. Fitted ‘for but not with’ airborne defence systems such as DragonFire and CIWS will allow for operating costs and risks to be reduced depending on the adversary and roles outside of FADS.

8. Future Work

A purpose-built radar picket platform may provide an efficient means of maintaining effective radar coverage over a wide area for extended periods of time, to provide early warning and protection for a CSG. However, for such platform to succeed, advancements in autonomy would need to be made. The development of the picket ship as a test bed for autonomous systems would permit confidence to be gained in the technology and permit ever leaner crewed vessels. This would have great utility far beyond the radar picket ship and allow for leaner crews to be used on all RN vessels in the future.

A radar picket platform would benefit greatly from such autonomy, and in turn FADS would benefit greatly from a radar picket capability. Investigation into the utility of the picket ship concept should be conducted as the FADS concept is progressed.

References

HC DEB, 2024. *UIN 10750.* [Online]
Available at: https://questions-statements.parliament.uk/written-questions/detail/2024-01-22/10750#
[Accessed 8 May 2024].

Horitski, K., 2016. *Joint Land Attack Cruise Missile Defense Elevated Netted Sensor System (JLENS): Missile Defense Advocacy Alliance.* [Online]
Available at: https://missiledefenseadvocacy.org/defense-systems/jlens/
[Accessed 28 June 2024].

Lobner, P., 2023. *U.S. Shipboard aerostats - U.S. Army SASS and USCG SBA / MIST programs,* s.l.: The Lyncean Group of San Diego.

Ministry of Defence, 2021. *Defence in a competitive age.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/974661/CP411

_-Defence_Command_Plan.pdf
[Accessed 9 May 2024].

Navy Lookout, 2022. *Crowsnest Airborne Surveillance and Control due to achieve Initial Operating Capability in 2023.* [Online]
Available at: https://www.navylookout.com/crowsnest-airborne-surveillance-and-control-due-to-achieve-initial-operating-capability-in-2023/
[Accessed 25 06 2024].

Navy Lookout, 2024. *After action report – Royal Navy's busiest air defence activity since 1982.* [Online]
[Accessed 8 May 2024].

Royal Navy, 2021. *Navy's new 'eyes in the sky' enter service ready for carrier mission: News: Royal Navy.* [Online]
Available at: https://www.royalnavy.mod.uk/news-and-latest-activity/news/2021/march/24/20210324-crowsnest-flies
[Accessed 2 July 2024].

Royal Navy, 2021. *Think Differently: Royal Navy.* [Online]
Available at: https://www.royalnavy.mod.uk/news-and-latest-activity/features/think-differently
[Accessed 29 May 2024].

TCOM, 2014. *Gallery-TCOM-Carlson-Tide-TCOM-Sea-Based-Aerostat: TCOM.* [Online]
Available at: https://tcomlp.com/gallery-tcom-carlson-tide-tcom-sea-based-aerostat/
[Accessed 1 July 2024].

A Future Green Navy - Sustainable Support to Royal Navy

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Synopsis

Defence maritime capability is enabled by support activities that span from design and acquisition throughout the life cycle to ultimate disposal of warships. External effects, such as climate change and environmental compliance obligations, act to increase the burden on platform support whilst also making it harder to deliver those activities.

Through-life support requirements are derived for each project by integrated logistic support engineers. They apply an online tool to provide assurance on how the support solution is developing (or operating if the platform is in-service) including consideration of sustainability indicators within the support solution. The suggested support development activities aid compliance and responsiveness to changing legislation and other sustainability considerations, as well as exploiting opportunities to use technology and learn lessons from previous programmes. Effective through-life planning can achieve support advantage, freedom of manoeuvre, and operational availability.

This paper explores how the requirements between through-life support and environmental protection come together to deliver sustainable support advantage for the Royal Navy. It concludes this may be achieved by verification that material state is environmentally sound and assurance the platform can be operated within the Environmentally Sustainable Operating Envelope whilst on military operations.

Keywords: Environmentally sound; Sustainability; Through-Life Support; Environmental Management.
Glossary of Terms: First use highlighted in blue text.

1. Introduction: Sustainable Support

Publication of the Climate Change and Sustainability Strategic Approach (CCSSA) has resulted in a step change in environmental culture across the Ministry of Defence (the Department). Rear Admiral Paul Beattie, Director of Naval Staff, described the measures necessary for climate change adaption in the military as the "*…biggest change programme in defence.*[3]" The Defence Policy effects are profound and diverse including a new strategy for Support and Operational Energy plus new environmental strategies for driving resilience into equipment and warship acquisition.

The Sustainable Support Strategy (SSS) sets out Defence Support's (DefSp) initial response to the challenges climate change poses. It outlines how "Sustainable Support Advantage" is the optimisation between delivering the operational capability requirements and sustainment of that capability in a way that is resilient to external effects (Figure 1). Perceived threats to operational effectiveness include changes in compliance obligations, operating environment, and the ability to sustain capabilities out to end of operational service. The SSS aligns with the CCSSA in delivering Sustainable Support Advantage across all DefSp activity; this paper will focus on its delivery for the Royal Navy (RN).

Figure 1: Dimensions of the Sustainable Support Strategy

Sustainability has a credible purpose in Defence Support

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Jim Goodship is a senior environmental manager within the acquisition organisation of the Ministry of Defence. He is responsible for developing the environmental management system and demonstrating that platforms are environmentally sustainable to operate.
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[3] Parliamentary Defence Committee Inquiry Defence and Climate Change 8th Report dated 4th July 2023.

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1.1 Context

Defence tasks form the basis of the Defence Plan and the delivery of Defence Outputs (*Figure 2*) where Value for Money, Compliance and Net Zero Carbon (NZC) are key government objectives. Military Capability requires platform material state and readiness aligned to planned military operations. Platform availability is therefore a strategic measure of the defence posture and is achieved through competing influences of maintaining the design intent (i.e., limiting the degradation of material state) and capability development to improve operational effectiveness. DepSp provides a governance role within the Department's operating model, adopted by Enabling Organisations and Front-Line Command to deliver their capabilities.

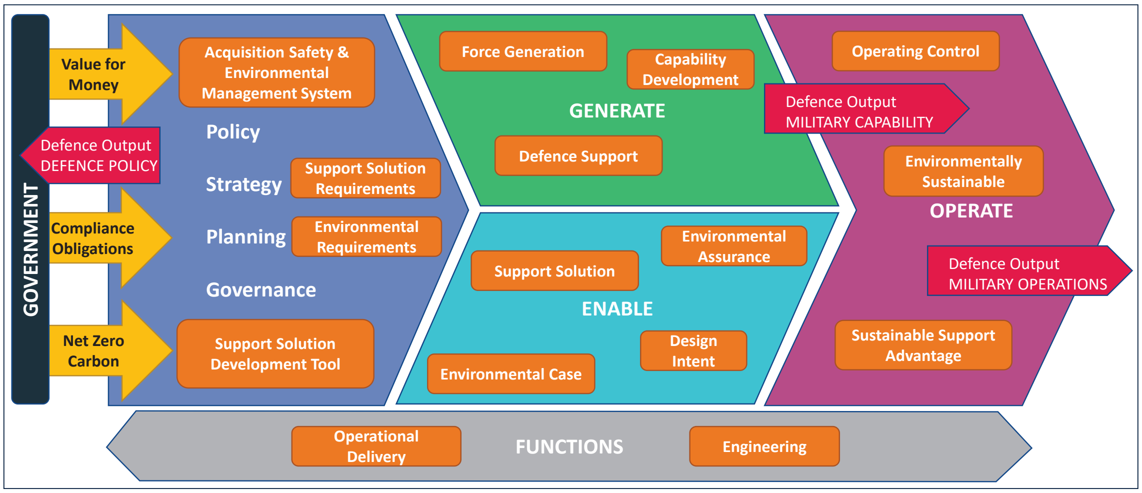

Figure 2: Sustainable Support within the Defence Operating Model

2. Defence Publications

Strategic Command (i.e., the fourth, pan-Domain Military Command) supports the breadth and depth of response to Climate Change and Sustainability across Defence. The Defence Policies relevant to CCS are presented pictorially in Figure 3,. The driving force for change is the CCSSA which sets out the expectations across defence equipment, support, and MOD estate with short (Epoch 1 2021-2025), Medium (Epoch 2, 2025-2035), and long term (Epoch 3, out to 2050) expectations.

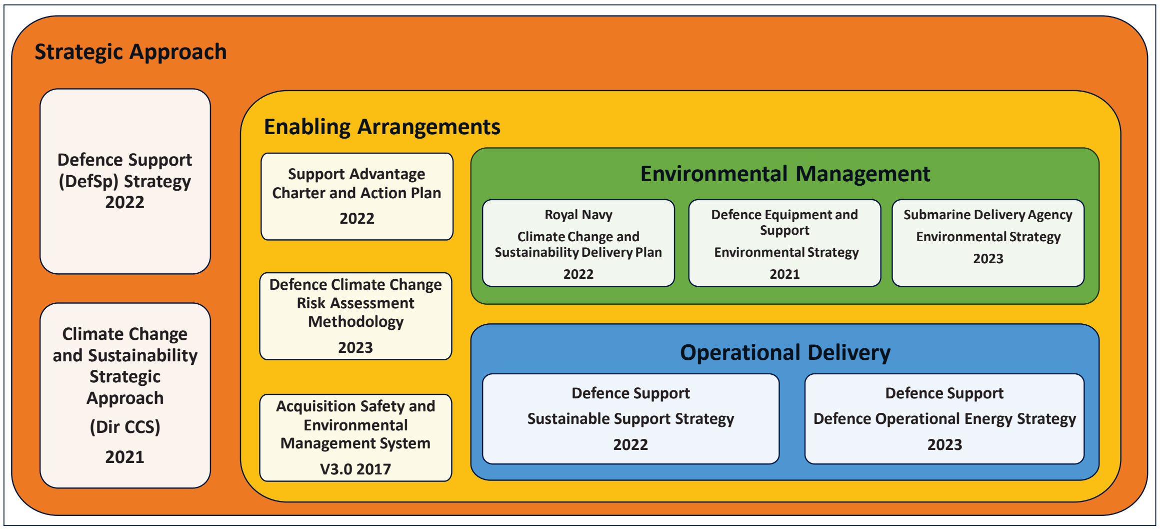

Figure 3: MOD Policy Documents applicable to Maritime Sustainability

2.1 The Support Solution

It is MOD policy to procure products that meet the required performance to time, cost, and quality, which are fully supportable at the optimum through-life cost. Configured processes shall be applied to all capability / product design, acquisition, and support to ensure they are supportable and sustainable through-life.

The Defence Support Strategy (2020) sets out CDLS' vision over the medium and long term with a diagnosis of the current state of the defence support function and the underlying reasons for the challenges and opportunities underpinned by the Defence Support Operating Model. The Support Advantage Charter[4] was published alongside the Defence Support Strategy and represents a collaboration where "*MOD and Industry agree to work together to improve [Support]*" through key drivers including behaviours, and environmental sustainability.

Aligned to the CCSSA, the SSS (2022) extends the principles of the Defence Support Strategy to Sustainable Support Advantage with six strategic initiatives within DefSp's direct sphere of influence that cover Support activity across Defence[5]. They represent opportunities to address structural factors that can yield significant climate change and sustainability benefits.

The SSS will be deployed (and Sustainable Support Advantage achieved) through the dimensions (Figure 1) that balance military capability with sustainability. Integrated Logistics Support (ILS) processes shall be applied to all capability / product design, acquisition, and in-service support to ensure sustainment. This begins at concept and includes planning for disposal; a 'cradle to grave' approach.

Through-Life Support (TLS) is enabled through the Support Solution Envelope (SSE) that measures performance through criteria that together form the support solution. The Support Solution Development Tool (SSDT) is an online tool to provides assurance on how the support solution is maturing within the acquisition phase (or operating if the platform is in-service).

2.2 The Environmental Case

Health, Safety, and Environmental Protection (HSEP) is an associated discipline with ILS and should already be intrinsic to TLS to prevent harm to people and the environment when operating equipment. HSEP ensures that equipment and services delivered are fit for purpose, safe, environmentally sound and operate within the constraints set by legislation and defence policy, together known as the Safe and Environmentally Sustainable Operating Envelope (ESOE). Also, the Department is held to account by society for its socio-economic, and environmental sustainability that must be factored into capability acquisition and support.

There should be no differentiation in how these requirements are employed for the design, manufacture, operation, or logistics and disposal phases. Therefore, the elements of ILS that contribute to Sound Environmental Performance should be clearly articulated in the response to the Acquisition Safety & Environmental Management System (ASEMS) requirements.

The Department has laid out its strategic approach to meet ambitious environmental objectives[6] and must start planning for the second epoch to achieve success by 2050. Enabling Organisations have issued environmental strategies for their capabilities to deliver these objectives and the RN phase 1 CCS Delivery Plan published in 2022. These documents align how the RN will embed requirements that contribute to support advantage and demonstrate unity under a common vision for CCS out to 2050 (*Table 1* details Goals relevant to Supportability).

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[4] 2022 Support Advantage Charter available from .GOV.MOD.UK.

[5] DefSp is the organisation within StratCom that delivers ILS Policy and Guidance across the MOD.

[6] Climate Change and Sustainability Strategic Approach ambitions are Adaptation and Resilience; Sustainability and net zero; and Global leadership.

Table 1: Ambitions for Sustainable Maritime Support

Defence Equipment & Support Environmental Strategy 2021	**Royal Navy Climate Change and Sustainability Delivery Plan 2022**	**Submarine Delivery Agency Environmental Strategy 2023**
SHARED AMBITIONS WITH OUR CLIENTS – DE&S and our clients will set out a shared ambition for our environmental protection and sustainability commitments	*SUPPORT, MAINTENANCE AND LOGISTICS* – A clear plan for implementing sustainable support and logistics will integrate the application of sustainability into its vision. • The Navy will proactively input into the Department's Sustainable Support Strategy to ensure that the Navy's needs are met in a sustainable way that maintains operational advantage. • The Navy will maintain engagement with the Department Support community. • The Navy will implement the MOD CCS Defence Operational Energy Strategy.	*SUSTAINABLE PROCUREMENT* – Work with its suppliers to encourage sustainable behaviours and ensure proactive approaches are integrated in procurement and support arrangements.
INFORMED SELECTION AND SUPPORT – DE&S will provide direction and clarity to all functions on the expectation for acquisition environmental performance objectives & targets. The equipment and support we provide will be designed to both minimise environmental impacts and increase resource efficiencies where possible, as well as be resilient to our changing climate.	*PROCUREMENT AND INDUSTRY* – The Navy will conduct coordinated cross sectoral engagement to influence and exploit the development of future maritime fuels. • The Navy will explicitly require suppliers to implement robust emissions management; also to implement robust sustainability and carbon reduction. • The Navy will ensure that robust Environmental Impact Assessments (including Lifecycle Carbon Assessments) are designed into procurement. • The Navy and its Delivery Agents will ensure that through life support and sustainability requirements are identified and planned for in the procurement process. • The Navy will agree with the Department a Phase 2 plan for sustainability in the Navy's supply chain.	*HAZARDOUS SUBSTANCES AND RESTRICTED MATERIALS MANAGEMENT* – Comply with our obligations applicable across the life cycle phases of our platforms, systems, and equipment.
INFLUENCING OUR SUPPLY CHAIN – DE&S will work closely with our suppliers to encourage sustainable behaviours and ensure proactive environmental management practices are integrated in procurement and support arrangements		*SUBMARINE LIFE CYCLE MANAGEMENT AND DISPOSAL* – Commit to the safe, secure, cost effective and environmentally sound disposal of decommissioned submarines.

In the same way that the support solution provides support advantage, maintaining the design intent is represented through an accurate understanding of the material state. Essentially, when material state is aligned with design intent the platform is available for military operations. This principle applies across all capability requirements but in the context of environmental protection this means that the engineered controls are in place with sufficient assurance that platforms are environmentally sustainable to operate in accordance with their design intent. This is the main function of the platform environmental case; where Claims, Arguments, and Evidence justify the ESOE for the platform. Put simply, the ESOE presents the limits of operation whilst remaining environmentally sustainable (*Figure 4*).

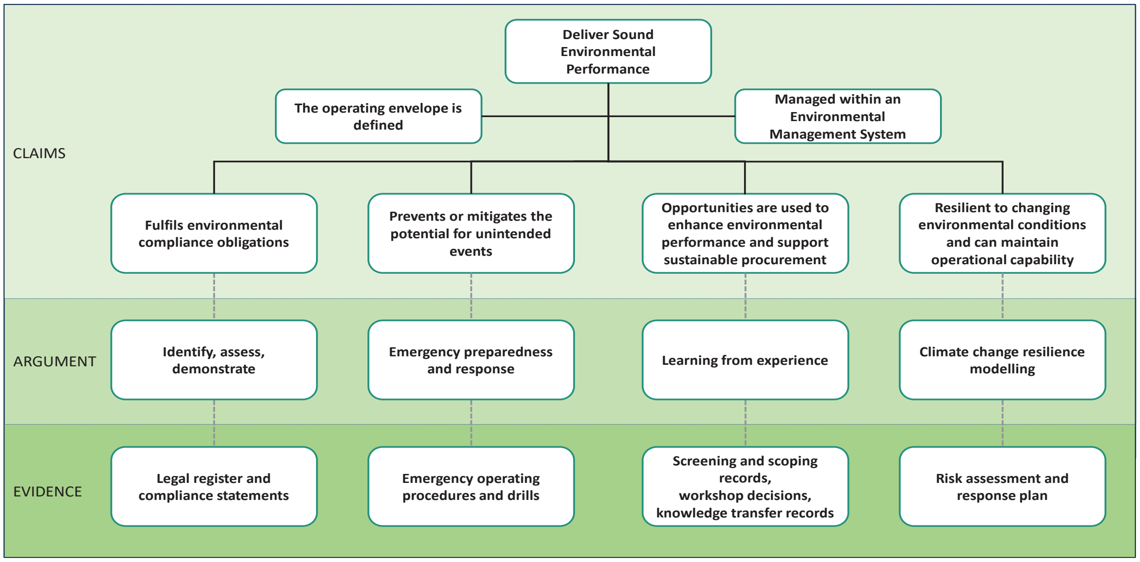


Figure 4: Environmental Case Argument

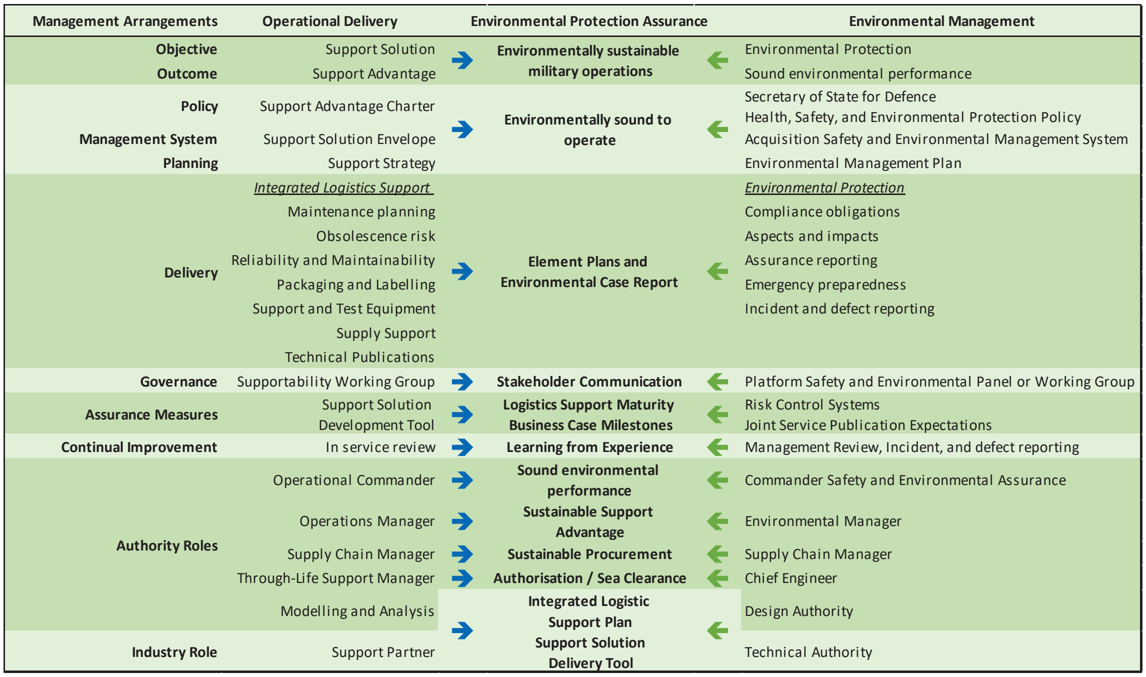
Where engineering controls are not sufficient to support environmentally sound operation then additional Operational Control is required to lessen the environmental impact (i.e., severity and / or frequency of the activity).

Operating controls should be overseen by the Operational Commander, effectively trained, practiced, and recorded within the operating documentation such that the platform is operated environmentally soundly.

2.3 Sustainability in the Support Solution

To realise socio-economic development that is sustainable requires breaking down barriers between individuals / organisations / regions / countries and authentic international co-operation (i.e., the 2030 United Nations Sustainable Development Goals, UN SDGs). Likewise, to achieve sustainable military operation requires a communication channel for co-operation between the distinct disciplines of supportability engineering and environmental management. It is not reasonable to expect TLS engineers to be expert environmental practitioners and vice versa. Therefore, to deliver environmentally sustainable military operations, these distinct areas must find common ground. The areas for requirement linkages and practitioner collaboration are presented in *Table 2*.

Table 2: Sustainability in Maritime Support



Management Arrangements	Operational Delivery		Environmental Protection Assurance		Environmental Management
Objective	Support Solution	→	**Environmentally sustainable military operations**	←	Environmental Protection
Outcome	Support Advantage				Sound environmental performance
Policy	Support Advantage Charter	→	**Environmentally sound to operate**	←	Secretary of State for Defence Health, Safety, and Environmental Protection Policy
Management System	Support Solution Envelope				Acquisition Safety and Environmental Management System
Planning	Support Strategy				Environmental Management Plan
Delivery	*Integrated Logistics Support*	→	**Element Plans and Environmental Case Report**	←	*Environmental Protection*
	Maintenance planning				Compliance obligations
	Obsolescence risk				Aspects and impacts
	Reliability and Maintainability				Assurance reporting
	Packaging and Labelling				Emergency preparedness
	Support and Test Equipment				Incident and defect reporting
	Supply Support				
	Technical Publications				
Governance	Supportability Working Group	→	**Stakeholder Communication**	←	Platform Safety and Environmental Panel or Working Group
Assurance Measures	Support Solution Development Tool	→	**Logistics Support Maturity** **Business Case Milestones**	←	Risk Control Systems Joint Service Publication Expectations
Continual Improvement	In service review	→	**Learning from Experience**	←	Management Review, Incident, and defect reporting
Authority Roles	Operational Commander	→	**Sound environmental performance**	←	Commander Safety and Environmental Assurance
	Operations Manager	→	**Sustainable Support Advantage**	←	Environmental Manager
	Supply Chain Manager	→	**Sustainable Procurement**	←	Supply Chain Manager
	Through-Life Support Manager	→	**Authorisation / Sea Clearance**	←	Chief Engineer
	Modelling and Analysis	→	**Integrated Logistic Support Plan**	←	Design Authority
Industry Role	Support Partner		**Support Solution Delivery Tool**		Technical Authority

3. Horizon Scanning

Horizon scanning is a key approach to better understand potential climate change threats and detect early signs that could have a significant effect on operation. Effective horizon scanning can assist policy makers to build resilience and manage risks and opportunities, clearly linking to SSS and creates a better understanding of environmental threat across the MOD. Within the 2024 Global Risks Report, the World Economic Forum listed climate change as the cause of five of the top ten global risks over the next ten years, with failure to mitigate climate change leading to extreme weather events being the highest long-term risk in terms of severity for the second year in a row.

With the CCSSA stating that defence accounts for 50% of the UK central Government's emissions at the time of publication (2021), it is essential that the MOD understands risks and the environmental threat of climate change. Reducing defence operational emissions positively contributes to legally binding Net Zero emission target by the 2050 (*Figure 2*). The Defence Support Sustainability Scorecard Delivery Partner (SSSDP) introduces the concept of a tangible scorecard of marking sustainability against key environmental impacts, targets, and key performance indicators. Using the balanced scorecard approach, this sprint aimed to identify performance metrics for the SSS initiatives to support the measurement, management, monitoring, and reporting of each impact discussed through the understanding of future environmental threats and then their relation back to Epochs presented in the CCSSA. This offers potential for assimilation by RN within their Climate Change and Sustainability Delivery Plan (CCSDP) where operational capability is one key lines of operation to 2025 (end of Epoch 1) by acting as a launch pad to understand the future threats in a climate-changed world.

The Defence Operational Energy Strategy (DOES) discusses the need to understand the transition risks for the RN on fuels and resilience that will make it harder to support defence capability in the future. Proactive risk management through horizon scanning to create an adaptive and informed approach to energy availability is needed to ensure the MOD can maintain its ability to operate globally without limiting capability DOES identifies the future cost of fossil fuels will escalate as commercial availability reduces and the price increases. Therefore, there remains need for investment in innovative technologies for propulsion and power generation that have lower through-life carbon emissions, whilst utilising sustainable material choices to aid the application of circular design principles.

3.1 Circling the square

Understanding the principles of reducing, reusing, remanufacturing, and recycling existing material is essential to embedding a Circular Economy within defence acquisition and support. Creating circularity by design breaks away from traditional linear ‘take-make-use-waste’, towards understanding the overall impact of materials to consider repurposing across their useful lifespan. Allowing margin within the design enables materials to be maintained and circulated to reduce the effect of obsolescence through-life. Integrating circular design principles for the benefit of platform life must not compromise military advantage therefore critical raw materials will continue to be used, but design decisions should consider the embedded value to the whole of defence.

When applying this to MOD shipping, both DE&S and SDA have goals to establish and embrace a circular economy[7]. The RN CCSDP discusses ambition for circular economy to be built into design through procurement and industry partners and a summary of these strategies can be found in *Table 1.*

SDA CEO Sir Chris Gardner KBE discusses that the SDA ‘*need to ensure that once a submarine has completed its final operations and is decommissioned from service, it is disposed of safely and efficiently, our nuclear legacy managed and the vessel itself recycled with a focus on building a circular economy across defence’*. This will be achieved by safely and securely disposing of our first complete nuclear submarine “Swiftsure” by the end of 2026. This programme aims to recycle at least 80% of the submarine and develop the capability for submarine dismantling within the UK before disposing of further submarines[8].

Identifying key themes in circular design with sustainable procurement in place at the earliest stage is central to success of ‘*circling the square*’. This includes efficient waste stream identification and minimisation to end of life. These disposal processes also highlight the importance of Learning from Experience (LfE) within the support enterprise. By maintaining disposal logs through platform life and optimising the support solution with decision making linked to the environmental case, the disposal element of the support solution captures key safety and environmental lessons for future disposal of similar assets earlier.

3.2 Supply chain vs Supply circle

Due to the sheer size of the Department, and the breadth of projects it is responsible for, it is obvious that the supply chain plays a vital role in the route to Net Zero and its direct influence on scope 3, the largest proportion of reported emissions[9]. MOD must therefore be aware of its role and relationship with supply chain to place sustainability targets and influence sustainability culture throughout industry. The supply chain is encouraged to enhance environmental performance on their defence contracts, as they are already expected to on civilian contracts by their shareholders. The CCSSA emphasises this responsibility by explaining that defence will *‘embrace the circular economy, driving it through our supply chain, the way we partner with others, behave and work.’*

Understanding how to improve circularity in the supply chain is advocated by The Ellen MacArthur Foundation, with three principles:

- **Distributed and interconnected networks** to leverage local and global partnerships with suppliers, customers, and industry peers.
- **Multidirectional flows of information**, goods, and money to enable data — such as the location, material composition, and disassembly options of an item — to flow between network partners.
- The ability to **capture and deliver value** by keeping products and materials in use.

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[7] DE&S Goal 5 and 10 focus on resource efficiency, informed selection and support, whilst SDA Goal 8 underlines the importance of submarine life cycle management and disposal in creating a circular economy.

[8] Submarine Delivery Agency Environmental Strategy 2024-2025.

[9] Kraft Foods, road tester for the GHG emissions protocol, found that value chain emissions comprise more than 90 percent of the company’s total emissions https://ghgprotocol.org/sites/default/files/standards_supporting/FAQ.pdf

Defence disposal planning processes that set direction in improving communication with manufacturers through-life, and the Department's recent acquisition of Sheffield Forgemasters, demonstrates that where there is a direct need for secure and sustained supply of materiel then a supply circle is preferential to a supply chain.

3.3 Circling back to other industries

The CCSSA uses the phrase 'fast follower' to exploit low carbon technology from applications beyond defence and to integrate sustainability (e.g. circular economy) and life cycle emissions angles. There is evidence of this consideration within the RN where Offshore Patrol Vessels (OPV), Fleet Solid Support Ships (FSS), and Type 26 frigates have considered sustainability requirements by-design.

In oral evidence to the Parliamentary Defence Committee Inquiry[10], Lt Gen (Rtd) Richard Nugee CBE[11] stated '*we can't rule out what the next navy fuel will be and must work collaboratively on this, both defence and industry, because we have to be able to take fuel from wherever it comes from*'. The term 'fast follower' applies beyond RN utilising alternative fuels through ambition to change and work with industry partners within the CCSDP.

4. Maritime Support

RN ships and submarines require global reach and availability to participate in routine military operations and force projection. The RN operate in the most demanding situations without external engineering support on the premise that *the equipped, empowered, and enabled maintainer should be at the heart of a support solution[12]*.

Support transformation programmes across flotillas have been implemented with the mandate deliver longer-term improvement in platform availability. They deliver through data driven decision making, collaboration and addressing root causes to achieve the availability that defence requires, underpinned by stable schedules and world-class through-life capability management; i.e., Support Advantage.

Platform availability is dependent on assurance that platforms select the best practicable environmental option by-design, and residual environmental impacts are minimised as far as reasonably practicable within an operational safety and environmental case; i.e., sound environmental performance.

Together, these concepts underpin environmentally sustainable military operation (*Figure 1*). This ambition may be achieved by aligning support solution and environmental protection requirements within the support regime; i.e., combining the requirements of ASEMS with the SSE under the enabling assurance provided by the SSDT (*Table 2*).

5. Conclusion

A decade has passed since the first Future Green Navy paper[13] focussing on design of warships, articulating the environmental expectation, and presenting the case for environmentally sustainable design. The requirements have not changed significantly, but the effects of climate change on military operations and global security have received far greater attention since the 2021 CCSSA. Whilst aspirations are not being met in all areas across defence[3], within the maritime domain force generation and enabling organisations are united under a common vision out to 2050. New enabling arrangements (*Figure 3*) will deliver against wider sustainability objectives within environmental management and through-life support. This paper has considered how these requirements affect the environmental and supportability cases for maritime through-life sustainability to provide assurance that platforms and equipment can perform within their ESOE.

Applying sustainability principles early in the life cycle through horizon scanning will allow the Department to create and embed a circular economy within defence, at concept design and through-life. CCS Delivery plans (*Table 1*) show the ambition of UK defence maritime community and how the Department continuously evolves to overcome future environmental threats (whilst protecting operational capability).

The 'Dimensions' of the SSS (*Figure 1*) represent the balance between military capability, support, and the operational environmental case respect to external threats (e.g. climate change) and minimising harm from capabilities through optimisation of platforms and equipment. However, supportability concepts do not currently feature within the ASEMS toolkit, beyond the concept of considering whole life cost in the assessment. This presents a project risk that the environmental case and support solution deviate from one another as they are driven by separate disciplines. Therefore, requirement linkages and practitioner collaboration should be forged between

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[10] Defence and Climate Change HC 179 dated 22nd November 2022.

[11] Climate Change and Sustainability Review Lead in Defence at time of publication of the CCSSA.

[12] Navy Support Division – Key Support Principles driving premise underpins Navy Command Support Directorate Requirements for Single Statement of User Need.

[13] A Future Green Navy – Managing environmental expectation on Naval Ships, INEC 2014.

support advantage, material state, and the environmental management system to avoid duplicate or conflicting outcomes from the respective analyses (i.e., TLS, Defect & Concession reporting, and ASEMS outputs).

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References

Acquisition Safety & Environmental Management System (ASEMS). Available from https://www.asems.mod.uk/policy (mod.uk) [Last Accessed 23rd July 2024]

Defence Equipment & Support, Environmental Strategy 2021 to 2025. Available from: https://des.mod.uk/wp-content/uploads/2021/12/ABW-21-139-DES-Environmental-Strategy-v11-web.pdf [Last Accessed 24th July 2024]

Defence Equipment & Support, "Delivering Sound Environmental Performance in DE&S Acquisition," S&EP Leaflet 18/2023. Available from: https://www.asems.mod.uk/guidance/safety-and-environmental-protection-leaflets [Last Accessed 24th July 2024]

Hammock L.: "Unlocking the Potential of Sustainable Submarine Design," Proceedings of WARSHIP Conference 2021, Online, June 2-3, 2021.

Laird A. Ledingham L. & Goodship J.: "A Future Green Navy – Managing environmental expectations on Naval Ships," Proceedings of the International Naval Engineering Conference 2014, Amsterdam, The Netherlands, May 20-22, 2014.

Ministry of Defence, Climate Change and Sustainability Strategic Approach. Available from: https://www.gov.uk/government/publications/ministry-of-defence-climate-change-and-sustainability-strategic-approach [Last Accessed 24th July 2024]

Ministry of Defence, Defence Capability Framework. Available from: https://assets.publishing.service.gov.uk/media/62d7d1668fa8f50c0a8a4029/MOD_Defence_Capability_Framework_Accessible_Jul22.pdf [Last Accessed 24th July 2024]

Ministry of Defence, Defence Climate Risk Analysis Method (DCRAM). Publicly available information available from Defence and Climate Change Inquiry Government response (8 November 2023): https://committees.parliament.uk/publications/41948/documents/209651/default/ [Last Accessed 24th July 2024]

Ministry of Defence, Defence Operational Energy Strategy (DOES). Available from: https://assets.publishing.service.gov.uk/media/6570b223809bc300133081cc/Defence_Operational_Energy_Strategy_2023.pdf [Last Accessed 23rd July 2024]

Ministry of Defence, Defence Operating Model. Available from: https://assets.publishing.service.gov.uk/media/5f6a2232e90e073fd9f7f466/20200922-How_Defence_Works_V6.0_Sep_2020.pdf [Last Accessed 24th July 2024]

Ministry of Defence, Defence Standard, 00-600 Part: 01 : Integrated Logistics Support (ILS) Requirements, Issue 4, May 2022. [Last Accessed 24th July 2024]

Ministry of Defence, Support Solution Envelope (SSE) 21, Available from Knowledge in Defence RLI (Knowledge in Defence) https://www.kid.mod.uk/maincontent/business/sse_21/content/cct6.htm [Last Accessed 24th July 2024]

Ministry of Defence, Defence Support Strategy 2020,published 14 December 2020, Available from: https://www.gov.uk/government/publications/defence-support-strategy [Last Accessed 24th July 2024] Ministry of Defence, Defence Support Sustainable Support Strategy 2022, published 8th November 2022, Available from: https://assets.publishing.service.gov.uk/media/6364e700d3bf7f388ba7dc55/Sustainable_Support_Strategy_2022.pdf [Last Accessed 24th July 2024]

Ministry of Defence, Royal Navy Climate Change and Sustainability Delivery Plan Phase 1, 2022.

Parliamentary Defence Committee Inquiry Defence and Climate Change 8th Report dated 4th July 2023 Available from: https://committees.parliament.uk/publications/41129/documents/200843/default/ [Last Accessed 24th July 2024] United Nations Sustainable Development Goals, Available from: https://www.undp.org/sustainable-development-goals [Last Accessed 24th July 2024]

World Economic Forum, The Global Risks Report 2024 19th Edition, published January 2024 Available from https://www3.weforum.org/docs/WEF_Global_Risks_Report_2023.pdf [Last Accessed 24th July 2024]

Glossary of Terms

Availability: The degree to which one can expect a piece of equipment or weapon system is available for use. Anon.

Best Practicable Environmental Option: During Assessment, environmental impacts and risks should be managed to have the least adverse environmental impact, whilst meeting legislative requirements, taking account of what is practicable and acceptable cost constraints. This results in the BPEO being established. Defence Maritime Regulations

Capability Development: to invest and explore opportunities to better develop the capabilities that the UK's Armed Forces, our allies, and partners, need to deter, defend and, if necessary, defeat our adversaries. The Defence Capability Framework

Circular Economy: a model of production and consumption which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. Circular economy: definition, importance and benefits | Topics | European Parliament (europa.eu)

Design Intent: The relationship between a required capability outcome and the design and its realisation in a product, service, or solution. Legacy JSP886 .GOV.uk

Environmental Impact: Any change to the environment, whether adverse or beneficial, wholly, or partially resulting from an organisation's aspects. ISO14001:2015

Environmental Threat: threats posed to military capability, effectiveness, and efficiency resulting from environmental conditions. Sustainable Support Strategy

Environmental Management: taking a consistent and proportionate approach to identify significant areas of concern and to target effort where it will deliver the greatest benefit. GREEN BOOK: An Introduction to Environmental Management in the MOD Acquisition Process

Environmentally Sound: Demonstration that all environmental aspects are being managed as part of an environmental management system so that harm to the environment is minimised as far as reasonably practicable.

Environmentally Sustainable Operating Envelope: the limits of operation whilst remaining environmentally sustainable. Anon.

Integrated Logistics Support: is a disciplined approach that influences the product design and develops the Support System to optimize supportability and Through-life Cost. DEFSTAN 00-600 pt 1.

Material State: [the difference between design intent and the] operating parameters that it defines to deliver its capability safely. Legacy JSP886 .GOV.uk

Military Capability (MilCap): development of the ability, both now and in the future, to have military influence and project force. Defence Operating Model

Operational Control: represents a mitigating activity to support delivery of sound environmental performance. ASEMS EMP08

Operational Delivery (OD): authority on the optimisation of through-life service support and the management of service delivery. SDA OD Function

Readiness: being the period measured from an initial order to the moment when the headquarters or unit is ready to perform its task from its peacetime location (permanent or forward deployed) or ready for deployment. Armed Forces Readiness Inquiry

Resilience: the degree to which people and capabilities will be able to withstand, or recover quickly from, difficult situations. The Defence contribution to resilience in the UK

Sound Environmental Performance: Valid reasoning and good judgement has been applied to proactively improve environmental performance. ASEMS S&EP Leaflet 18/2023

Support Advantage: Support ensures Defence has the forces and equipment, ready when and where we need them, fully fit, armed, provisioned, and able to deploy quickly and efficiently to confront the threats we face.

Support Solution: the optimised design and provision of a series of interrelated activities and resources required to sustain a capability through-life, in accordance with extant MOD policy; to meet defined user requirements, for a defined period, in defined environments. Support Solutions Envelope (SSE) - KiD - UK MOD

Supportability: Supportability refers to the inherent characteristics of the system and the enabling system elements that allow effective and efficient sustainment (including maintenance and other support functions) throughout the system's life cycle. Anon

Sustainability: Meeting the needs of the present without compromising the ability of future generations to meet their needs. Brundtland UN

Sustainment: involves the provision of in-service support, including repair and maintenance, engineering, supply and replacement parts, configuration management and disposal action. Anon.

Through-Life Support (TLS): maintaining the design intent of platforms and equipment across their operational life to dismantling and ultimate disposal Anon.

Improving Energy Efficiency of HVAC Systems on Navy Ships

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Synopsis

The function of the heating, ventilation, and air conditioning (HVAC) system on a Navy ship is to provide the required ventilation, heating, and cooling to the occupants and equipment on board. HVAC systems for Navy ships are designed to operate in areas with diverse and extreme ambient environmental conditions, ranging from sub-Arctic winter conditions to humid, hot coastal deserts. The HVAC system is sized for these extreme conditions, resulting in oversized systems for the more moderate environments these ships mostly encounter throughout the year. This leads to low efficiency, high energy consumption, and increased CO2 emissions. This paper proposes options for improving the energy efficiency of HVAC systems by incorporating free cooling, energy recovery, direct and indirect evaporative cooling, and the use of absorption chillers that utilise waste heat for generating chilled water. Engine waste heat is harnessed to provide heat to the hot water system, resulting in significant power savings and increased system efficiency.

Keywords: Efficiency; Energy consumption; Waste heat recovery; HVAC.

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems on board Navy ships are significant consumers of hotel load power. These systems are designed to operate in diverse and extreme ambient environmental conditions, ranging from sub-Arctic winters to humid, hot coastal deserts. Consequently, they are often oversized for the more moderate environments typically encountered throughout the year, leading to low efficiency, high energy consumption, and increased CO2 emissions.

The efficiency of HVAC systems on Navy ships can be enhanced by incorporating free cooling through economisers, energy recovery, direct and indirect evaporative cooling, and absorption chillers. Engine waste heat can be utilised to provide heat to the hot water system and as a power source for absorption chillers, resulting in significant power savings and increased system efficiency.

To evaluate these options for improving the HVAC system, an environmental model of the ship was created using IES VE software (IES, 2023). This model includes the ship's structure and insulation, heat loads from people and equipment, and a detailed representation of the HVAC system. The HVAC system is modelled using a schematic component-based interface, which allows for the accurate representation of cooling coils, heaters, fans, chilled water plants, and controllers. This interface also enables the linking of the HVAC system to the relevant compartments in the model using duct and room components.

The environmental model can predict the internal environmental conditions (temperature, humidity) of the ship under various weather conditions and operational scenarios. The options for improving the HVAC systems are simulated using a weather file that represents conditions encountered in Arctic areas in January and hot, humid areas such as the Arabian Gulf from February to December.

Author's Biography
Younus Abbas is a Principal Mechanical Engineer at Babcock International Group. He currently leads the HVAC functional group at Babcock UK ME. A Chartered Engineer, he has a background in HVAC, marine auxiliary systems, and noise and vibration. He has delivered several major projects, ranging from the delivery of an HVAC system for a Navy frigate to the design of the auxiliary cooling system for an amphibious transport dock vessel. His research work includes improving HVAC and auxiliary cooling systems for ships.

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2. Ship Environmental Model

The ship's environmental model was created using Dynamic Thermal Simulation software IES VE (IES, 2023), which incorporates the following features:

- Weather data based on ship location and time,
- Ship structure and insulation,
- Internal heat gains, including lighting, people (latent and sensible heat), and equipment heat emission,
- Profiles for simulating people's movement within the ship and equipment operating frequency,
- Modelling of the HVAC system, including chillers, cooling coils, heaters, controllers, etc.

A weather file simulating conditions encountered in Arctic areas in January and hot, humid areas such as the Arabian Gulf from February to December was created by combining weather data from Truro, Canada, for January and Kuwait for the period from February to December.

The ship and compartment geometries were modelled by importing DXF files for each deck. These files were then converted to 3D geometry, with insulation and construction materials applied to each compartment bulkhead, deck, and deckhead. All external surfaces below the waterline were set to a profile that allows for easy adjustment of seawater temperature to suit the ship's location. For winter conditions, a seawater temperature of 2°C was assumed, and for summer conditions, a seawater temperature of 32°C was assumed. Figure 1 presents an isometric view of the modelled ship geometry, highlighting the position of the waterline.

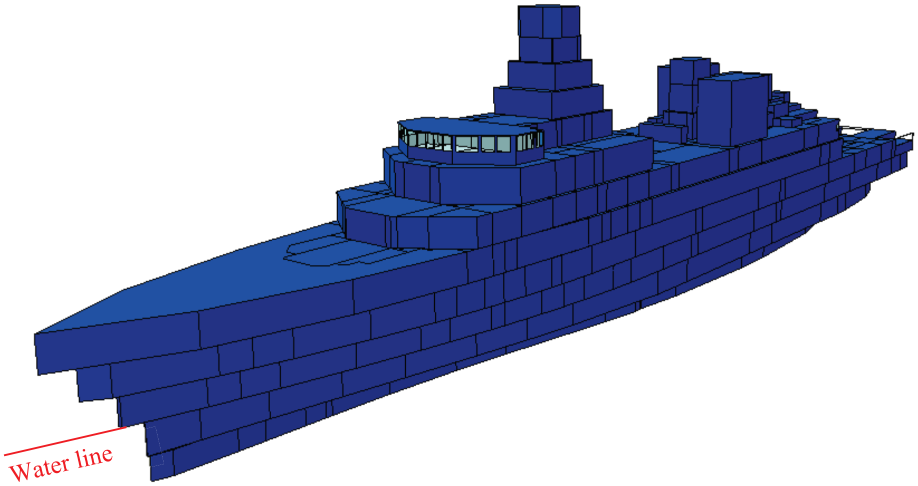


Figure 1: ISO view of the modelled ship geometry.

Internal heat gains for people, lighting, and equipment were assigned to each space with a profile, allowing for control of these heat gains at different times of day or year using daily, weekly, and yearly profiles.

Each compartment is assigned a relevant occupancy profile, enabling the simulation of people's movement within the ship. For this model, it is assumed that cabins are occupied from 19:00-07:00 and 16:00-18:00 hours, dining halls are occupied from 07:00-08:00, 12:30-13:30, and 18:00-19:00, and working areas are occupied between 08:00-12:30 and 13:30 -16:00.

Heat loads from personnel were input into the model as 70 W/person sensible heat and 50 W/person latent heat for all occupied compartments, except for the gym, which used values of 85 W/person sensible and 150 W/person latent heat. Lighting loads of 8 W/m² were applied to all lit compartments.

The HVAC system is modelled using a schematic component-based interface, which enables the accurate representation of cooling coils, heaters, fans, chilled water plants, and controllers. This interface also allows for the linking of the HVAC system to the relevant compartments in the model using duct and room components. Figure 2 illustrates part of the HVAC model.

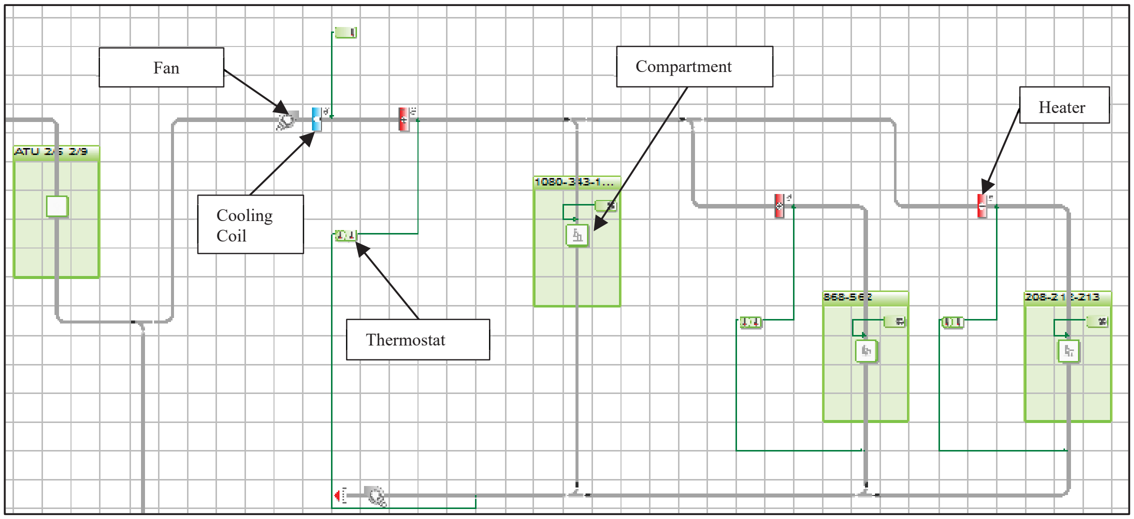


Figure 2: HVAC system components.

3. HVAC system energy recovery on current navy ships

The Heating, Ventilation, and Air Conditioning (HVAC) system on a naval ship is divided into two sub-systems:

1. Air-Conditioning (AC) system; and
2. Mechanical ventilation system.

The AC system provides conditioned air to accommodation areas, recreation spaces, the galley, messes, and other living spaces, as well as command and control areas, ship control spaces, and other working environments. This system is served by air-handling units (AHUs) installed in dedicated compartments.

Figure 3 illustrates a basic example of the air conditioning (AC) system on board a navy ship. Cooling and dehumidifying the air in this system is achieved using chilled water-cooled heat exchangers, while heating is provided by electrical heater elements or hot water heat exchangers supplied by an oil-fired boiler for preheating. Fresh air enters the Air Handling Unit (AHU) and mixes with the recirculated air within the AHU. The air mixture passes through the heat exchanger, reducing its temperature and humidity (W). Before being supplied to the compartment, the air passes through an electric heater. This heater regulates the compartment's temperature via feedback from a thermostat installed in the compartment or the recirculating duct. Dry, cool air is supplied to the compartment (S), removing heat and moisture until it reaches the desired condition. Part of the air is extracted as exhaust (E), while the remainder is recirculated back to the AHU to be mixed with fresh air (M).

In this AC system, limited exhaust energy recovery is achieved by recirculating the exhaust air from the HVAC system back to the AHU inlet. Typically, only 50% to 80% is recirculated and mixed with fresh air. This energy recovery method is widely used on naval ships but is limited in effectiveness, as the energy in the percentage of air exhausted to the atmosphere is not recovered.

Machinery spaces such as engine rooms, chilled water plant rooms, and steering gear rooms are served by mechanical ventilation systems, with no air conditioning or heat recovery methods typically used. These systems utilise a supply fan to provide fresh air to each space and an extraction fan to remove the exhaust air. Air is not recirculated in these systems. Chilled water-cooled Fan Coil Units are sometimes used for cooling in extremely hot climates to prevent compartment temperatures from exceeding equipment operational limits.

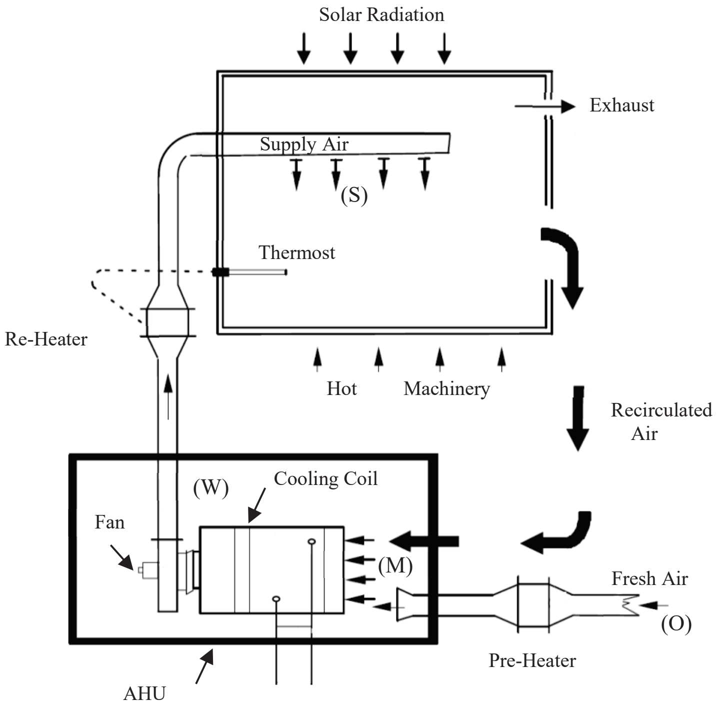


Figure 3: General AHU layout (MOD, 2005).

Naval vessels are typically equipped to survive in a Chemical, Biological, Radiological, and Nuclear (CBRN) environment. In such scenarios, a CBRN safe containment, commonly known as a Citadel, is formed by isolating all external intake and exhaust terminals. A relatively small amount of fresh air is supplied to the AHUs through Air Filtration Units (AFUs) to prevent CO2 concentration and maintain the minimum required overpressure of 5-8 mbar in the containment. Pressurisation of the Citadel ensures that no contaminated air from outside the ship enters. Overpressure dampers are used to bleed air from the Citadel through the cleansing station airlocks, which serve as entry and exit points. Under these conditions, the majority of the air is recirculated within the Citadel, making heat recovery impossible.

4. Use of Air Economisers

Air economisers can reduce HVAC energy costs and improve indoor air quality in cold and temperate climates by using cool outside air to cool the indoor space. When ambient conditions are hot and humid or very cold (Arctic conditions), economisers cannot be used, as outdoor air will increase the cooling or heating loads on the system. In these conditions, only the minimum required ambient air is supplied to the system.

An air-side economiser is a duct and damper arrangement with a control system that enables the HVAC system to use outdoor air to meet the cooling load when outdoor conditions are favourable, by closing the return air damper and fully opening the fresh air damper. Figure 4 shows a basic HVAC system with an economiser. Control of the economiser is achieved by comparing the return and outdoor air temperature or enthalpy. If the return air temperature or enthalpy is greater than the outdoor temperature or enthalpy, the economiser is activated (cooling). If the return air temperature or enthalpy is less than the outdoor, the economiser is isolated. Dry-bulb sensors work well in all but humid climates, where enthalpy sensors are more appropriate. For naval ships, it is recommended that enthalpy sensors are used due to the varied ambient conditions encountered and the potential for operating in hot, humid climates.

For naval ships that primarily operate in areas with cold and temperate climates, economisers can provide significant energy savings.

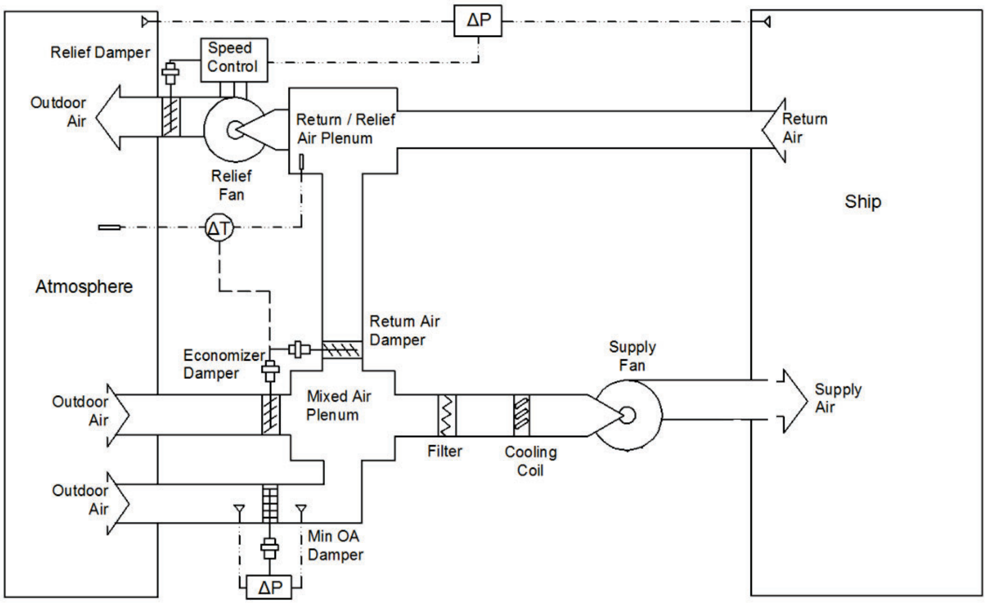


Figure 4: Basic schematic of an Economiser (EDR, 2009).

4.1. Economiser Case Study:

To assess the impact of introducing an economiser to the HVAC system on board a typical naval frigate, an economiser is added to the HVAC environmental model Air Handling Units (AHUs).

The model simulation results presented in Figure 5 show the monthly chilled water system load comparison between the HVAC baseline system and the HVAC system with economisers added to the AHUs. Figure 6 shows the simulation ambient annual mean temperature. Both figures show that the economisers are only active when the ambient mean temperature drops below 27°C and are inactive between May and September.

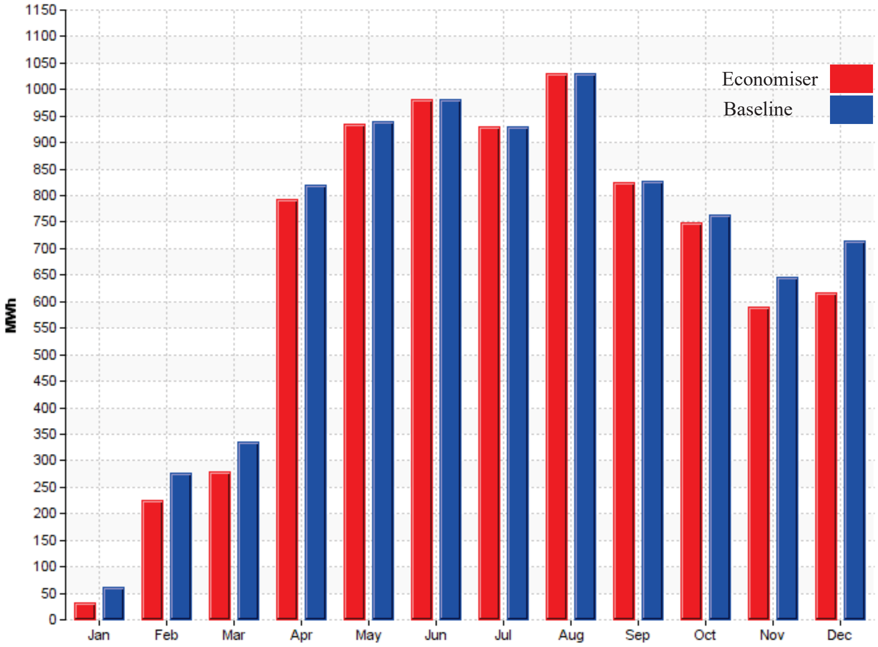


Figure 5: Monthly Chilled water load (kWh) simulation results, comparison between baseline and using Economisers.

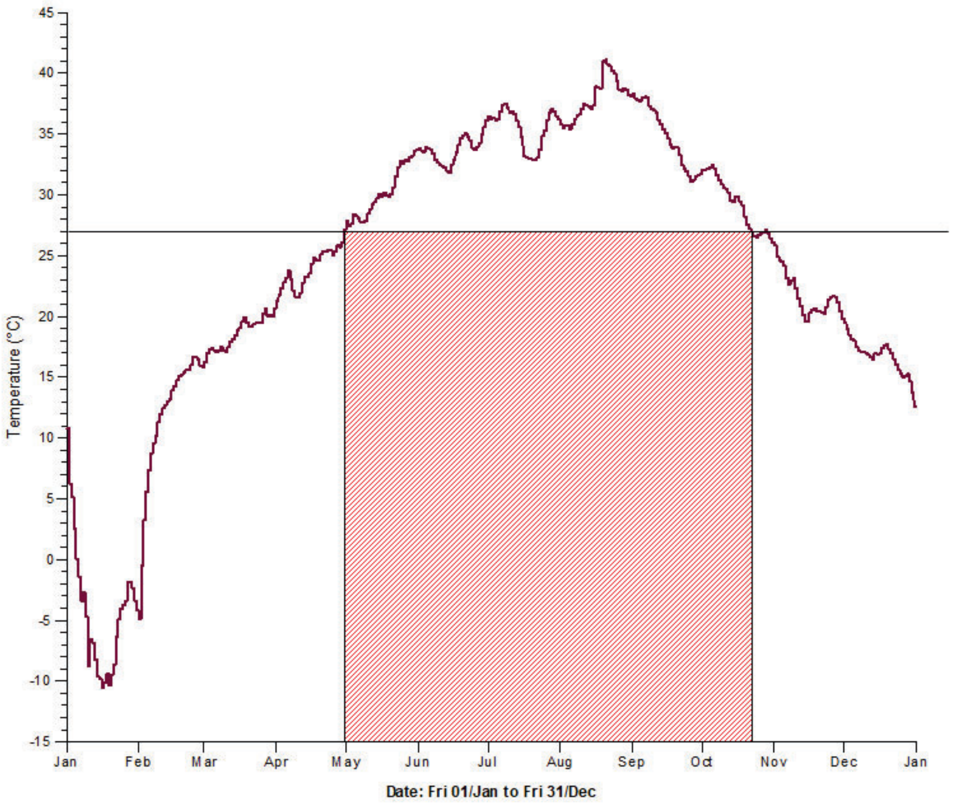


Figure 6: Simulation ambient mean temperature. Showing zone where economiser is not active.

Table 1: Reduction of Chilled water plant power consumption when using economisers

Month	**Baseline CW Load (MWh)**	**Economiser CW Load (MWh)**	**Reduction (%)**
Jan	15.0	7.8	48%
Feb	41.8	32.5	22%
Mar	51.7	41.4	20%
Apr	148.8	143.8	3%
May	191.7	191.2	0%
Jun	214.8	214.8	0%
Jul	196.2	196.2	0%
Aug	224.5	224.6	0%
Sep	172.2	172.0	0%
Oct	146.9	144.4	2%
Nov	113.6	103.4	9%
Dec	118.1	101.7	14%
Summed total	1635.3	1573.7	4% (61.7 MWh)

The model simulation results presented in Table 1 show that the total annual Chilled Water Plant (CWP) energy saving when using an economiser is 61.7 MWh. The use of an economiser is more effective in energy saving in more moderate climates.

5. Air-to-Air Heat Recovery

Air-to-air heat recovery involves the transfer of heat between two airstreams at different temperatures. This process is crucial for maintaining acceptable indoor air quality (IAQ) while minimising energy costs, overall energy consumption, and carbon dioxide emissions. This section outlines various air-to-air energy recovery technologies that can be implemented on navy ships.

5.1. Fixed-Plate Heat Exchangers

Fixed-plate heat exchangers are available in numerous configurations, materials, sizes, and flow patterns. Many have modules that can be arranged to meet almost any airflow, effectiveness, and pressure drop requirement. The heat transfer resistance through the plates is minimal compared to the airstream boundary layer resistance on each side of the plates. Consequently, the heat transfer efficiency is not significantly affected by the heat transfer coefficient of the plates. Aluminium is the most popular construction material due to its non-flammability and durability. Polymer plate exchangers may enhance heat transfer by inducing some turbulence in the channel flow and are favoured for their corrosion resistance and cost-effectiveness.

Typically, plate exchangers conduct sensible heat only; however, water-vapour-permeable materials, such as treated paper and microporous polymeric membranes, can be used to transfer moisture, thus providing total (enthalpy) energy exchange. One advantage of the plate exchanger is that it is a static device with minimal or no leakage between airstreams.

The effectiveness of heat exchangers depends significantly on the airflow direction and pattern of the supply and exhaust airstreams. Parallel flow exchangers (Figure 7 A), where both airstreams move along heat exchange surfaces in the same direction, have a theoretical maximum effectiveness of 50%. Counterflow exchangers (Figure 7B), where airstreams move in opposite directions, can theoretically achieve effectiveness approaching 100%, though typical units have lower effectiveness. Cross-flow heat exchangers have somewhat lower theoretical effectiveness than counterflow exchangers, with typical units achieving 50 to 70% effectiveness (Figure 7C) and 60 to 85% for multiple-pass exchangers (Figure 7D).). In practice, construction limitations favour designs that use transverse flow (or cross-flow) over much of the heat exchange surface (Figures 5C and 5D) (ASHRAE, 2020).

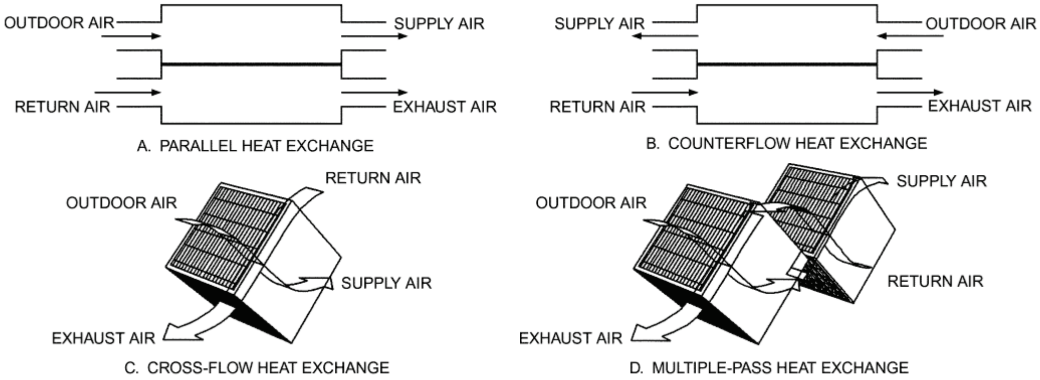


Figure 7: Plate Heat or Heat and Mass Exchanger Airflow Configurations (ASHRAE, 2020)

5.2. Coil Energy Recovery (Runaround) Loops

A typical coil energy recovery loop (Figure 8) places extended surface, finned-tube water coils in the supply and exhaust airstreams. These coils are connected in a closed loop by counterflow piping through which an intermediate heat transfer fluid (typically water or an antifreeze solution) is pumped.

A three-way temperature control valve prevents the supply coil from freezing. The valve is controlled to maintain the temperature of the solution entering the exhaust coil at 5°C or above. This condition is maintained by bypassing some of the warmer solution around the supply air coil. The valve can also ensure that a prescribed air temperature from the supply air coil is not exceeded. Coil energy recovery loops are highly flexible and well-suited to retrofitting. The loop accommodates remote supply and exhaust ducts and allows simultaneous transfer of energy between multiple sources and uses. An expansion tank must be included to allow fluid expansion and contraction. A closed expansion tank minimises oxidation when ethylene glycol is used. Typical effectiveness values range from 45 to 65% (ASHRAE, 2020).

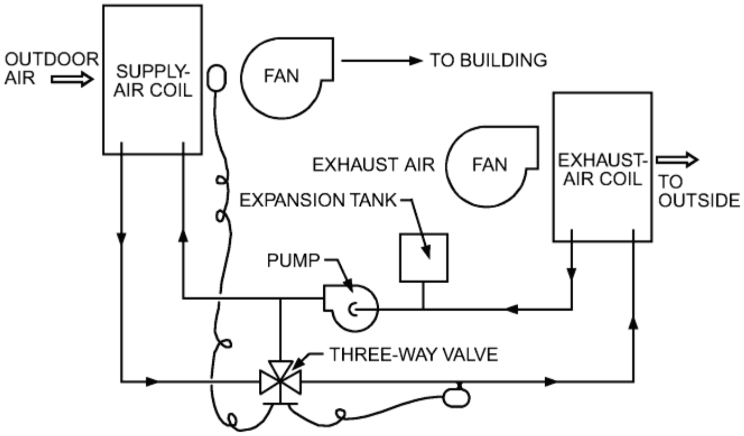


Figure 8: Coil Energy Recovery Loop (ASHRAE, 2020)

5.3. Thermosiphon Heat Exchangers

Two-phase thermosiphon heat exchangers are sealed systems comprising an evaporator, a condenser, interconnecting piping, and an intermediate working fluid present in both liquid and vapour phases. In coil-type thermosiphons, evaporator and condenser coils are installed independently in the ducts and interconnected by the working fluid piping, similar to a coil energy recovery loop. In thermosiphon systems, a temperature difference and gravity force are required for the working fluid to circulate between the evaporator and condenser (ASHRAE, 2020).

A small pump is introduced to assist in the circulation of the condensed refrigerant, enabling temperature control and an extended piping system.

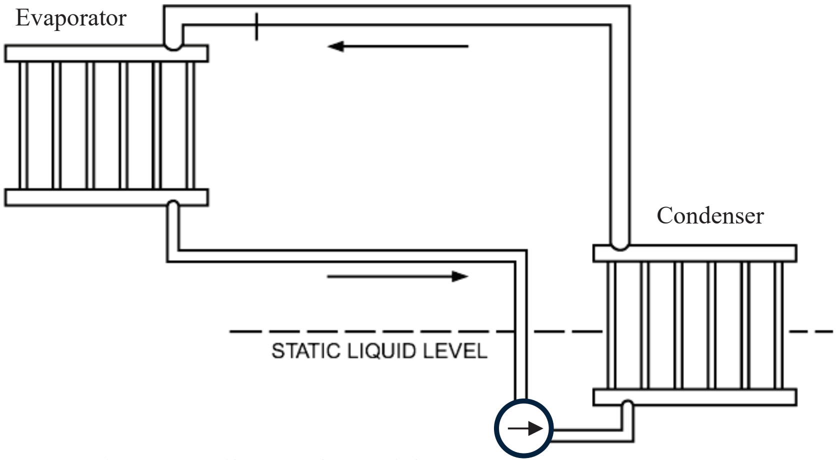


Figure 9: Coil-Type Thermosiphon Loops (ASHRAE, 2020).

5.4. Heat Recovery Unit Case Study

To evaluate the impact of integrating heat recovery units into the HVAC system of a typical naval frigate, units with an effectiveness of 60% were added to all fresh air supply and exhaust ducts for all AC systems in the HVAC model.

The simulation results, illustrated in Figure 10, display the monthly sensible heat recovery from the exhaust air of an AHU via a heat recovery unit. The bar chart indicates that the highest cooling heat recovery occurs in August, while the greatest heating heat recovery is observed in January. These months represent the peak ambient conditions for which the system is designed. Unlike economisers, heat recovery units reduce the peak load, leading to smaller equipment sizes.

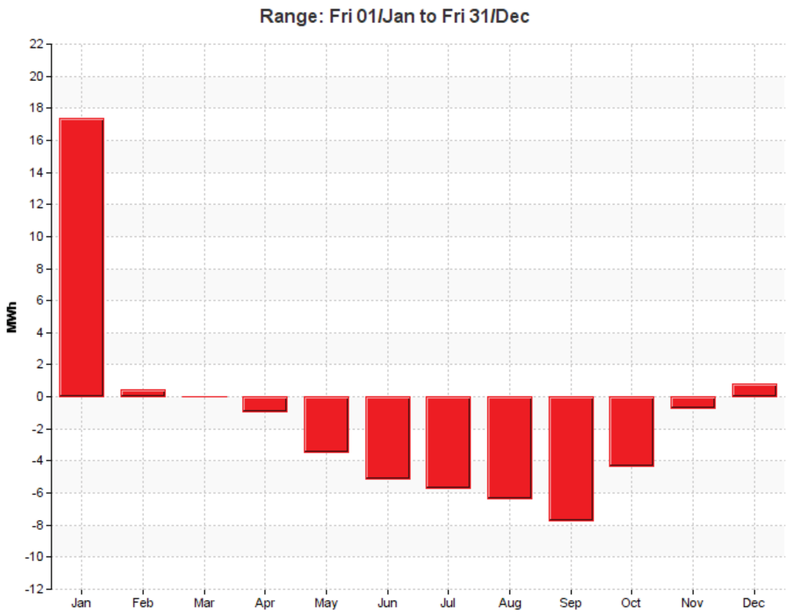


Figure 10: Monthly sensible heat recovery (MWh) from the exhaust air of an AHU heat recovery unit.

The model simulation results presented in Figure 11 show the monthly chilled water system load comparison between the HVAC baseline system and the HVAC system with heat recovery units added to the AHUs. The bar chart indicates that the chilled water loop peak heat load is reduced during summer peak ambient conditions.

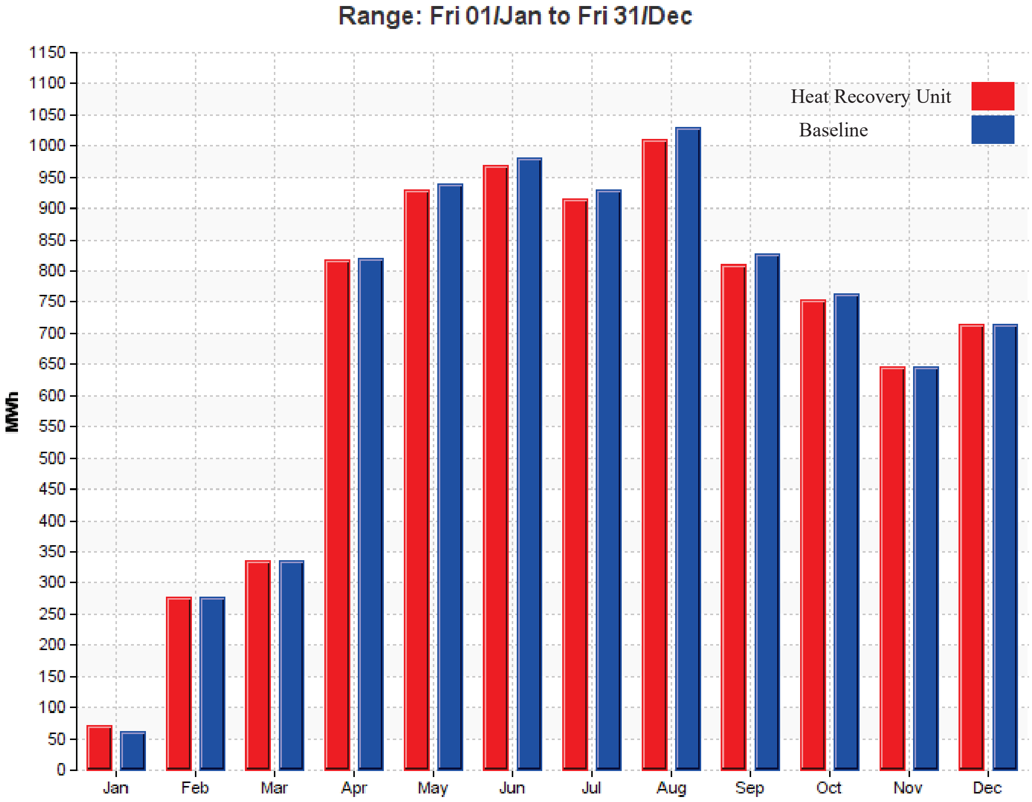


Figure 11: Monthly Chilled water load (kWh) simulation results, comparison between baseline and using heat recovery units on AHUs.

Table 2: Reduction of chilled water plant power consumption when using heat recovery units on AHUs

Month	Baseline CWP Energy (MWh)	Heat Recovery Unit CWP Energy (MWh)	Reduction in CW Plant load (%)
Jan	15	15	0%
Feb	42	42	0%
Mar	52	52	0%
Apr	149	149	0%
May	192	190	1%
Jun	215	213	1%
Jul	197	194	2%
Aug	225	221	2%
Sep	173	169	2%
Oct	147	145	1%
Nov	114	114	0%
Dec	118	118	0%
Total	1638	1622	1% (17MWh)

The model simulation results presented in Table 2 demonstrate that the use of heat recovery units is more effective in saving energy at peak ambient conditions. However, it also shows that the total annual Chilled Water Plant (CWP) energy saving when using heat recovery units on AHUs is only 17 MWh, representing a reduction of just 1% from the baseline power consumption. This limited saving is due to the high percentage of air recirculation (80%) in the system. Therefore, the use of energy recovery units alone in this application would not be a cost-effective solution.

6. Indirect Evaporative Air Cooling

In indirect evaporative cooling, the exhaust air passes through a water spray and absorbs water vapour until it becomes nearly saturated. As the water evaporates, it absorbs sensible energy from the air, lowering its temperature. The evaporatively cooled exhaust air is then used to cool supply air through an air-to-air heat exchanger.

As the exhaust air is cooled by passing it through a water spray, wet filter, or other wetted media, a greater overall temperature difference between the supply and exhaust air is achieved, resulting in more heat transfer. Energy recovery is further enhanced by improved heat transfer coefficients due to the wetted exhaust-side heat transfer surfaces. No moisture is added to the supply airstream, and there are no auxiliary energy inputs other than fan and water pumping power. Because less mechanical cooling is required with evaporative cooling, both energy consumption and peak demand load are reduced. Overall mechanical refrigeration system requirements are reduced, allowing for the use of smaller mechanical refrigeration systems (ASHRAE, 2020). Water for the evaporative cooling process can be provided from the ship’s existing water supply.

6.1. Indirect Evaporative Air-Cooling Case Study

To evaluate the impact of using indirect evaporative cooling in the HVAC system on board a typical naval frigate, heat recovery units with an effectiveness of 60% were added to all fresh air supply and exhaust ducts in the AC system and mechanically ventilated systems that serve machinery spaces, excluding the engine rooms. Evaporative coolers were also added to the exhaust duct upstream of all heat recovery units. Figure 12 shows the schematic arrangement of the indirect evaporative cooling implemented in the HVAC model.

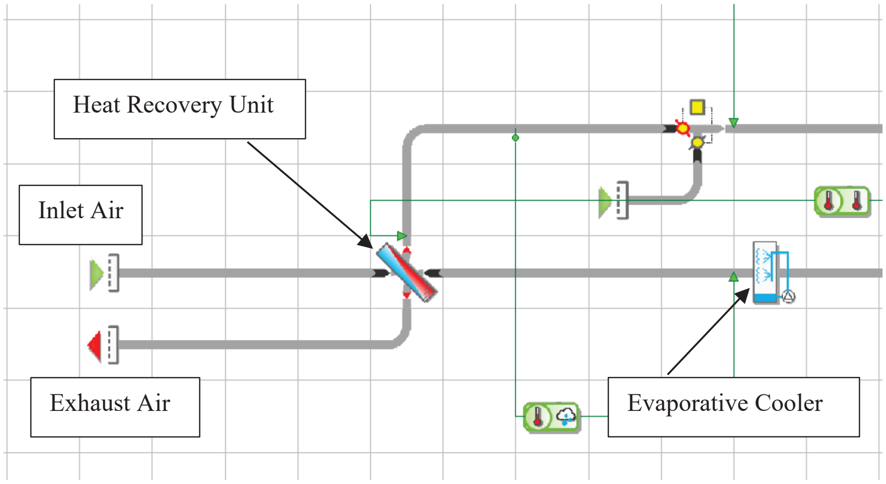
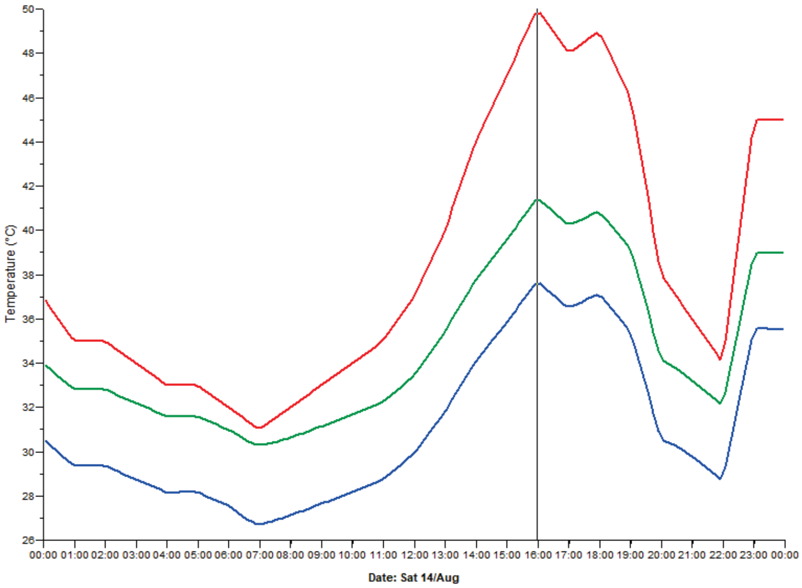


Figure 12: Indirect evaporative cooling schematic arrangement in the HVAC model.

Figure 13 presents the simulation results of the inlet air temperature to an AHU when using a heat recovery unit and indirect evaporative cooling, compared to no form of heat recovery. The results indicate a reduction in AHU inlet temperature from 50°C to 41°C when using a heat recovery unit, and a further reduction to 37°C when using indirect evaporative cooling.

Figure 14 shows the model simulation results for air entering a mechanically ventilated space. The graph indicates that the reduction in temperature when using a heat recovery unit alone is negligible. However, there is a significant reduction of 13°C in temperature when indirect evaporative cooling is used. This demonstrates that, due to the high exhaust temperature from mechanically ventilated spaces, the use of heat recovery units alone is not effective. The use of indirect evaporative cooling significantly impacts energy savings and improves indoor conditions.



Variable Name	Line Colour	Value
Base line air entering temperature (°C)	🟥	50
Heat recovery unit air entering temperature (°C)	🟩	41
Indirect evaporative cooling air temperature (°C)	🟦	37

Figure 13: Comparison between peak AHU air entering temperature using heat recovery unit and Indirect evaporative cooling.

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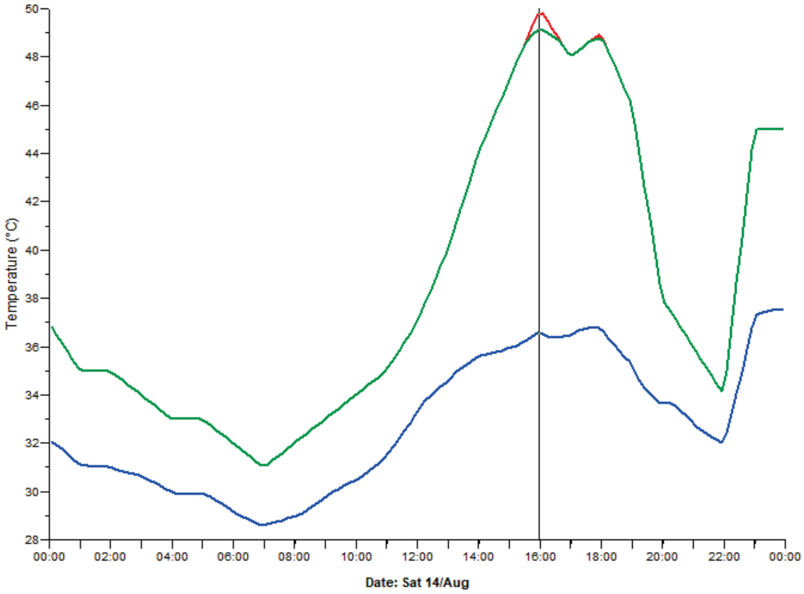
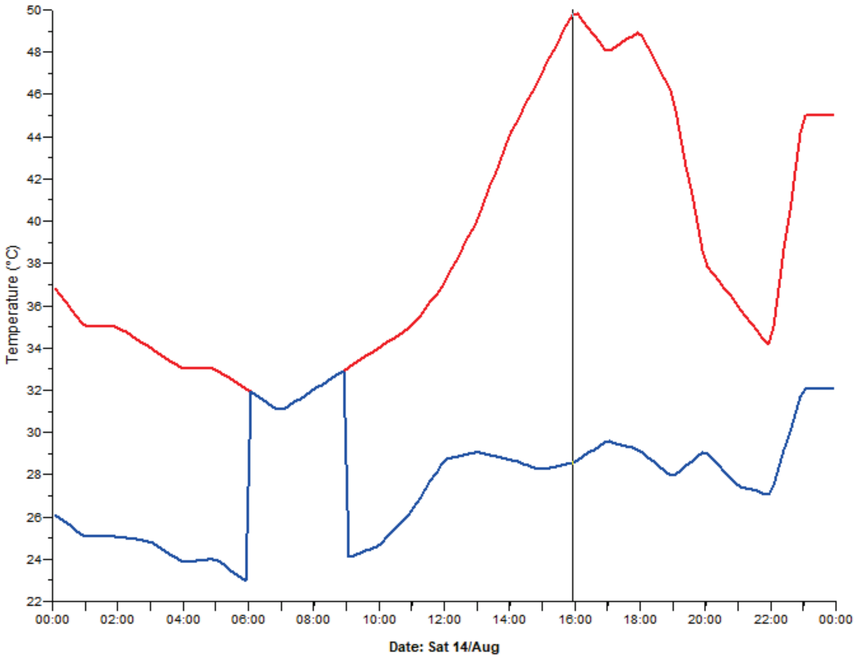


Variable Name	Line Colour	Value
Base line air entering temperature (°C)	🟥	50
Heat recovery unit air entering temperature (°C)	🟩	49
Indirect evaporative cooling air temperature (°C)	🟦	37

Figure 14: Mechanically ventilated space- Comparison between peak air entering temperature using heat recovery unit and Indirect evaporative cooling.

The main and auxiliary engine rooms' supply and exhaust air ducts are very large and are typically part of the ship's structure, known as downtakes and uptakes, respectively. It would be impractical to fit heat recovery units in these ducts. However, by using direct evaporative cooling through the installation of water mist nozzles in the intakes, it is possible to significantly reduce the air inlet temperature, providing the required cooling in hot climates and eliminating the need for cooling through chilled water Fan Coil Units (FCUs).

One drawback of direct evaporative cooling is the increase in supply air humidity. However, due to the nature of the space and the high IP rating of an engine room, this should not be an issue in this case.



Variable Name	Line Colour	Value
Ambient air temperature and relative humidity	🟥	50°C-13%RH
Air entering the engine room temperature and relative humidity	🟦	29°C – 74%RH

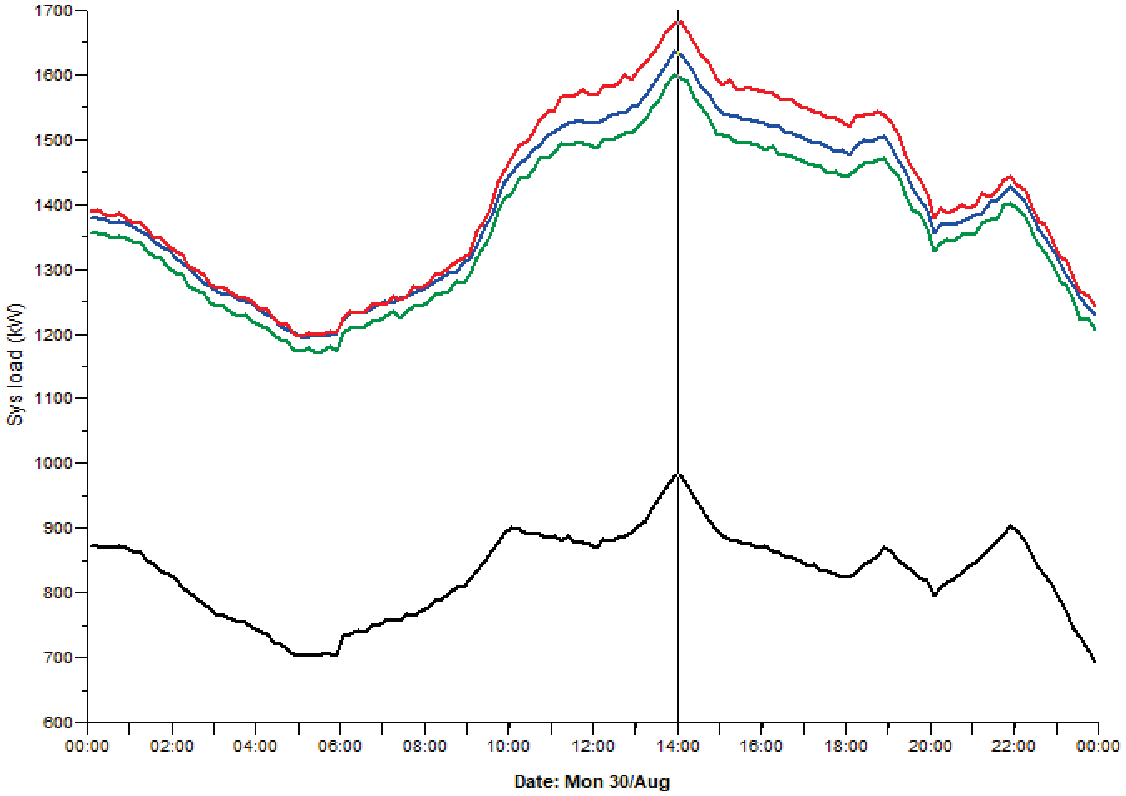
Figure 15: Mechanically ventilated space peak air entering temperature using heat recovery unit and Indirect evaporative cooling.

Table 3: Reduction of Chilled Water Plant (CWP) energy consumption when combining indirect evaporative cooling, engine room direct evaporative cooling and economisers

Month	Baseline CWP Energy (MWh)	Combined Direct and Indirect Evaporative Cooling with Economisers - CWP Energy (MWh)	Reduction in CWP Energy (MWh)	Reduction in CWP Energy (%)
Jan	15.0	7.8	7.2	48%
Feb	41.9	19.3	22.6	54%
Mar	51.8	21.9	29.9	58%
Apr	149.1	59.8	89.3	60%
May	192.1	95.9	96.1	50%
Jun	215.2	121.3	94.0	44%
Jul	196.7	116.0	80.7	41%
Aug	225.0	135.9	89.1	40%
Sep	172.6	101.2	71.4	41%
Oct	147.2	78.8	68.4	46%
Nov	113.8	48.9	64.8	57%
Dec	118.2	30.6	87.7	74%
Total	1638.5	837.2	801.3	49%

By combining indirect evaporative cooling, engine room direct evaporative cooling, and economisers, significant energy savings can be achieved at peak and moderate ambient conditions. The HVAC model simulation results presented in Table 3 show that the annual total reduction in energy consumption of the CWPs is 801.3 MWh. Assuming a diesel generator with a fuel consumption of 208 g/kWh, the total annual fuel consumption saving would be 166.7 tonnes for a typical navy frigate. This would lead to an increase in the frigate's range or a reduction in diesel tank capacity and weight.

Additionally, due to the significant reduction in the chilled water system peak load, the size of the chilled water plant required would be reduced. HVAC model simulation results for the chilled water system peak load presented in Figure 16 show a comparison between several options. The results from the simulations indicate that the chilled water peak load has reduced from 1681.4 kW to 980.1 kW, a 42% reduction.



Chill Water Peak Load (kW)	Line Colour	Chill Water Peak Load (kW)
Baseline	🟥	1681.4
Heat recovery units	🟦	1632.9
Indirect evaporative cooling	🟩	1597.1
Indirect evaporative cooling and engine room direct evaporative cooling	⬛	980.1 (42% reduction)

Figure 16: Chilled water system peak load comparison.

7. Absorption Chillers and Engine Waste Heat Recovery

Absorption chillers are refrigeration systems that use heat and a concentrated salt solution (lithium bromide) to produce chilled water. These chillers utilise waste heat from other processes to produce chilled water, which is then distributed for cooling needs. The system employs lithium bromide as the absorbent and water as the refrigerant, eliminating ozone-depleting refrigerants and using very little electricity compared to conventional chillers.

Absorption chillers consist of an evaporator, absorber, condenser, generator, solution heat exchanger, absorber heat exchanger, refrigerant/solution pumps, and controls. Water is used as the refrigerant in vessels maintained under low absolute pressure (vacuum). The chiller operates on the principle that under vacuum, water boils at a low temperature. In this case, water boils at approximately 5.5°C, thereby cooling the chilled water circulating through the evaporator tubes. A refrigerant pump circulates the refrigerant water over the evaporator tubes to improve heat transfer.

To make the cooling process continuous, the refrigerant vapour must be removed as it is produced. For this, lithium bromide solution (which has a high affinity for water) is used to absorb the refrigerant vapour. As this process continues, the lithium bromide becomes diluted, reducing its absorption capacity. A solution pump then transfers this weak (diluted) solution to the generator, where it is concentrated by hot water. The refrigerant vapour released in the shell side of the generator enters the condenser to be cooled and returned to a liquid state. The refrigerant water then returns to the evaporator to begin a new cycle.

To remove heat from the machine, cooling seawater is first circulated through the tubes of the absorber to remove the heat of vaporisation. The seawater is then circulated through the tubes of the condenser. The strong solution from the generator flows back to the absorber to begin a new cycle. For efficiency reasons, the strong solution from the generator is passed through the heat exchanger to preheat the weak solution while pre-cooling the strong solution (Berg Group, 2023).

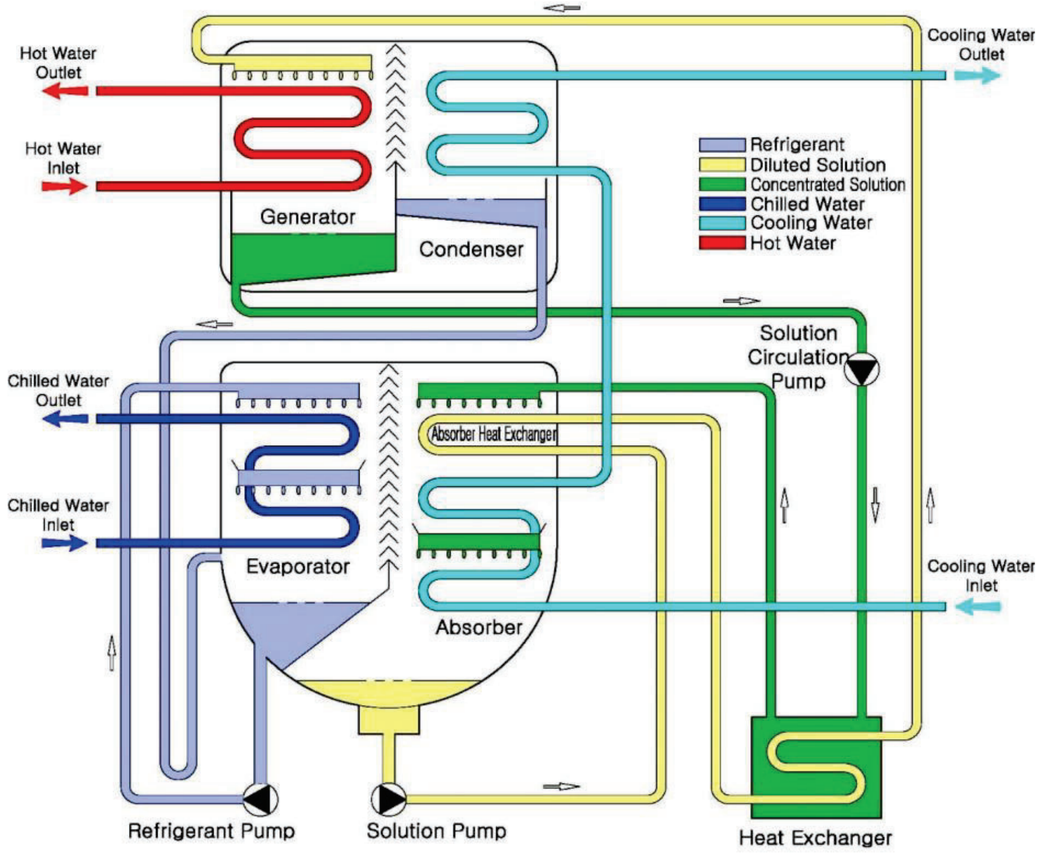


Figure 17: Absorption chiller refrigeration process (Berg Group, 2023)

Conventional chilled water plants rely on refrigerant compressors, which significantly increase the ship's electrical load. In this study, the baseline frigate is equipped with two chilled water plants, collectively consuming 528.3 kW of electricity. By replacing these with two equivalent absorption chillers, each with a cooling capacity of 1000 kW, the total electrical load would drop to 6.6 kW, achieving a 99% reduction. This change would decrease the overall electrical load by 521.7 kW, allowing for a smaller diesel generator due to the reduced peak electrical hotel load.

Annually, the absorption chillers would consume 58 MWh of power, compared to the 1638 MWh consumed by the conventional chillers (as shown in Table 3). This results in an electrical energy saving of 1580 MWh per year, which equates to a reduction of 328.6 tonnes of diesel fuel annually.

Absorption chillers do not use F-gases as refrigerants, making them more environmentally friendly than conventional chillers. They are not subject to F-gas quota restrictions and phase-out regulations. Additionally, absorption chillers have fewer moving parts, making them more reliable and reducing noise and vibration.

7.1. Utilising Engine Waste Heat

Only a portion of the fuel energy consumed by a marine engine goes to propulsion or electrical power, with a large amount lost as heat in the engine exhaust. It is sensible to reclaim as much of this energy as possible. The diesel generator (DG) exhaust waste heat can be recovered to power the absorption chillers and hot water system using engine exhaust waste heat recovery systems currently available in the market. One example is the Alfa Laval Aalborg Micro Waste Heat Recovery Boiler for marine auxiliary engines (Alfa Laval, 2024). It is installed after the vessel's DG. When the exhaust gas passes over its heating surface, the waste heat energy in the gas is absorbed to produce hot water or steam.

The heat recovery unit is used in conjunction with oil-fired boiler(s) or steam drum(s), which serve as the steam/water space. Forced circulation supplies the heat recovery unit with water at saturation temperature from the oil-fired boiler(s) or steam drum.

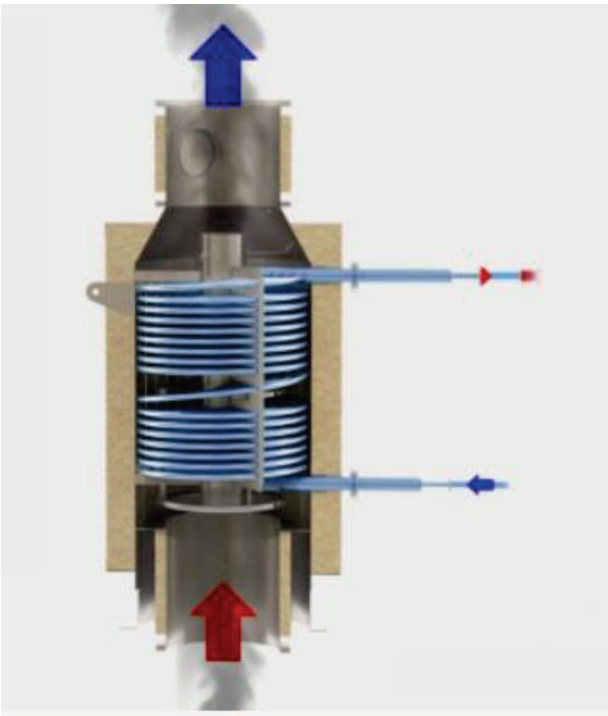


Figure 18: Engine exhaust waste heat recovery unit (Alfa Laval, 2024).

Figure 19 illustrates how exhaust heat recovery units can be integrated into a naval frigate's hot water system to supply hot water to absorption CWPs. Each auxiliary engine exhaust is connected to the heat recovery unit, so if any one of the four engines is running, heat will be recovered to the system. On a naval frigate, there are typically two auxiliary engines running and two on standby. This arrangement also provides redundancy for the hot water heater. If the ship is docked and using shore power, where no auxiliary engine is running, hot water for the absorption CWPs can be provided by the HW heater.

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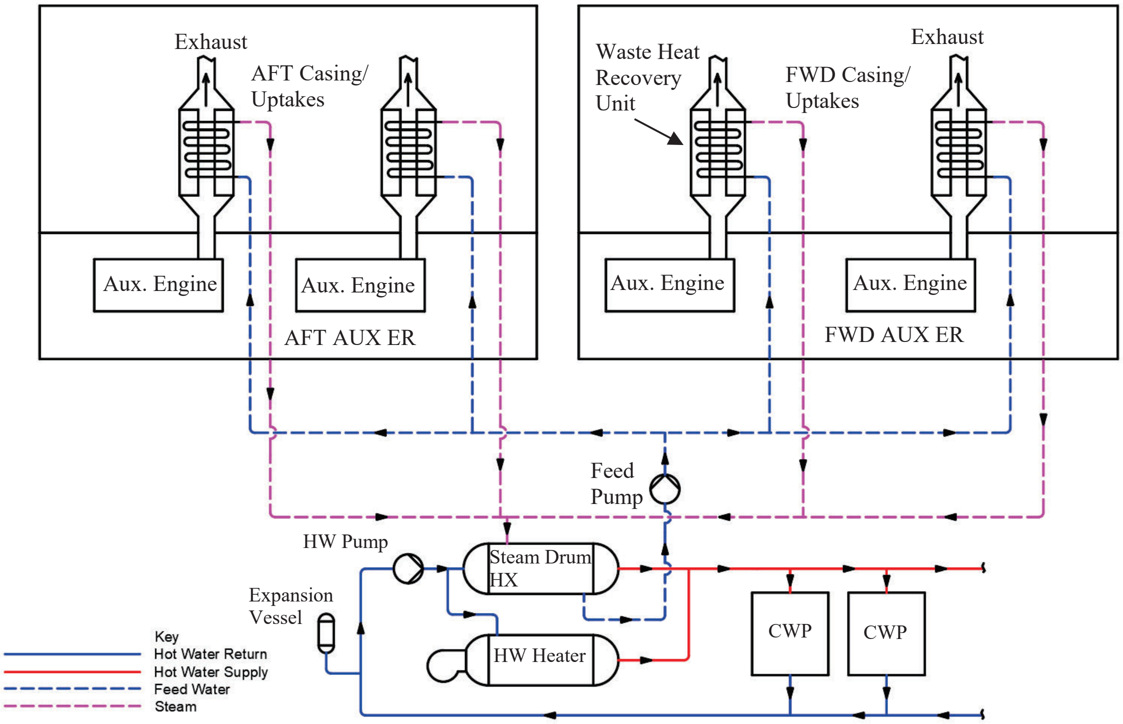

Figure 19: Integration of exhaust heat recovery units into a naval frigate's hot water system.

8. Conclusion

This study has explored various strategies to enhance the efficiency of HVAC systems on naval ships, with a focus on reducing energy consumption and CO2 emissions. By incorporating advanced technologies such as economisers, air-to-air heat recovery units, indirect evaporative cooling, and absorption chillers, significant improvements in system performance can be achieved.

Environmental model simulations demonstrated that the integration of these technologies leads to substantial reductions in peak loads and overall energy consumption. For instance, the use of economisers showed notable energy savings, particularly in moderate climates. Indirect evaporative cooling further enhanced energy efficiency by significantly lowering the inlet air temperature to AHUs and mechanically ventilated spaces. Additionally, by employing direct evaporative cooling in engine rooms, it is possible to significantly reduce the air inlet temperature, providing the required cooling in hot climates and eliminating the need for chilled water cooling.

The adoption of absorption chillers, powered by engine waste heat, presented a compelling case for reducing the electrical load on the ship. This approach not only decreases the reliance on conventional chillers but also leverages waste heat, contributing to a more sustainable and environmentally friendly solution. Additionally, absorption chillers do not use F-gases as refrigerants, making them more environmentally friendly than conventional chillers. They are not subject to F-gas quota restrictions and phase-out regulations. Furthermore, absorption chillers have fewer moving parts, making them more reliable and reducing noise and vibration.

Overall, the findings indicate that a combination of these advanced HVAC technologies can lead to a more efficient, reliable, and environmentally sustainable system for naval ships. Future work should focus on the practical implementation of these technologies and the evaluation of their long-term performance and cost-effectiveness in real-world naval operations.

9. References

Alfa Laval, 2024, Aalborg Micro. Available at: https://www.alfalaval.ca/products/heat-transfer/boilers/exhaust-gas-economizer/aalborg-micro/ (Accessed: 01/05/2024).

ASHRAE, 2020, ASHRAE Handbook—HVAC Systems and Equipment (SI). Atlanta: ASHRAE.

Berg Group, 2023, World Energy: HWAR-LHH (Marine) Hot Water Driven Absorption Chiller. Available at: https://berg-group.com/brochure/downloads/world-energy-hwar-lhh-marine-hot-water-driven-absorption-chiller/ (Accessed: 01/05/2024).

EDR, 2009, Energy Design Resources VAV System Design Guide, Advanced Variable Air Volume.

IES , 2023, Virtual Environment Version 2023.2.0.0. Environmental Solutions Ltd.

MOD, 2005, DEF STAN 02-102 Pt1 Issue 3, Requirements for Air-Conditioning and Ventilation.

10. Glossary of terms

AC :	*Air Conditioning*
AFU:	*Air Filtration Unit*
AHU :	*Air Handling Unit*
CBRN:	*Chemical, Biological, Radiological, and Nuclear*
CW :	*Chilled Water*
CWP :	*Chilled Water Plant*
DG :	*Diesel Generator*
DB :	*Dry Bulb*
DXF :	*Drawing Exchange Format*
FCU:	*Fan Coil Unit*
HVAC:	*Heating Ventilation and Air Conditioning*
HW:	*Hot Water*
IAQ :	*Indoor Air Quality*
WB :	*Wet Bulb*

Experimental and modelling studies on HVO-methanol mixtures separation for superyachts applications

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Synopsis

A growing concern is associated to the greenhouse gases emissions of superyachts, consequently alternative fuels are introduced to the market. For the yachting decarbonisation, this work focuses on hydrotreated vegetable oil (HVO) and methanol. Nevertheless, the uncertain global availability of these fuels can undermine the operations of ocean-crossing superyachts. Thus, a multi-fuel system is installed allowing for fuels switchover and built-in flexibility. Moreover, non-dedicated tanks are installed for the alternative storage of HVO and methanol to make optimal use of the tanks' capacity. However, the alternative storage of HVO and methanol causes mutual fuels' contamination. The lack of standards and research on accepted fuels impurity makes full fuels' separation relevant to be explored. In this work, to avoid degradation of dual-fuel engines or fuel cells, gravity-settling tanks and disc-bowl centrifuges were studied to separate HVO-methanol mixtures. Shake tests were conducted on HVO-methanol mixtures to quantify the separation time and relative concentrations to obtain complete gravity separation. The gravity tests revealed methanol traces in HVO for all the tested mixtures within the 1 hour-3 days observation time, due to the low-density difference between the fuels. This makes the use of gravity-settling tanks impractical onboard for quasi-instantaneous fuels supply to the converters. A mathematical model was developed for disc-bowl centrifuges to assess the separator performance and separation time. Furthermore, the centrifuge was sized by providing the separator working conditions for varying engine modes. Moreover, spin tests were conducted to validate the mathematical model. The model showed that full separation is achievable with a larger centrifuge compared to existing designs. The larger design is due to the low-density difference between the fuels. The maximum separation time ranges from 5-10 minutes. Nevertheless, all the tested mixtures with the spin tests failed at achieving a state of full separation due to the dilution of a certain residual volume in the continuous liquid. The discrepancy between the mathematical model and the spin test results can lie in the neglected diluted phase of the dispersed fuel in the continuous liquid in the mathematical model. However, the mathematical model is a good tool to simulate the dynamic behaviour of the dispersed droplets. Consequently, the onboard use of a centrifuge for separating HVO-methanol mixtures should be evaluated by quantifying the concentration of the fuels' mixture entering the separator tailored per yacht. Furthermore, tests on dual-fuel engines or fuel cells are recommended to establish tolerable limits of fuel's contamination.

Keywords: Centrifuge, HVO, Liquid-liquid separation, Methanol, Superyachts

1 Introduction

Ships emit approximately 1076 million tonnes of CO_2, representing 3% of the global greenhouse gas (GHG) emissions (European Commission, n.a.), while superyachts emit yearly about 5 Mt of CO_2 equivalent (Kries, 2021). The International Maritime Organisation (IMO) aims to reduce ship-released CO_2 by 40% by 2030 compared to 2008 and achieve zero GHG emissions by 2050 (IMO, 2023). The IMO identified alternative fuels as a prevention for harmful emissions release (IMO, 2022). To cut yachts' emissions, *Feadship* largely researched hydrogen (Siepmann, 2019; Lambregts, 2021), hydrotreated vegetable oil (HVO) (van der Vliet, 2021), methanol (Kries, 2021) and hybrid propulsion (Visser, 2021). Despite the positive features of these alternative fuels, their large-scale availability is uncertain in the near term.

To overcome this challenge, a multi-fuel system enables refuelling alternative fuels where possible today, with diesel representing a viable option while alternative fuels become increasingly available. HVO and methanol were prioritised among alternative fuels for the relatively high readiness level of associated energy converters, market uptake and reduced emissions.

In a multi-fuel system, HVO and methanol can be alternatively stored in all tanks to make optimal use of the tanks' capacity. Additionally, dual-fuel (DF) engines and proton exchange membrane (PEM) fuel cells are

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Authors' Biographies

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selected. Nevertheless, when storing multiple fuels in the same tank alternatively, fuels' contamination occurs. In DF engines contamination can yield wear and corrosion (Washecheck, P. H., Liu, A. T. C., Kennedy, E. F., 1983; Estefan and Brown, 1990; Cheung et al., 2009; Hazar and Temizer, 2012; Nautiyal et al., 1989), while fuel cells can be permanently damaged (Sterchi, 2001). However, research lacks specific mixture studies and marine quality standards. Hence, limits of HVO-methanol mutual contamination remains undefined for their usage in DF engines and fuel cells, making full HVO-methanol separation relevant to be explored.

The separation systems' selection depends on the mixture formed in storage tanks. Gravity-settling tanks or centrifuges can be used given the properties of HVO/methanol (Green and Perry, 2008) and their usage in existing vessels (McGeorge, 1998; Taylor, 1996). Specifically, disk-bowl types are chosen among centrifuges. Nevertheless, uncertainties remain on the separation efficacy and the required separation time.

Concerning gravity, generally, a 0.1-difference in specific gravity in a binary mixture sufficiently ensures phase separation (Kerr, 2007). Conversely, HVO and methanol have a maximum specific gravity difference of 0.03 (Ellis and Tanneberger, 2015; Neste, 2020). Moreover, the phase separation time of HVO-methanol mixtures is unclear (Kato et al., 1991). This might generate concerns for required high processing flows onboard. Consequently, if low settling rates are anticipated, centrifuges are identified as an alternative technique (Sorsamäki and Nappa, 2015; Green and Perry, 2008; B. Vermeire, 2021).

Effectiveness of disc-stack centrifuges is challenged by fuel density. Methanol and HVO densities differ by up to 30.5 $\mathrm{kg/m^3}$ and possibly overlap (Ellis and Tanneberger, 2015; Neste, 2020). Literature is inconsistent on the minimum density difference allowing complete separation (Flottweg SE, n.a.; ECHA, n.a.; Towler and Sinnott, 2013; Green and Perry, 2008), leaving uncertainties on methanol-HVO separation effectiveness. This is enforced by lack of tests on these fuels and influence of tailored separator design parameters on performance (Dolphin Centrifuge, 2020). Thus, the separator sizing and its performance assessment are fundamental for separating HVO-methanol mixtures.

Literature shows lack of research on HVO-methanol mixtures separation, inconsistency between parameters to predict full separation and undefined separation time. This study investigates the efficacy of gravity-settling tanks and centrifuges as separation systems, alongside the time required for full separation. For gravity-settling tanks, phase separation tests are conducted. Regarding centrifuges, a centrifugal model is computed and spin tests performed for validation.

2 Methodology

This section presents methodologies for gravity-separation and centrifugation to determine HVO-methanol separation effectiveness.

2.1 Gravity separation

For gravity-settling tanks, experiments are performed on HVO-methanol mixtures to determine the time required by the fuels to fully separate by gravity.

Tests were performed on HVO and methanol with specifications as per Table 1. A camera placed in front of the beakers recorded the volume variation relative to a millilitres-scaled beaker. The camera helped detecting a transition from cloudy to clear appearance, indicating a shift from a single-homogeneous to binary phase. A light microscope was used to identify methanol droplets in HVO and measure their diameter, impacting dispersed liquid coalescence (Frising et al., 2008; Kamp et al., 2016) and exhibiting an inverse relationship with the settling time (De Haan et al., 2020; Ishii and Zuber, 1979; Richardson and Zaki, 1954).

The procedure followed is:

- The fuels were poured into a beaker at different concentrations relative to a fixed mixture's total volume. The mixture's total volume equals 100 ml and the tests were conducted on methanol at 1, 5, 10-70% v/v and 20°C.
- Fuels were mixed with a magnetic stirrer. The rotational speed of the magnetic stirrer was set at 1200 rpm and the stirring time at 1 minute, based on (Green and Perry, 2008).
- Liquid samples were removed from the beaker. To monitor the mixture's behaviour over time, samples were extracted after 5, 30 and 60 minutes. Extraction was conducted with a Pasteur pipette from half the height of the light phase for results' consistency.
- The samples were transferred to slide chambers to be observed at the microscope.

2.2 Centrifugal separation

Disc-bowl centrifuges are mathematically modelled as an alternative technology to gravity-settling tanks. Spin tests are conducted to validate this model.

Table 1: Main specifications of used HVO and methanol for phase-separation tests
(* at 15°C, ** at 20°C)

Parameter	**Unit**	**HVO**	**Methanol**
Colour (appearance)	[-]	Colourless (Clear and bright)	Colourless (pale)
Relative density	[-]	0.7811^{*}	0.7927^{**}
Purity on dry basis	[% m/m]	-	99.97
Water	[% m/m]	0.04	0.005
Sulfur	[mg/kg]	< 3	4
FAME	[% v/v]	< 0.05	-
Total aromatic hydrocarbons	[% m/m]	< 0.2	-
Kinematic viscosity	[$\mathrm{m^2/s}$]	$3.127 \cdot 10^{-6}$	-
Dynamic viscosity	[$\mathrm{Ns/m^2}$]	-	$0.54 \cdot 10^{-3}$

2.2.1 Mathematical model

The mathematical model of the disc-stack centrifuge outputs the time required by the separator to start its operations and the separator performance. The time refers to the starting time for a continuously operating centrifuge. The separator performance assessment aims at full separation. Furthermore, the centrifuge outlet flows are inputs for this problem, influencing the fuels flow exiting the separator. Their values are constrained to match the fuel flows required by the engines onboard.

The model is computed using two methods: one observes the trajectory of heavy-fuel droplets, while the other focuses on the interface position variation within the disc-bowl formed by the two liquids.

Regarding the droplets' trajectory, the motion of individual heavy-fuel droplets within a two-consecutive discs' section is considered (see figure 1). This was found as the sole way to obtain the desired outputs (Plat, 1994; Di Pretoro and Manenti, 2020; Greenspan, 1983). Precisely, motion equations of the denser droplets are computed as time equations found within the literature are in disagreement (Plat, 1994) or studies on centrifuge are not entirely representative of this case (Plat, 1994; Schaflinger and Stibi, 1987; Schaflinger et al., 1986; Ungarish, 1989; Perazzolo Disconzi and Torres Borghi, 2020). From the motion equations it is possible to calculate the separation time and plot the denser droplets trajectory to assess the centrifuge performance.

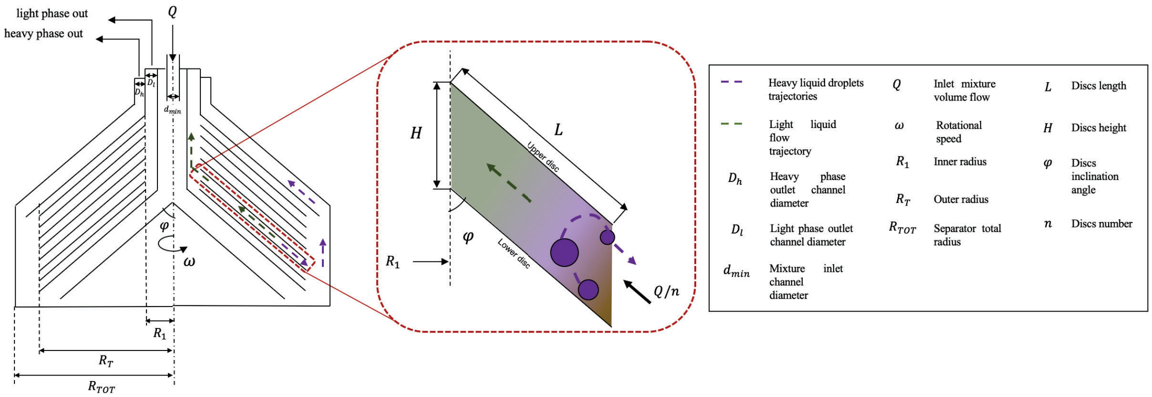

Figure 1: Disc-stack centrifuge (left) and view of two-consecutive-disc section (right), adapted from (B. Vermeire, 2021; Plat, 1994; Di Pretoro and Manenti, 2020).

The motion equations are built by computing the drag, buoyancy and centrifugal forces exerted on the denser droplets (Greenspan, 1983). Other forces are present but they are negligible compared to the centrifugal force (Plat, 1994). The model is built around the following assumptions:

- Binary mixture: HVO and methanol are the only mixture's constituents.

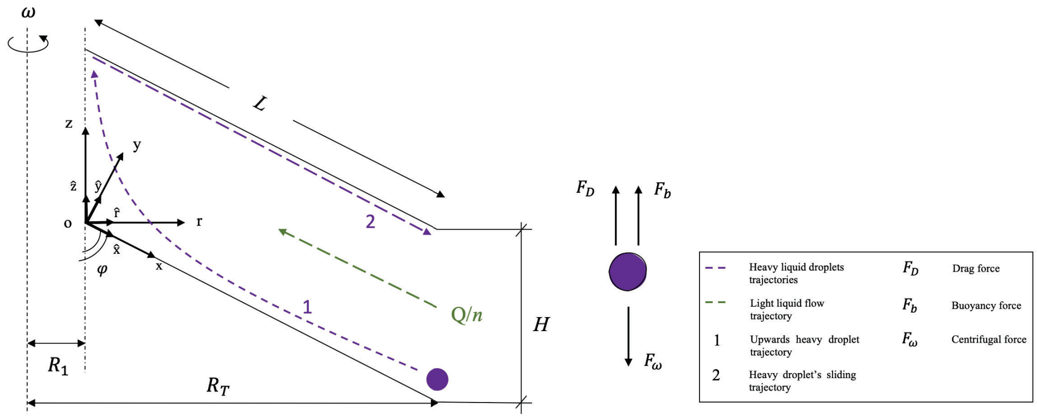

Figure 2: Fuels' trajectories within two-consecutive-disc section and forces on the heavy-fuel droplet.

- Ideal separation: the outlet flow equals the inlet throughput.
- The denser droplet maintains a perfect spherical shape and constant size from inlet to outlet conditions. This assumption follows the hypothesis of negligible shear stress.
- The flow through the discs' section is uniform. This stems from neglecting droplets break-up as the motion is representative of a single droplet.
- When the droplets hit the upper disc they slide along it without friction.

The motion equations are derived by constraining the two-dimensional spacial domain to a two-consecutive-disc section and for the reference frame of figure 2. The dispersed droplets enter the discs' section travelling a certain distance before hitting the upper disc. Here, they coalesce towards the outer wall getting discharged (Di Pretoro and Manenti, 2020; Plat, 1994). Derivation of the equations is given in appendix A.1. The obtained motion equations are:

$$\ddot{x} = \frac{\pi}{6}\frac{{D_p}^3 \Delta\rho}{m_d}(x\, sin\varphi + y\, cos\varphi)\omega^2 sin\varphi - \frac{N}{m_d}(\dot{x} + V_F) \tag{1}$$

$$\ddot{y} = \frac{\pi}{6}\frac{{D_p}^3 \Delta\rho}{m_d}(x\, sin\varphi + y\, cos\varphi)\omega^2 cos\varphi - \frac{N}{m_d}\dot{y} \tag{2}$$

Explanation of terms as in appendix A and figure 1. N is a function of Reynolds number:

$$N = \begin{cases} -3\pi\mu_l D_p & Re < 1 \\ \left(\frac{3\pi\mu_l D_p}{\dot{x}+V_F} + \frac{9}{16}\pi\rho_l {D_p}^2\right)\cdot & 1 \leq Re < 5 \\ \cdot\left(\sqrt{(\dot{x}+V_F)^2 + \dot{y}^2}\right) & \\ \frac{\pi}{8}\rho_l {D_p}^2 \cdot 1.85\cdot & 5 \leq Re < 5000 \\ \cdot\left(\frac{\rho_l D_p}{\mu_l}(\dot{x}+V_F)\right)^{-0.6} & \end{cases} \tag{3}$$

Regarding the interface, its correct allocation inside the disc-bowl, is a supplementary method to assess the centrifuge performance alongside the denser droplets' motion. This because equations 1 and 2 depend on the droplet's diameter, whose exact value is hard to determine in a liquid mixture. The interface is a section formed by the two liquids. Its correct allocation ensures no mutual liquids' contamination (B. Vermeire, 2021). There are contrasting viewpoints for siting this demarcation (Ambler, 1952; B. Vermeire, 2021; van der Linden, 1987). Overall, the interface shall be as close as possible to the disc periphery ($x = L$, see Figure 2) (GEA Westfalia, n.a.b), with equation stemming from the pressure difference at this boundary (Di Pretoro and Manenti, 2020):

$$R_{int} = \sqrt{R_T^2 + \frac{\rho_l}{\rho_h}\left(\frac{Q_l^2}{S_l^2\omega^2}\right) - \frac{Q_h^2}{S_h^2\omega^2}} \tag{4}$$

Q_l and Q_h are the discharged flows of the light and heavy liquid respectively, which, for an ideal separation stem from the relative concentrations in the fed mixture X_l and X_h:

$$Q_l = X_l \cdot Q \tag{5}$$

$$Q_h = X_h \cdot Q \tag{6}$$

Assumed methanol volume in the mixture is 10%, based on (GEA Westfalia Separator Group GmbH, n.a.). Moreover, in equation 4, S_l and S_h are the outlet sections of the light and heavy phase respectively (Di Pretoro and Manenti, 2020).

2.2.2 *Centrifugal model input*

Equations 1, 2 and 4 to assess the centrifuge performance depend on the centrifuge inlet flow. This is derived by the HVO/methanol flows required in single- and dual-fuel engine modes, computed from the shaft power (Woud and Stapersma, 2003). The inlet centrifuge's flow is determined from equations 5 and 6. In single (SF)- and dual fuel (DF) modes it equals:

$$Q_{sep,SF} = \frac{Q_{HVO,eng,max}}{X_{HVO}} \tag{7}$$

$$Q_{sep,DF} = \frac{Q_{MeOH,eng,max}}{X_{MeOH}} \tag{8}$$

Where $Q_{MeOH,eng,max}$ and $Q_{HVO,eng,max}$ respectively are the maximum methanol and HVO volume flows demanded by the gensets. More details in (La Colla, 2023). Operations on multiple fuels yield different HVO-methanol mixtures in the storage tanks during bunkering. The studied cases comprise:

- Single-fuel (HVO) engine mode: bunkered HVO with residual methanol in the storage tanks at 5% v/v.
- Dual-fuel (HVO-methanol) engine mode: bunkered methanol with residual HVO in the storage tanks at 5% v/v.

Additional assumptions are:

- Dedicated service tanks as to SOLAS (IMO, 2018).
- Both methanol and HVO service tanks full at bunkering.
- The mixture fed to the separator consists of methanol-HVO at 10-90% v/v. This ratio is kept constant as based on (GEA Westfalia Separator Group GmbH, n.a.).

2.2.3 *Centrifuge performance assessment and sizing*

The study aims at finding a separator design guaranteeing complete fuels' separation in both SF and DF engine modes. Iteration through the motion equations 1 and 2 is followed. The minimum droplet diameter for denser droplets to separate, coalescing towards the heavy-phase outlet, is determined by varying the rotational speed. Additionally, a single-objective optimization finds the optimal combinations of the centrifuge design parameters satisfying:

$$0.7 \cdot L \leq min\ f \leq 0.3 \tag{9}$$

With:

$$f = \frac{\frac{R_{int}}{sin\varphi} - L}{\frac{R_T}{sin\varphi} - L} \tag{10}$$

And R_{int} calculated as in equation 4, while equation 9 defines an acceptable interface position range given a limited quantitative definition of its ideal location within the literature. Furthermore, referring to figure 1, the separator total diameter equals:

$$D_{TOT} = 2 \cdot \left(\frac{D_l}{2} + R_T \right) \tag{11}$$

2.2.4 *Spin tests*

Spin tests were conducted to validate the mathematical model. They are the first industrial step to predict a centrifuge performance (SEPARATECH, n.a.). Liquid-filled spin tubes are placed in a bench-top machine, applying centrifugal force to the mixtures at specified temperature and time.

Tests were conducted on HVO and methanol mixtures with respectively a density of 771 and 793 kg/m^3 at 20°C. The fuels were poured in glass tubes and mixed manually. Subsequently, the mixture was poured in spin tubes for centrifugation within 30-40 seconds. The mixture's total volume equals 10 ml and tests were performed on methanol at 2 and 98% v/v. The mixtures were centrifuged in the spin machine for 4, 8 and 16 minutes at 20°C and 2100 rpm.

3 Results

Results are presented for the phase separation experiments, the centrifuge mathematical model and the spin tests.

3.1 Gravity separation

The results of the gravity separation experiments are shown in figure 3. Overall, bigger droplets settled faster, confirming an inverse relationship between settling time and droplet's diameter (De Haan et al., 2020; Ishii and Zuber, 1979; Richardson and Zaki, 1954). The microscope showed methanol droplets in HVO for all mixtures and time intervals. A result confirmed by the cloudy appearance of all mixtures. Different behaviours were observed with varying methanol concentrations and a correlation was found between the separation time and the methanol droplets' diameter. In figure 3, results are shown for methanol at 5-70% v/v at the time intervals at which the liquid samples were extracted from the beaker. The average methanol droplets' diameter and associated standard error are indicated.

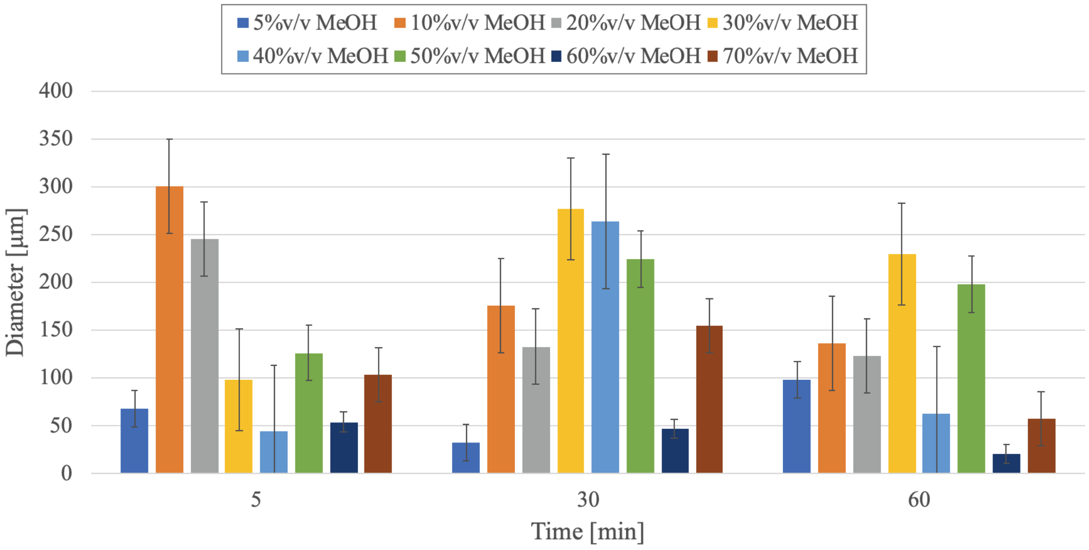

Figure 3: Average diameter of methanol droplets for different methanol concentrations.

For methanol at 5-20% v/v, figure 3 shows droplets size decreasing after 30 minutes compared to the 5-minute case. Larger droplets settled within 30 minutes, while smaller droplets persisted in the beaker column due to the relatively low methanol ratio, which inhibited coalescence by maintaining small inter-droplet distances. Droplets' conjunction occurred after 1 hour for methanol at 5% v/v. Nevertheless, this is not the case for 10-20% volumes. Precisely, after 1 hour methanol droplets remained smaller compared to the 30-minute observation. It is hypothesized that the droplets already merged between 30 and 60 minutes, leaving only the tiny droplets in the HVO column.

For methanol at 30-50% v/v droplets increased after 30 minutes and reduced after 60 minutes. Larger droplets settled faster leaving the smaller droplets behind, thus explaining the relatively small diameters after 5 minutes. Subsequently, these small droplets merged after 30 minutes, forming bigger ones. The size decrease became less pronounced with methanol at 50% v/v.

For methanol at 60-70% v/v. with methanol as the continuous phase, droplets displayed a different behaviour. For 60% v/v methanol, coalescence is faster because methanol droplets after 30 and 60 minutes are smaller than the first observation. This could be explained by the higher HVO dynamic viscosity compared to methanol. In fact, a lower viscosity of the continuous phase accelerates coalescence, hence droplets settling (Jeffreys and Davies, 1971). Thus, the methanol droplets already merged and coalesced in the 5-30 minute interval. This trend continues after 30 minutes, with the methanol droplets becoming even smaller. Conversely, for methanol at 70% v/v, droplets increase in size only after 30 minutes, indicating a longer merging time compared to the 60% v/v case.

Samples with methanol at 1 and 50% v/v were inspected after three days. The droplets became tinier than in all shown cases, especially for methanol at 50% v/v. Observed methanol in HVO after three days indicates that full separation does not happen within three days, due to the low-density difference between the fuels (see Table 1) and the dynamic viscosity of both substances (Green and Perry, 2008). Conversely, partial separation may result from the different fuels' polarity (Roberts et al., 1971; Neste, 2020; Lapuerta et al., 2015).

Lastly, a test was performed by doubling the mixture's total volume with methanol at 30% v/v, showing methanol droplets size decreasing, particularly after 1 hour. This result can extend the time required for full separation onboard yachts, as the gravity-settling tanks' capacity is significantly larger than the tested mixture's total volume.

Consequently, all the tested mixtures failed to achieve full separation in the 1 hour-3 day time-frame, rendering the use of gravity-settling tanks onboard impractical for quasi-instantaneous clean fuel supply to converters.

3.2 Centrifugal separation

This section presents the results of the centrifuge mathematical model and spin tests.

3.2.1 Mathematical model

Results are presented for the centrifuge's dimensions and the droplets' motion.

- **Interface position**: to iteratively meet the condition in equation 9, a first set of input design values is given to the model based on (McGeorge, 1998; Plat, 1994; Di Pretoro and Manenti, 2020; van der Linden, 1987; GEA Westfalia, n.a.b; Alfa Laval, n.a.). The results are depicted in Figure 4 and shown for the single- and dual-fuel yacht's modes, i.e. respectively for the separator inlet flows $Q_{sep,SF}$ and $Q_{sep,DF}$.

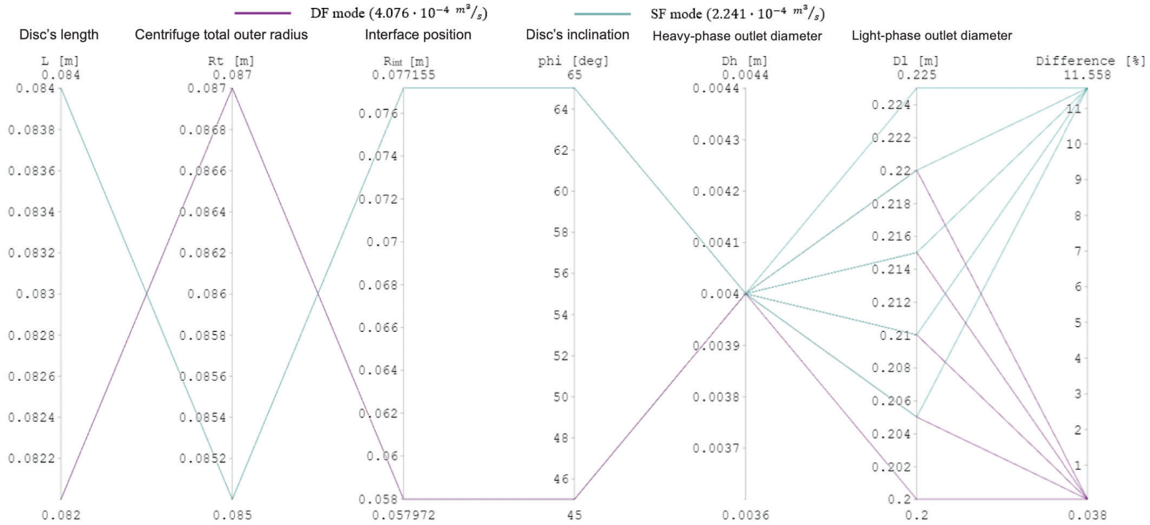

Figure 4: Five best combinations of centrifuge design parameters for optimal interface position. Results from last iteration process for dual- and single-fuel engine modes.

Across iterations, discs' length values neared the highest in the range, whilst the total centrifuge's radius (R_T) scored the lowest, due to the small values added to R_T as in equation 4. Given similar densities, $\rho_l/\rho_h \approx 1$, hence the R_{int} variation is dictated by volume flow, outlet sections diameter and rotational speed. Concerning the volume flow, the plot depicts minimal variation among input values. However, the percentage difference is lower in the dual-fuel mode case, particularly at higher volume flows. This may be due to pressure difference variation at the interface and higher mixture flow velocity entering the separator, dragging dispersed droplets towards the discs' section rather than the outer wall, as shown in equation 17. However, although the volume flow is varied to simulate the two engine modes, the assumed value is a constant within the separator design. Hence, ω, D_h and D_l are the parameters varying the added terms to R_T in equation 4. Nevertheless, the rotational speed is constant within the iterations. Hence, regarding the outlet sections' diameter, for heavy phase at fixed 10% v/v, $Q_l > Q_h$. Moreover, $D_l > D_h$ in existing separators, compensating for the difference between Q_l and Q_h. Consequently, given two fuels with close densities, the value of R_{int} strictly depends on the discs' length and the total outer radius.

- **Droplets' trajectory**: The results of the separator specification are used as inputs for the iteration on the motion equations 1, 2. Results are depicted in Figures 5 to 8 for single- and dual-fuel yacht's modes, i.e. at a centrifuge inlet flow of respectively $2.241 \cdot 10^{-4}$ and $4.076 \cdot 10^{-4}$ $\mathrm{m^3/s}$. The droplets' trajectories are plotted for droplet's diameter (D_p) of 5-100 μm as found in (Frising et al., 2008; Plat, 1994). The graphs portray the methanol (heavy-phase) droplets' trajectories within a separator discs' section.

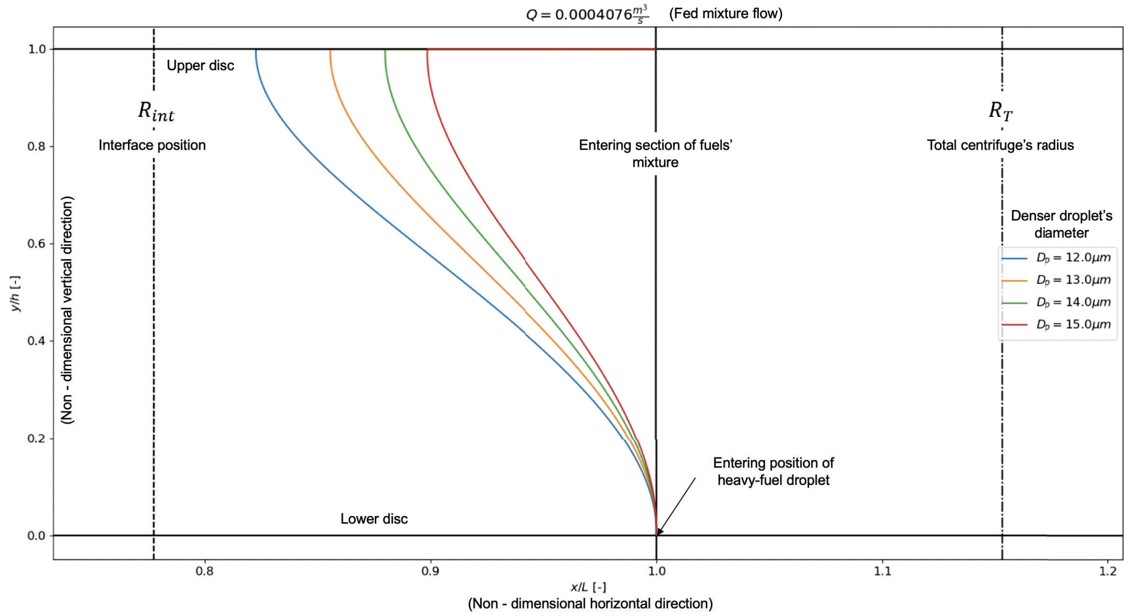

Figure 5: Trajectories of medium-sized methanol droplets within two-consecutive-disc section (dual-fuel engine mode).

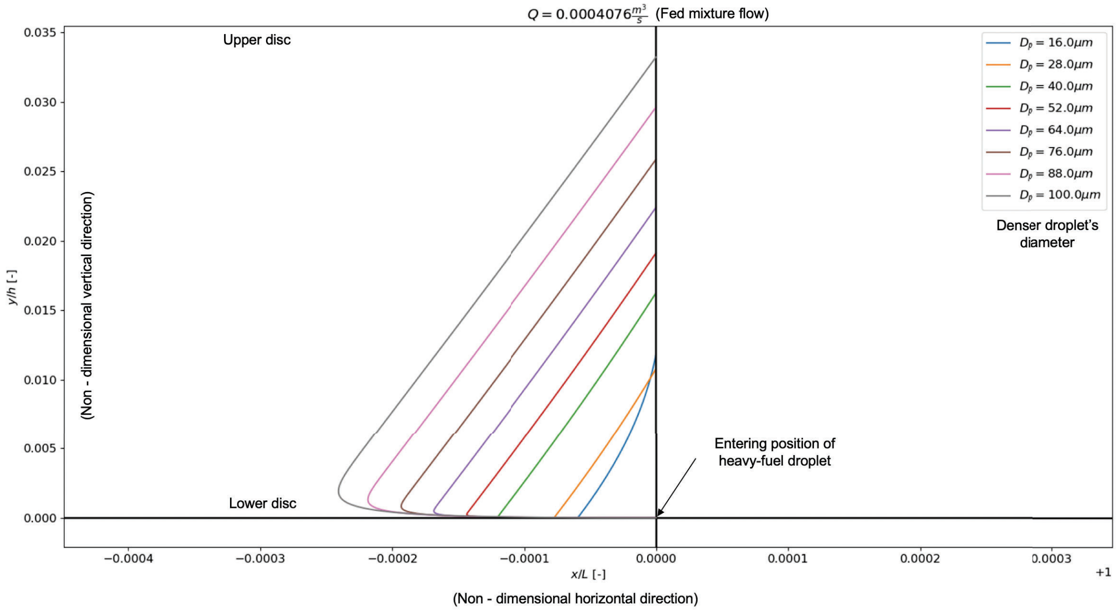

Figure 6: Trajectories of big-sized methanol droplets within two-consecutive-disc section (dual-fuel engine mode).

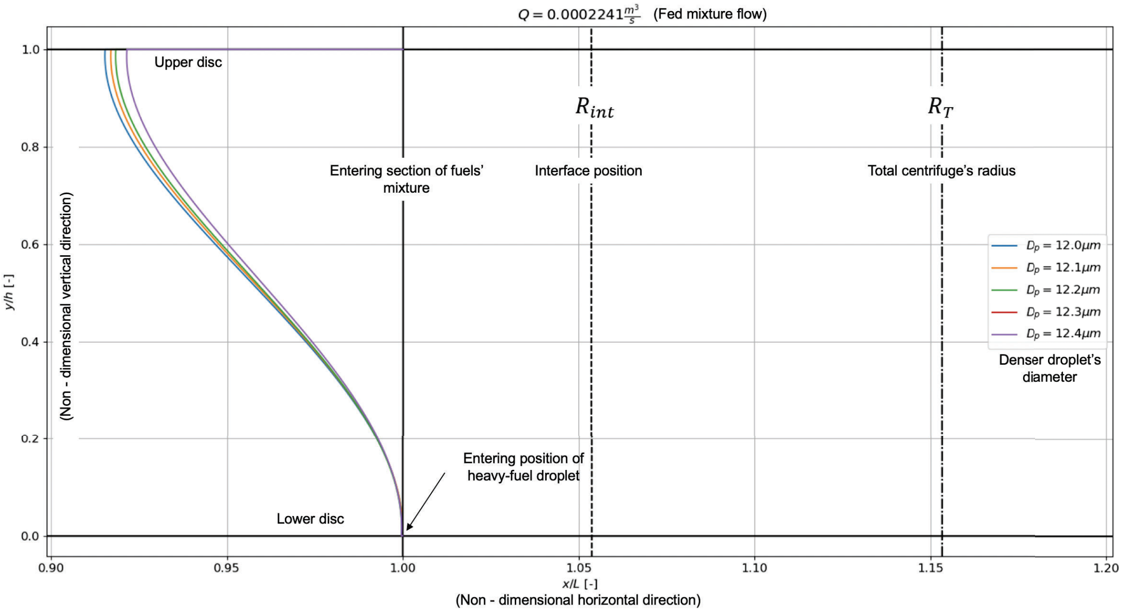

Figure 7: Trajectories of medium-sized methanol droplets within two-consecutive-disc section (single-fuel engine mode).

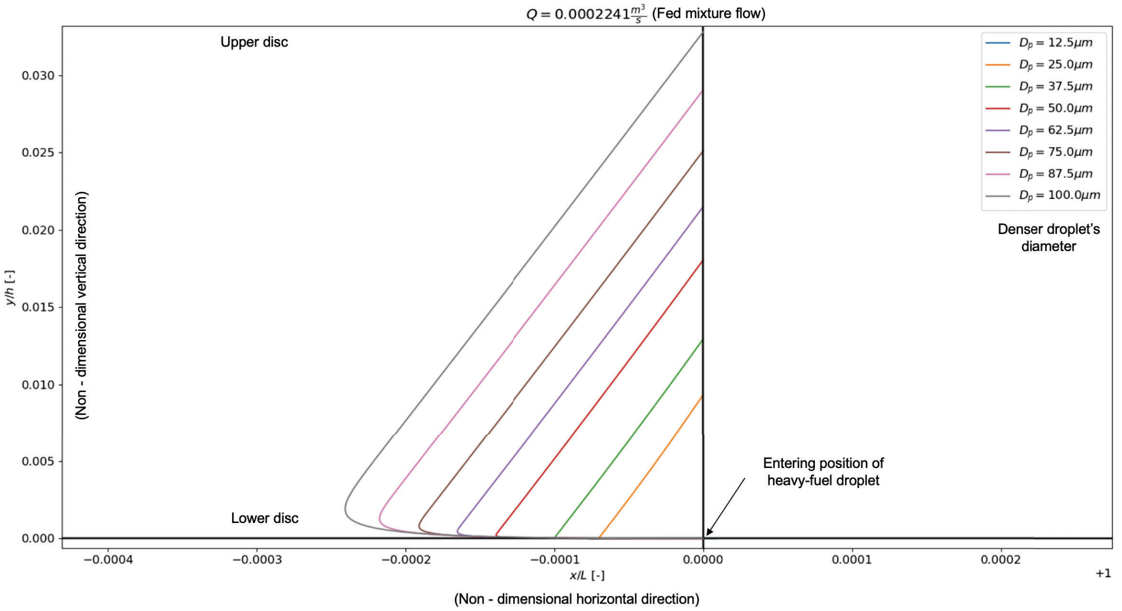

Figure 8: Trajectories of big-sized methanol droplets within two-consecutive-disc section (single-fuel engine mode).

In all plots droplets coalescence towards the heavy-phase outlet. Thus, with the found separator design, full separation is achieved. Droplets with diameters smaller than the presented values also get discharged in the methanol outlet. Their trajectories are not shown here for graph's readability and due to negligible differences found between the studied operational modes.

Figures 5 and 7 show the trajectories for droplets with diameter from 12-15 μm. For a higher flow, the travelled distance by the droplets is bigger compared to a lower flow, due to greater velocity of the single droplet. Furthermore, the travelled distance rises the smaller the droplet, yielding the assumption that smaller droplets show less resistance to the fed mixture's flow. Additionally, for a higher flow, the interface (R_{int})

falls inside the discs' section, whilst it allocates outside for a lower flow. Hence, for higher flows the denser droplets are dragged more towards the discs' section rather than the outer wall.

Regarding bigger droplets, figures 6 and 8 show no major differences between the two operational modes. All droplets leave the discs' section quasi-instantaneously, assuming centrifugal force dominating over drag. For higher flows the droplets travel a bigger distance compared to lower flows. However, this difference is slighter than the medium-sized droplets' case.

Lastly, the resulting separation time is discussed. For continuously-operating centrifuges, this is dictated by the denser droplets' coalescence time. Droplets sized 16-100 μm in diameter get discharged in few milliseconds. Droplets sized 12-15 μm coalesce within some minutes. Specifically, their velocity is dominated by the entering mixture's velocity, thus the droplets require some seconds to move upwards and hit the upper disc. Here, kinetic energy is lost (Di Pretoro and Manenti, 2020), thus the droplet needs to overcome the incoming mixture's resistance when flowing towards the methanol outlet section. The demanded time increases the lower the droplet's diameter. The 12 μm sized droplets need around 10 minutes to get discharged in dual-fuel mode. In single-fuel engine mode, when the separator-fed volume flow is lower, the discharged time is also lower, accounting for about 5 minutes.

The final centrifugal separators' specifications are listed in Table 2.

Table 2: Final specifications of the modelled centrifugal separator

Parameter	**Symbol**	**Unit**	**Value**
Fed mixture volume flow (DF mode)	$Q_{sep,DF}$	[m^3/s]	$4.076 \cdot 10^{-4}$
Fed mixture volume flow (SF mode)	$Q_{sep,SF}$	[m^3/s]	$2.241 \cdot 10^{-4}$
Discs' length	L	[m]	0.084
Methanol outlet section diameter	D_h	[m]	0.004
HVO outlet section diameter	D_l	[m]	0.205
Separator total diameter	D_{TOT}	[m]	0.379
Rotational speed	ω	[rad/s]	50

3.2.2 Spin tests

HVO-methanol mixtures separation at 98-2 and 2-98 % v/v was tested in a spin machine. It resulted that both mixtures failed at achieving full separation.

For the case of HVO-methanol at 98-2 % v/v, 0.5% v/v methanol coalesced to the bottom of the test tube after 4 minutes. Nevertheless, no further improvement resulted when increasing spin time to 8 and 16 minutes.

Regarding HVO-methanol mixture at 2-98% v/v, traces of HVO were observed at the top of the tube after 4 minutes. Similar result occurred after 8 and 16 minutes, accounting for approximately 0.2% v/v emulsion.

Full separation was not achieved under the tested conditions. A volume percentage, relative to the dispersed fuel, was present in the continuous liquid for all mixtures. This suggests a dilution of the residual fuel in the bunkered fuel, which cannot be separated using the applied methodology.

3.2.3 Results validation

The validity of the centrifugal separation mathematical model and spin tests are scrutinized in this subsection. Evaluation of the model's hypotheses is performed showing consistency with the results (see appendix B). Below the mathematical model results are compared with literature findings and a comparison is conducted between the model and the spin test results.

- **Validation of centrifuge's dimensions**: the centrifuge's results of Table 2 are scrutinized to ascertain the model's validity.

  A centrifuge by *Alfa Laval* (Alfa Laval, n.a.) works at 71.7 rad/s, faster than 50 rad/s obtained in this study due to the higher separator capacity. The *Alfa Laval* design works at a 35-64 times higher flow than the one in this case. Hence, a higher rotation efficiently allocates the liquids' interface. Furthermore, density difference of separated compounds in the manufacturer's separator is larger than the HVO-methanol case

(ECHA, n.a.). Similarly, due to the interface allocation, the manufacturer's design presents a heavy-phase outlet diameter larger than the result here obtained. Same discussion applies to the tested oil-water separator by (van der Linden, 1987) at a rotation of 91.7 rad/s. The design by (Plat, 1994) leads to similar conclusions, where the discs' length and the separator radius are respectively 16.7% and 47.2% smaller than the obtained values. This can still be due to the higher density difference between the tested oil and water by (Plat, 1994) compared to the HVO-methanol case. The resulting centrifuge diameter is 34.9% bigger than the maximum diameter of separators in yachts (GEA Westfalia, n.a.a). Likewise, the cause can be the lower density difference between HVO and methanol compared to the diesel-water case of marine separators. The centrifuge diameter is, in fact, influenced by the HVO outlet diameter, as evident from Table 2, aligning with the recommendations from (GEA Westfalia, n.a.b).

Moreover, the calculated starting time is 5-10 minutes depending on the separator inlet flow. The already mentioned centrifuges report 2-4 (GEA Westfalia, n.a.b) and 6-8 minutes (Alfa Laval, n.a.) starting time. Nevertheless, it is unclear if this time only comprises droplets' coalescence or it includes other processes, namely ramp-up.

- **Mathematical model - validation**: the results of the centrifuge's model and spin tests are discussed for comparison. The model showed achievable full separation with a larger separator compared to existing designs. Conversely, the tests evidenced incomplete separation. This deriving from the dilution of the residual fuel in the bunkered one. An effect possibly stemming from forces exerted on the fuels and the velocity of the dispersed droplets while mixing, which could have affected the droplets' size (Coulaloglou and Tavlarides, 1977; Howarth, 1964; Sovová, 1981). In fact, as subsection 3.1 reported, the droplets' size determines the dispersed liquid's coalescence. The dilution phenomenon was not integrated in the mathematical model, which limits to describe the individual denser droplet's motion by neglecting the droplets relative interference. This derives from neglected shear forces. These phenomena can occur in storage tanks, however they are hard to predict.

  Additionally, the spin tests were conducted with the dispersed phase at 2% v/v whilst a 10% v/v was assumed in the mathematical model. The dispersed liquid's concentration can affect the mixture's status (Privat et al., 2013).

  Furthermore, in a disc-stack centrifuge, the heavy-droplet's dynamics differ from spin tests. Droplets move between two consecutive discs, separating upon impact with the upper disc or if deviating towards the desired outlet. Among influencing parameters, the fed mixture flow affects droplet behavior and interface position variation. Conversely, in spin tubes, droplets move within a disc-free cylindrical space, independent of inlet flow. Additionally, no interface position is identifiable, thus not accounting for pressure balance.

  Consequently, the mathematical model and spin tests yield differing results due to the dilution effect of residual fuel and the spatial domain of dispersed droplets. The model accurately simulates the dynamics of individual dispersed droplets within the centrifuge's discs. Conversely, spin tests offer insights into potential dilution effects in storage tanks or during centrifugation.

4 Conclusions and further research

This work explored separation of HVO-methanol mixtures, given concerns about mutual contamination in dual-fuel engines and fuel cells, and lack of fuels standards and research.

For separation, gravity-settling tanks and disc-bowl centrifuges were researched. Phase separation tests on HVO-methanol mixtures revealed incomplete separation within 1 hour-3-day time-frame due to the low-density difference between the fuels, rendering gravity-settling tanks impractical for use onboard.

Regarding centrifuges, a mathematical model was computed to observe denser droplets' trajectory within the discs' interspace and the interface position's variations. A centrifuge design enabling full separation per engine mode was defined. Moreover, spin tests were conducted for model's validation.

The model suggests achieving full fuels separation with a disk-stacked centrifuge 34.9% larger in diameter than typical separators onboard yachts, due to the low-density difference between HVO and methanol. Furthermore, the maximum startup time ranges 5-10 minutes for droplets of 12-16 μm in diameter.

Droplets break-up and merge were identified as causes of the different results in spin tests where HVO-methanol mixtures partially separated, due to full liquids' dilution. This could be attributed to forces on dispersed droplets affecting coalescence. Additionally, the different results between the mathematical model and spin tests can lie in the different spacial domain of the dispersed droplets. The model remains valid for individual dispersed droplets' motion within centrifuge discs' sections. Conversely, spin tests provides insights into possible dilution, occurring in storage tanks, piping or during centrifugation.

For future work:

- Quantification of contaminants' limits of combusted fuels per technology type is suggested. Dual-fuel engines and fuel cells are recommended to be tested with HVO and methanol mutually contaminated.
- For efficient fuels treatment onboard, research into precise mixture concentration detection along the onboard converters' supply path is suggested. In gravity tests, in fact, quantifying the separated mixture over time proved unfeasible. Moreover, investigation on separation time reduction is recommended by altering stirring time and rotation in gravity tests. Here, in fact, these parameters were kept constant but can impact the dispersed droplets' size and thus the separation time.
- Investigation on centrifugal separation time and droplets' motion is suggested by including the disregarded Coriolis effects and droplet break-up and merge in the mathematical model.
- Exploration on various fuel concentrations and $\leq 7\%$ v/v FAME in HVO is suggested, as per standards (Neste, 2020). Different concentrations and FAME addition may affect the compounds' solubility and therefore the fuels' separation.

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References

Alfa Laval, n.a. High-capacity disc stack centrifuge for biodiesel production. `https://www.alfalaval.com/globalassets/documents/products/separation/centrifugal-separators/disc-stack-separators/bd_95.pdf`.

Ambler, C., 1952. The evaluation of centrifuge performance. Chemical Engineering Progress 48, 150–158.

B. Vermeire, M., 2021. Everything you need to know about marine fuels. Ghent, Belgium.

Brennen, C.E., 2005. Fundamentals of multiphase flow.

Cheung, C.S., Zhang, Z.H., Chan, T.L., Yao, C., 2009. Investigation on the effect of port-injected methanol on the performance and emissions of a diesel engine at different engine speeds. Energy Fuels 23, 5684–5694. doi:`https://doi.org/10.1021/ef9005516`.

Coulaloglou, C.A., Tavlarides, L.L., 1977. Description of interaction processes in agitated liquid-liquid dispersions. Chemical Engineering Science 32, 1289–1297. doi:`https://doi.org/10.1016/0009-2509(77)85023-9`.

De Haan, A., Eral, H.B., Schuur, B., 2020. Industrial Separation Processes: Fundamentals. Boston: De Gruyter, Berlin. URL: `https://doi.org/10.1515/9783110654806`.

Di Pretoro, A., Manenti, F., 2020. Non-conventional Unit Operations: Solving Practical Issues. PoliMI Springer-Briefs, Gewerbestrasse 11, 6330 Cham, Switzerland. URL: `https://doi.org/10.1007/978-3-030-34572-3`.

Dolphin Centrifuge, 2020. Disadvantages of a disc-stack centrifuge — illustrated guide. `https://dolphincentrifuge.com/disadvantages-disc-stack-centrifuge/`.

ECHA, n.a. Chemicals regulated substances. `https://www.echa.europa.eu/`.

Ellis, J., Tanneberger, K., 2015. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. EMSA, SSPA.

Estefan, R.M., Brown, J.G., 1990. Evaluation of possible methanol fuel additives for reducing engine wear and/or corrosion. Section 4: JOURNAL OF FUELS & LUBRICANTS 99, 942–964. doi:`https://doi.org/10.4271/902153`.

European Commission, n.a. Reducing emissions from the shipping sector. `https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-shipping-sector`.

Flottweg SE, n.a. Flottweg separation technology for the production of biodiesel. Technical Report. Flottweg SE.

Frising, T., Noïk, C., Dalmazzone, C., Peysson, Y., Palermo, T., 2008. Contribution of the sedimentation and coalescence mechanisms to the separation of concentrated water-in-oil emulsions. Journal of Dispersion Science and Technology 29, 827–834. doi:`10.1080/01932690701781501`.

GEA Westfalia, n.a.a. GEA Westfalia Separator OTC 2-02-137/OTC 3-02-137. Technical Data: Continuous treatment of fuel and lube oils, hydraulic, diesel, turbine and waste oils. Technical Report. GEA Westfalia.

GEA Westfalia, n.a.b. Westfalia Separator Mineraloil Systems GmbH. Technical Report. GEA Westfalia.

GEA Westfalia Separator Group GmbH, n.a. Marine system technology: Concepts and high performance equipment for the engine room gea westfalia separator. .

Green, D.W., Perry, R.H., 2008. Perry's Chemical Engineers' Handbook. 8 ed., McGraw-Hill.

Greenspan, H., 1983. On centrifugal separation of a mixture. Journal of Fluid Mechanics 127, 91–101. doi:`https://doi.org/10.1017/S0022112083002633`.

Hazar, H., Temizer, I., 2012. The engine performance of a diesel engine and the research of the effect of fuel additives on engine oil and engine parts. Scientific Bulletin of the ”Petru Maior” University of Tîrgu Mureș 9(XXVI), 50–57. URL: `http://scientificbulletin.upm.ro/`.

Howarth, W.J., 1964. Coalescence of drops in a turbulent flow field. Chemical Engineering Science 19, 33–38. doi:`https://doi.org/10.1016/0009-2509(64)85003-X`.

IMO, 2018. Solas 2018 - consolidated edition. .

IMO, 2022. Report of the Marine Environment Protection Committee on its seventy-eight session. `https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-78th-session.aspxx`.

IMO, 2023. Revised ghg reduction strategy for global shipping adopted. `https://www.imo.org/en/MediaCentre/PressBriefings/Pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx`.

Ishii, M., Zuber, N., 1979. Drag coefficient and relative velocity in bubbly, droplet or particulate flows. Aiche Journal 25, 843–855. doi:`https://doi.org/10.1002/aic.690250513`.

Jeffreys, G.V., Davies, G.A., 1971. Chapter 14 - coalescence of liquid droplets and liquid dispersion. Recent Advances in Liquid–Liquid Extraction , 495–584doi:`https://doi.org/10.1016/B978-0-08-015682-8.50018-3`.

Kamp, J., Villwock, J., Kraume, M., 2016. Drop coalescence in technical liquid/liquid applications: a review on experimental techniques and modeling approaches. Reviews in Chemical Engineering doi:`https://doi.org/10.1515/revce-2015-0071`.

Kato, M., Muramatsu, T., Tanaka, H., Moriya, S., Yaginuma, F., Isshiki, N., 1991. Density behavior of alcohol-diesel fuel mixtures. Journal of The Japan Petroleum Institute 34, 186–190.

Kerr, R.M., 2007. Biodiesel Production Techniques. Technical Report.

Kries, M.J., 2021. A Methanol impact tool for yachts, assessing the impact of using methanol as an alternative fuel on the design, emissions and costs of yachts. Master’s thesis. Delft University of Technology.

La Colla, E., 2023. Experimental and modelling studies on HVO-methanol mixtures separation for superyachts applications. Master’s thesis. Delft University of Technology.

Lambregts, T., 2021. Fuel-Flexibility, Fuel-flexible fuel cell systems for super yachts. Master’s thesis. Delft University of Technology.

Lapuerta, M., Rodríguez-Fernandez, J., García-Contreras, R., Bogarra, M., 2015. Molecular interactions in blends of alcohols with diesel fuels: Effect on stability and distillation. Fuel 139, 171–179. doi:`https://doi.org/10.1016/j.fuel.2014.08.055`.

van der Linden, J., 1987. Liquid-liquid separation in Disc-Stack Centrifuges. TR Diss 1525, Delft University of Technology.

McGeorge, H.D., 1998. Marine Auxiliary Machinery. Elsevier, Oxford.

Nautiyal, P., Gondal, A., Kumar, D., 1989. Wear and lubrication characteristics of a methanol-fuelled compression ignition engine — a comparison with pure diesel and bifuel operation. Wear 135, 67–78. URL: `https://doi.org/10.1016/0043-1648(89)90096-3`.

Neste, 2020. Neste Renewable Diesel Handbook. Technical Report.

Perazzolo Disconzi, F., Torres Borghi, F., 2020. Modeling, simulation, and optimization of the centrifugal separation of a microalgae-culture medium mixture. Biomass and Bioenergy 143. doi:`https://doi.org/10.1016/j.biombioe.2020.105871`.

Plat, R., 1994. Gravitational and centrifugal oil-water separators with plate pack internals. Delft University of Technology.

Privat, R., Jaubert, J.N., Molière, M., 2013. The thermodynamics of alcohols-hydrocarbons mixtures. MATEC Web of Conferences 3, 01018. doi:`https://doi.org/10.1051/matecconf/20130301018`.

Richardson, J., Zaki, W., 1954. The sedimentation of a suspension of uniform spheres under conditions of viscous flow. Chemical Engineering Science 3, 65–73. doi:`https://doi.org/10.1016/0009-2509(54)85015-9`.

Roberts, J.D., Stewart, R., Caserio, M.C., 1971. Organic chemistry: Methane to macromolecules. W. A. Benjamin, INC., New York.

Schaflinger, U., Köppl, A., Filipczak, G., 1986. Sedimentation in cylindrical centrifuges with compartments. Ing. arch 56, 321–331. doi:`https://doi.org/10.1007/BF02570612`.

Schaflinger, U., Stibi, H., 1987. On centrifugal separation of suspensions in cylindrical vessels. Acta Mechanica 67, 163–181. doi:`https://doi.org/10.1007/BF01182130`.

SEPARATECH, n.a. Spin test for evaluating the centrifugation performance of centrifuge. `https://www.separatech.com/spin-test-for-evaluating-the-centrifugation-performance-of-centrifuge/`.

Siepmann, T., 2019. Integrating Large-Scale Hydrogen Storage on Superyachts: A Feasibility Analysis and Concept Study. Master's thesis. Chalmers University of Technology.

Sorsamäki, L., Nappa, M., 2015. Design and selection of separation processes. Technical Report. VTT.

Sovová, H., 1981. Breakage and coalescence of drops in a batch stirred vessel—ii comparison of model and experiments. Chemical Engineering Science 39, 1567–1573. doi:`https://doi.org/10.1016/0009-2509(81)85117-2`.

Sterchi, J., 2001. The effect of hydrocarbon impurities on the methanol steam -reforming process for fuel cell applications. Master's thesis. University of Florida.

Taylor, D.A., 1996. Introduction to marine engineering. Elsevier, Oxford.

Towler, G., Sinnott, R., 2013. Chapter 16 - separation of fluids. Chemical Engineering Design (Second Edition) , 753–806doi:`https://doi.org/10.1016/B978-0-08-096659-5.00016-X`.

Ungarish, M., 1989. Side wall effects in centrifugal separation of mixtures. Physics of Fluids A: Fluid Dynamics 1, 810–818. URL: `https://doi.org/10.1063/1.857378`.

Visser, B., 2021. The Plug-in Hybrid Electric Superyacht: An operational data-driven design. Master's thesis. Delft University of Technology.

van der Vliet, N., 2021. Green Refits: Reducing yacht operational emissions through refitting. Master's thesis. Delft University of Technology.

Washecheck, P. H., Liu, A. T. C., Kennedy, E. F., 1983. Methanol fuel and methanol fuel additives. `https://patents.google.com/patent/US4375360A/en`.

Woud, H.K., Stapersma, D., 2003. Design of Propulsion and electric generation system. IMarEST - The Institute of Marine Engineering, Science and Technology, London.

Appendix A

A.1 Derivation of motion equations

The denser droplets enter the discs' section with an acceleration in the x-direction which can be decomposed as:

$$\ddot{\vec{x}}_d = \ddot{x}\hat{x} + \ddot{y}\hat{y} \tag{12}$$

This is used to express the forces balance via the Newton's second law:

$$\sum \vec{F} = m_d \ddot{\vec{x}}_d \tag{13}$$

Where m_d is the heavy droplet mass proportional to the denser droplet's diameter D_p(De Haan et al., 2020; Plat, 1994). The forces vector is the summation of the buoyancy, centrifugal and drag forces experienced by the droplet (McGeorge, 1998; De Haan et al., 2020; Plat, 1994). Respectively:

$$\vec{F_b} = -\frac{\pi}{6} {D_p}^3 \rho_h r \omega^2 \hat{r} \tag{14}$$

$$\vec{F_\omega} = \frac{\pi}{6} {D_p}^3 \rho_l r \omega^2 \hat{r} \tag{15}$$

$$\vec{F_D} = C_D \frac{\pi {D_p}^2}{4} \frac{1}{2} (\vec{V}_F - \vec{V}_d) \tag{16}$$

In equation 16 $\vec{V}_F$ and $\vec{V}_d$ respectively indicate the velocity of the flow entering the single discs' section and the velocity of the denser droplet. The expression for $\vec{V}_F$ is computed from the denser droplet's initial conditions, as expressed n appendix A.2 and derived in appendix A.3. Its final expression is:

$$V_F(x,y) = \frac{3QL}{\pi n x H^2 sin^2\varphi} yL \left(1 - \frac{y}{H\ sin\varphi}\right) \tag{17}$$

The term C_D in equation 16 represents the drag coefficient and it is a function of the Reynolds number (De Haan et al., 2020):

$$C_D = \begin{cases} \frac{24}{Re} & Re < 1 \\ \frac{24}{Re}(1 + \frac{3}{16}Re) & 1 \leq Re < 5 \\ 1.85Re^{-0.6} & 5 \leq Re < 5000 \end{cases} \tag{18}$$

With the Reynolds number of the droplet (Brennen, 2005):

$$Re = \frac{\rho_l D_p}{\mu_l}(\dot{x} + V_F) \tag{19}$$

By manipulating equations above, the motion equations 1 and 2 are obtained.

A.2 Initial conditions

Initial conditions are imposed to solve the coupled second-order differential motion equations 1 and 2, and confine the spatial domain of the droplet movement within a two-successive discs' section. Referring to Figure 2, initial conditions are imposed for both trajectories 1 and 2. The subscripts *i,j* respectively *i* refer to the first ($i = 1$) and the second trajectory ($i = 2$). The subscript *j* equals 0, meaning that that condition is set for the relative time $t = 0$ at which the droplet enters the section. The initial conditions for the first trajectory are:

$$\begin{cases} x_{10} = L \\ y_{10} = 0 \\ \dot{x}_{10} = \dot{x}_{10} \\ \dot{y}_{10} = 0 \end{cases} \tag{20}$$

The droplet enters at the lower disc's edge with a velocity of the fed mixture in x-direction (Di Pretoro and Manenti, 2020). This is defined by imposing the forces equilibrium along x:

$$\dot{x}_{10} = \frac{16\mu_l}{3\rho_l D_p}\left(-1 + \frac{{D_p}^2 \Delta\rho\,\omega^2 L\,sin^2\varphi}{18\mu_l}\right) \tag{21}$$

If at the time $t = \tau$ the droplet hits the upper disc at $y = H\ sin\varphi$ before leaving the discs' section for $x < 0$, the droplet coalesces towards the heavy phase outlet channel sliding along the upper disc. Hence, for the trajectory 2 the initial conditions are:

$$\begin{cases} x_{20} = x_{1,\tau} \\ y_{20} = y_{1,\tau} = H\ sin\varphi \\ \dot{x}_{20} = \dot{x}_{1,\tau} \\ \dot{y}_{20} = 0 \end{cases} \tag{22}$$

A.3 Velocity profile

The fed mixture flow velocity V_F is derived to determine the relative velocity subsisting between the two liquids. V_F is a function of the Reynolds number and a build-up of a boundary layer at the discs' surface exists, leading to parabolic velocity profile (Plat, 1994). The expression for the velocity V_F assuming a parabolic profile can be found as in (Plat, 1994). The mixture flow velocity $\tilde{V}_F$ can be expressed as function of *x* (Di Pretoro and Manenti, 2020):

$$\tilde{V}_F = \frac{Q}{2\pi n x H\ sin\varphi} \tag{23}$$

And for a parabolic velocity profile and for $0 \leq y \leq H\ sin\varphi$:

$$V_F(x,y) = \tilde{V}_F(x)\frac{y}{H\ sin\varphi}\left(1 - \frac{y}{H\ sin\varphi}\right) \tag{24}$$

Integrating between 0 and $H\ sin\varphi$ and manipulating the equations it results:

$$V_F(x,y) = \frac{3QL}{\pi n x H^2 sin^2\varphi} yL\left(1 - \frac{y}{H\ sin\varphi}\right) \tag{25}$$

Appendix B

B.1 Mathematical model - hypotheses evaluation

The hypotheses behind the developed centrifuge mathematical model covered in section 2.2.1 are evaluated. Firstly, all the droplet sizes are collected with the developed model, verifying the hypothesis of full fuels' separation. Among the hypotheses, Coriolis and shear forces were neglected. This assumption holds for the obtained separator design. Both forces are insignificant compared to the centrifugal force (F_ω). Starting with the Coriolis force (F_{cor}), its ratio with the centrifugal force equals (Plat, 1994):

$$\frac{F_{cor}}{F_\omega} = \frac{\rho_l \omega D^2}{9\mu_h} \tag{26}$$

With the methanol droplet's diameter (D_p) ranging 5-100 μm, the above ratio equals 0.00025-0.0921. Regarding the shear force, this is dictated by the lift forces ((F_L)) due to droplets' rotation. The lift-centrifugal force ratio is (Plat, 1994):

$$\frac{F_L}{F_\omega} = \frac{0.172 G_s^{1/2} \rho_h g D_p sin\varphi cos\vartheta}{\omega^2 \frac{D_{TOT}}{2} {\mu_h}^{1/2}} \tag{27}$$

Where ϑ is the angle between the lift and centrifugal forces, and unknown in this problem, while G_S is the shear rate expressing the flow velocity gradient:

$$G_S = \frac{V_F(y = Hsin\varphi - D) - V_F(y = Hsin\varphi)}{D_p} \tag{28}$$

F_L/F_ω depends on the droplet's diameter and G_S is implicitly a function of the flow. Hence, F_L/F_ω is calculated for the diameter at the extremes of the 5-100 μm range and for the inlet volume flow equal to $4.076 \cdot 10^{-4}$ and $2.241 \cdot 10^{-4}$ m^3/s dictated by the yacht's operational modes. It results that F_L/F_ω ranges 0.00136$cos\vartheta$- 0.0340$cos\vartheta$. Thus, the droplet's break-up and deformation caused by shear forces can be neglected for the droplet's sizes considered and for the resulting separator design. Consequently, the assumptions employed in the model can be considered valid.

Safety Critical Items in naval systems

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Synopsis

What components make a ship safe to operate? Many; but not all are of equal importance. Applying a proportionate level of scrutiny and analysis to components and systems during design and safety case development, and then through life is key to the efficient management of the "safe to operate" argument. Applying true proportionality would be individual to every component and system – this would be cumbersome. Categorising safety related items to delineate between those that are essential to the platform safe to operate argument from those that provide a safety function that whilst important is not essential, allows appropriate focus to be placed on those essential items. Many would contend that this rationale has already been incorporated into existing design codes with terms in use such as Safety Critical Functions, Mobility or Ship Systems, Essential Services, Vital Services, Essential Safety Functions. However, these are generally loosely and subjectively defined and so open to interpretation. Furthermore, existing design codes tend to prescribe design outcomes. This leads to safety cases placing considerable emphasis and reliance on code compliance and certification rather than arguments focused on robust control and mitigation of hazards. Taking the lessons from offshore oil & gas, and other regulatory regimes and practices Defence Standard (Def Stan) 02-904, Surface Ship Safety Critical Items, was drafted to provide a consistent definition of Safety Critical Items and how they should be treated. The intent behind this standard is to generate a more risk focused approach to the management of component and system integrity through a platform life cycle and a leaner and more focused set of safety arguments. This paper examines the rationale behind Def Stan 02-904 and the work underway to implement its requirements.

Keywords: Safety; Safety Critical Items; Safety Case; Safety Function

1. Introduction: the problem space

Currently, many UK Naval Surface Ship Safety Cases do not clearly articulate the arguments that the platform is safe to operate. Causes of this are multi-faceted and include the following:

- There is no delineation between platform safety risks and occupational safety risks.
- The Claims, Argument, Evidence trail is not easy to follow.
- Assessment of design suitability and associated evidence is weak or fragmented.

In parallel to the above, it is observed that:

- Safety arguments required to underpin certification submission are developed outside the safety case.
- Existing design codes tend to prescribe design outcomes, and hence platform safe to operate arguments place considerable emphasis and reliance on code compliance and certification.

Instead of relying on code compliance and certification, platform safe to operate arguments should instead focus on robust control and mitigation of hazards; however, a risk-based approach based upon scrutiny and analysis of all components and systems during design and safety case development, and then through life, is impractical.

Categorising safety related items to delineate between those that are essential to the platform safe to operate argument from those that provide a safety function that whilst important is not essential, allows appropriate focus to be placed on those essential items.

Whilst this concept is relatively straightforward, commonly used associated terms, such as Safety Critical Functions, Mobility or Ship Systems, Essential Services, Vital Services, and Essential Safety Functions, have been loosely and subjectively defined to date and hence open to interpretation. This is a significant barrier to any implementation of the concept.

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[1] **Author's Biographies**

Dan Gardner is Deputy Head of Engineering and Chief Marine Electrical Engineer in the Ships Engineering HQ at DE&S. He has a background in the offshore, nuclear and renewables industries, and has been leading the work to develop Def Stan 02-904.

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2. Approach

To enable proportionate, risk based, platform safe to operate arguments to be generated, a Safety Critical Items approach has been developed and will be implemented within MoD Surface Ships Environment. This Safety Critical Items approach is based upon good practice used in the Offshore Industry (SCR, 2015, PFEER, 1995) and the Submarine Domain (MOD, 2015). Importantly, it also aligns with the expected update of the ANEP-77 Naval Ship Code to include the following definition:

> *Essential Safety Function: Those safety functions identified as being of primary importance in the prevention (and/or reduction) of the level of significant risk to the ship or several persons onboard, from Foreseeable Damage events to (at least) a level of safety deemed acceptable by the Naval Administration.*

The approach has been introduced to MoD Surface Ships via Defence Standard (Def Stan) 02-904 Surface Ship Safety Critical Items) which establishes a clear framework for the identification and management of Safety Critical Items for UK Naval Surface Ships (MOD, 2023).

Within this framework, Safety Critical Items are identified as being core to delivering a safe to operate platform as they perform the Essential Safety Functions that are central to the control of key hazards. Def Stan 02-904 specifically defines Safety Critical Items as:

> *Any part of a platform, providing a safeguard or mitigation against, or failure of which could cause or contribute substantially to:*
>
> - *a reasonably foreseeable loss of multiple lives associated with a Key Hazard Area, as defined in DSA03-DMR – Naval Authority Rules for Certification of MOD Shipping.*
> - *the failure of life support systems for diving operations or the trapping of a diver.*
> - *a platform-level effect with the potential to lead to severe damage or loss of platform and multiple fatalities.*
>
> *Safety Critical Items may be structures, systems, equipment, components, or software.*

3. Benefits

Implementation of the Safety Critical Items approach will enable those responsible for the provision of safe platforms to better understand the items they are reliant upon to make the platform safe to operate. Justified arguments that the specified Safety Critical Items are suitable to deliver the platform's Essential Safety Functions enables development of a more compelling and comprehensive argument that the platform is safe to operate. This facilitates an improvement in the utility of Platform Safety Cases, such that they can, for example, directly substantiate requests for certification, and more effectively support pre-sailing seaworthiness assurance reviews.

The approach also supports the prevention of unintentional Essential Safety Function degradation. When Safety Critical Items are clearly identified and tagged, it is possible to introduce prohibitions or controls on the modification or replacement of those items unless an assessment of the potential impact on the Platform Safety Case has been undertaken.

Importantly, the approach also supports assessment of the impact of material state degradation on the Platform Safety Case. In particular, it enables the requirements for live material state data to be focussed on those items and measures of performance associated with the Essential Safety Functions. With the appropriate information available, the safe to operate argument can be updated dynamically, better informing decisions regarding operation of the platform. This is of particular value when considering the cumulative impact of ostensibly unrelated Safety Critical Item degradations.

4. Identification of Safety Critical Items

Def Stan 02-904 requires that:

- *For each platform, the Safety Critical Items associated with that platform shall be recorded.*
- *For each Safety Critical Item, the related safety functions shall be recorded.*

Recording first requires identification of the Safety Critical Items. This is not always straightforward as Safety Critical Items may come in various forms: structures, systems, equipment, components, or software. For example a Safety Critical Item may be an entire system (e.g. fire detection system), or an individual component (e.g. pressure relief valve). In addition, Safety Critical Items do not solely comprise items that must correctly function in emergency situations; they may also comprise items that must correctly function on a continuous basis to enable safe operation of the platform.

It should be noted that systems (e.g. electrical generation and distribution systems, fuel supply systems, hydraulic systems etc) upon which identified Safety Critical Items are dependent, may also be considered to be Safety Critical Items. This is due to the significant role they play in ensuring that dependent Safety Critical Items can continue to deliver their safety functions.

As a result, application of engineering judgement, by personnel with thorough knowledge of the platform and platform systems, is vital when identifying Safety Critical Items at an appropriate level of system breakdown. Identification at too low a level will result in an unmanageable number of Safety Critical Items. Identification of Safety Critical Items at too high a level may result in important safety functions not being identified.

The process of identification is shown in Figure 1. It draws heavily on the risks recorded in the Platform Hazard Log, and comprises:

1. Review of platform hazards to identify 'major accidents'; i.e. those that align with '*a reasonably foreseeable loss of multiple lives associated with a Key Hazard Area*' etc.
2. Application of engineering judgement to identify Safety Critical Items:
    a. That provide a safeguard or mitigation against the accidents; or
    b. The failure of which could cause or 'contribute substantially to' the accidents[2].
3. Recording of each Safety Critical Item within a Schedule of Safety Critical Items, together with the safety function(s) delivered by the Safety Critical Item (in relation to the hazard). Recording the safety functions at this stage ensures that Performance Standards (discussed below) are focussed on the safety functions of interest, not other functions that the Safety Critical Item may deliver. In each case, the boundary of the Safety Critical Item must be defined, as not all of a 'system' may be performing the safety functions of interest.

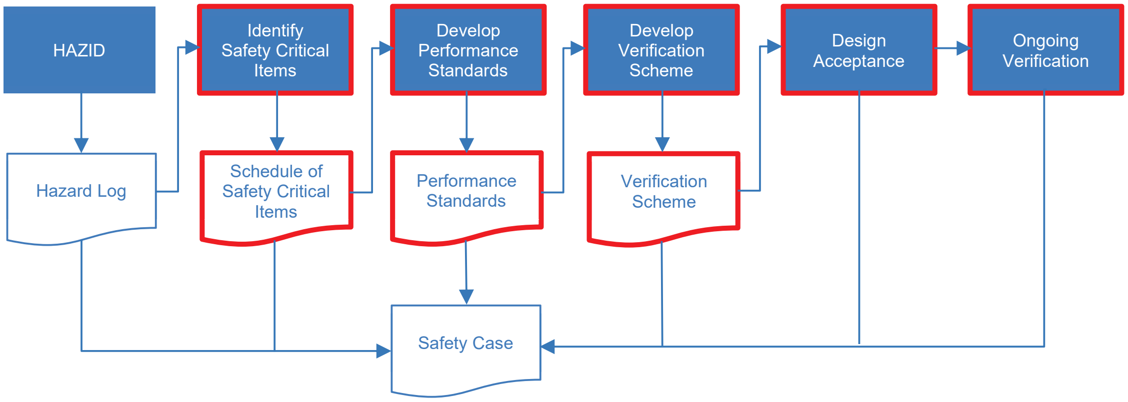

Figure 1. The Platform Hazard Log as an input to the Safety Critical Item identification process.

To support thorough identification of Safety Critical Items, it is recommended that hazards and Safety Critical Items are portrayed together in bowtie diagrams. An example of a bowtie developed for a Landing Craft hazard of Broaching is presented in Figure 2. This shows both Safety Critical Items that directly perform a safety function (Kedge Anchor and Winch), and those that have been defined as Safety Critical Items given the dependencies upon them (Hydraulic System etc).

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[2] 'Contribute substantially to' is used to ensure that those Safety Critical Items, whose failure would make a significant contribution to a chain of events that could result in or aggravate the defined accidents, are included.

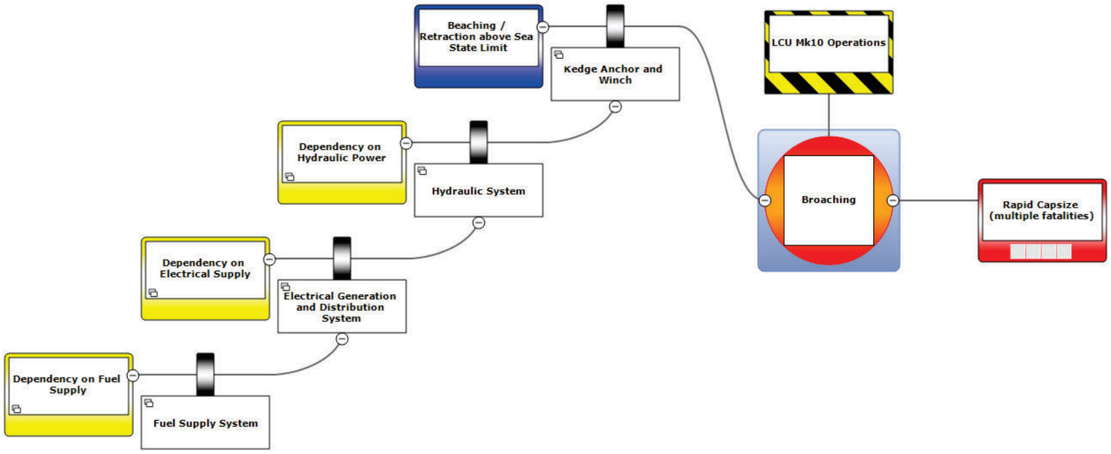

Figure 2. Bowtie showing Safety Critical Items in relation to the Landing Craft hazard of Broaching.

5. Performance Standards

Performance Standards define clear Safety Critical Item performance requirements, compliance with which prevents major accidents from occurring or escalating.

Def Stan 02-904 requires that:

> *For each related safety function, the Safety Critical Item shall have a record of its required Performance Standard.*

Def Stan 02-904 also provides the following definition:

> *Performance Standards are statements which can be expressed in qualitative or quantitative terms. A performance standard shall contain sufficient information against which to assess the suitability and condition of the items to which they apply and cover functionality, reliability, availability, survivability, reversionary modes, and interdependence where appropriate.*

To meet the above requirements, Performance Standards should developed against the following FARSI criteria:

Functionality – What safety functions must the Safety Critical Item be able to deliver? Functionality refers to what the Safety Critical Item must do to prevent, detect or mitigate hazards that may lead to a major accident. It can be expressed as the overall goal of the Safety Critical Item against the specific major accidents to which it relates. This may be qualitative or quantitative, but either way must be verifiable. Functionality requirements may include reference to applicable standards, if their applicability is justified. A Safety Critical Item may relate to more than one major accident and may be performing slightly different functions in each case; the specific functionality requirements in each case must be clearly recorded.

Availability – When must it be ready and able to perform? Availability refers to the scenarios in which Safety Critical Item are required to perform. This may differ between different operating conditions of the platform, e.g. some Safety Critical Items will not be required to be available when a platform is alongside, some may not be needed if no munitions are embarked, etc. Availability should be expressed in quantitative or semi-quantitative terms and must be verifiable.

Reliability – What level of reliability is required? Reliability refers to how likely the Safety Critical Item is to perform on demand. Required reliability may differ between different operating conditions of the vessel. Reliability may be achieved by redundancy or alternative back-up systems. The full benefit of Performance Standards will be realised during acquisition, when they are used to assess candidate Safety Critical Items. Quantitative derivation of reliability requirements is likely to be required to support this. For in-service platforms, taking a quantitative approach may not be proportionate; a semi-quantitative or qualitative approach may be more suitable. Either way, reliability requirements must be verifiable.

Survivability – What kind of events does it need to survive and for how long? Survivability refers to how the Safety Critical Item will perform after a major accident has occurred, i.e. how well it will survive a fire, flood, etc. Required survivability may differ between different operating conditions of the vessel, as discussed further below. Survivability may be achieved by redundancy or alternative ‘reversionary’ or fragmented or fall-back operating modes. Survivability should be expressed in qualitative terms against the various threat levels. As for other criteria, survivability performance must be verifiable.

Interdependence – What other systems does the Safety Critical Item interact with? Interdependence refers to the way that the Safety Critical Item:

- Is dependent upon other Safety Critical Items to operate.
- Is dependent upon other systems or equipment to operate.
- Otherwise interacts with other Safety Critical Items.

Where Safety Critical Items are reliant upon common systems, e.g. electrical power, an assessment should be made of the impact of common cause failure. As noted above, systems that do not directly perform a safety function may themselves be identified as Safety Critical Items due to their high levels of interdependence. Interdependence must be considered when determining availability, reliability and survivability.

6. Operating Conditions

Unlike other industries, e.g. Oil & Gas, where assets operate in a single, defined, operating scenario, Naval Surface Ships are required to operate in multiple scenarios ranging from peacetime operations, through maritime security, to combat operations. The Performance Standards for Safety Critical Items may vary between these scenarios.

For example, multiple simultaneous compartment fires may be a credible risk during combat operations; however, during peacetime operations it may be that the credible risk is limited to a single compartment fire. As a result the Performance Standard associated with the fire-fighting system Safety Critical Item may be more demanding for combat operations (e.g. require higher levels of functionality and greater redundancy). Peacetime operations may not require such a stringent Performance Standard.

It is noted that ANEP-77 already defines the following scenarios:

Foreseeable Damage – which includes damage that could be caused by one’s own cargo or weapons, navigational hazards (collision, grounding), naval exercises (certain types of navigational exercise, replenishment at sea, landings, boat operations, etc), system failures or maloperation.

Extreme Damage – which includes damage that could be caused by freak waves or typhoons.

Extreme Threat Damage – which includes damage that could be caused by weapon attacks and extreme acts of aggression.

To maintain alignment with ANEP-77, it is recommended that requirements for each of these scenarios are included within the Performance Standards. Recording variation of requirements in this way enables safe to operate assessments to be made in the context of the planned platform operations.

7. Verification Schemes

Once Performance Standards are in place, Safety Critical Items can be managed, with proportionate rigour and scrutiny, via the use of Verification Schemes.

Def Stan 02-904 requires that:

> *For each platform, a verification scheme shall be established for ensuring that the Safety Critical Items will be suitable and remain in good repair and condition, such that the required Performance Standards will continue to be achieved.*

Importantly, Verification Schemes cover both the initial suitability of the Safety Critical Item design (via Design Acceptance), and its ongoing ability to meet the required Performance Standard (via Ongoing Verification).

7.1. Design Acceptance

Before any Safety Critical Item is brought into operation on the platform, Safety Critical Item suitability must be demonstrated. The Verification Scheme should detail the design acceptance activities to be undertaken to assess the suitability of the Safety Critical Items. It is expected that these activities will predominantly focus on the review of design disclosure reports (or similar), which, for each Safety Critical Item, substantiate how the Safety Critical Item design meets the requirements of the associated Performance Standard. The substantiation should demonstrate how the design, and associated support solution (considering aspects such as maintenance schedule and provisioning of spares), will address all the FARSI criteria.

7.2. Ongoing Verification

Ongoing verification will ensure that the Safety Critical Items continue to deliver the Essential Safety Functions throughout the platform’s life. Discovering weaknesses by having a near miss or accident is too late and too costly. Early warning of dangerous deterioration within Safety Critical Items provides an opportunity to avoid associated accidents.

The determination of ongoing Safety Critical Item suitability should involve ongoing verification of Safety Critical Item performance through review of suitable reports or key performance indicators (KPIs). The Verification Scheme must therefore align the maintenance / inspection routines and the records made by Ships Staff / Industry Participants (e.g. within the maintenance management system) with the Performance Standards.

8. Material State Monitoring

When a Safety Critical Item fails to meet its Performance Standard, measures must be taken to assess and mitigate the risks to the platform. If the Safety Critical Item is operable but in a degraded state, a risk assessment should be undertaken to determine if the platform continues to be safe to operate. Temporary mitigating measures should be implemented to reduce the risks to As Low As Reasonably Practicable (ALARP) and help support the justification for continued use. Appropriate limitations of use should be set and the mitigating measures monitored until a permanent repair has been carried out.

Use of live material state data will enable Safety Critical Item degradation to be monitored, and the impact on the Platform Safety Case to be assessed. In support of this, linkages should exist between digital systems to facilitate the timely provision of required information. Ideally, these linkages would support Safety Critical Items material state reporting on demand.

With the appropriate information available, the safe to operate argument can be updated dynamically, better informing decisions to stay on the wall, sail, or sail with suitable operating limitations in place.

9. Trial Implementation

While the Safety Critical Items approach is common practice in offshore Oil & Gas and many onshore process industries, it is new for UK Naval Surface Ships. Adoption of the approach therefore requires development of suitable guidance, which, to be effective, needs to be based on lessons learned from real-world implementation of the approach. As a result, trial implementation of the approach on the Landing Craft Utility (LCU) Mk10 has been undertaken. LCU Mk10 was selected on the basis that this was a comparatively simple platform (compared to other complex warships).

To date, the trial has identified LCU Mk10 Safety Critical Items and associated bowtie diagrams, and has developed a number of Performance Standards and Verification Schemes. Work to create to linkages between digital systems to facilitate the timely provision of material state data is ongoing.

Overall, the trial implementation, conducted with the support of the LCU Mk10 platform engineering team, has been successful. Observations / Learning from Experience, obtained from conducting the trial, and from wider briefings on the introduction of Def Stan 02-904, include:

- A lack of recognition of the need for, and benefits of, the Safety Critical Items approach. This has resulted in resistance to implementation of the standard. It is hoped that this paper, together with outputs of work seeking to provide on-demand material state data for Safety Critical Items, will help to demonstrate the overall benefits of the approach.
- Difficulties in defining reliability requirements for Safety Critical Items on in-service platforms. This is predominantly due to a lack of reliability data. Item failure rates are not recorded, and hence it is difficult to set informed, quantitative reliability requirements. Work is currently ongoing to determine whether Failure Modes, Effects and Criticality Analysis (FMECA) undertaken as part of Reliability Centred Maintenance (RCM) may contain data that could support the setting of reliability requirements.
- Incomplete design acceptance information associated with the original design. Substantiation was only undertaken against the requirements set at the time; however, as Performance Standards were not generated, these requirements did not cover all FARSI criteria.
- Variation in data storage locations. Whilst technical documentation is held centrally, records of ongoing verification activities are sometimes only held by the organisation who has conducted that activity. This limits the ability to create digital linkages required to support material state monitoring.
- Configuration control issues. Design changes have been embodied through life (e.g. to meet modern standards); however, supporting technical documentation and equipment databases are not always updated.
- Determination of critical components within a Safety Critical Item. Whilst equipment databases identify all the components that make up a Safety Critical Item, it is not clear which of these are critical for the Safety Critical Item to deliver its safety functions. Classifying all components as critical could result in unduly stringent requirements (e.g. spares requirements) for those components that do not support delivery of the safety function of the Safety Critical Item. Again, it is hoped that RCM FMECAs will have identified which components are critical, and which are not.

10. Conclusions

Implementation of the Safety Critical Items approach enables those responsible for the provision of safe platforms to better understand, and proportionately focus effort on, the items they are reliant upon to make the platform safe to operate. Justified arguments that the Safety Critical Items are suitable to deliver the platform's Essential Safety Functions enables development of a leaner, but more focused, compelling and comprehensive argument that the platform is safe to operate.

The approach also supports assessment of the impact of material state degradation on the Platform Safety Case. With live material state data available, the safe to operate argument can be updated dynamically, better informing decisions regarding operation of the platform and providing continuous assurance.

The LCU Mk10 trial showed the Safety Critical Items approach to be effective, but also identified some issues associated with implementation on in-service platforms. It is anticipated that following the approach will be easier and more beneficial if implemented early in the platform lifecycle. Notably, the following benefits would be realised:

- Increased value in undertaking more detailed analysis, such as quantitative analysis to support setting of reliability requirements. This increased value is based upon being able to enjoy the benefit over the full platform life (c.f. remaining life for an in-service platform).
- Use of Performance Standards and Verification Schemes to influence and assess candidate Safety Critical Items during the design phase, thereby ensuring that they will be suitable for delivery of the required Essential Safety Functions.
- Ability to develop data requirements to ensure that all required information is recorded and is easily accessible, in support of material state monitoring.

References

MOD, 2015. *Def Stan 02-207—Quality Management Framework and Requirements for Materiel Safety in Submarines*. Glasgow: Ministry of Defence, Defence Standard No. 02-207 Part 1.

MOD, 2023. *Def Stan 02-904—Surface Ships Safety Critical Items*. Glasgow: Ministry of Defence, Defence Standard No. 02–904.

SCR, 2015. The Offshore Installations (Offshore Safety Directive)(Safety Case etc) Regulations 2015.

PFEER, 1995. The Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) Regulations 1995, (SI 1995/743).

A Lean, Mean, Green Atomic Queen? - The ultimate mission module

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Synopsis

The Queen Elizabeth class is an amazing asset for the Royal Navy which provokes endless operational debate about planes, ramps, catapults, propulsion, etc. It is well known that she is a long-life, upgradeable, flexible asset, with a large hangar, large flight deck, and large electrical power system. As one of the world's largest integrated full-electric propulsion warships, there are many questions about why her grid was conventionally powered, not nuclear, with answers such as cost, maintainability, disposal, and entering nuclear free zones cited as various reasons. This paper, authored by the QE power system designer, poses the idea, why not make her nuclear? Not with a big, costly refit, or billions of pounds, but over a weekend. She has the unique flexibility with her electrical power system for that not to be a crazy notion.

Small, containerised micro nuclear reactors are coming; many are in development and testing, with a number of companies looking to containerise them and place them in neighbourhoods around the world, of course managing the safety case around these modular micro reactors.

If you can drop it off a truck into a neighbourhood and plug it into a grid, then why not fit it into a warship that is already electric and already has a high-power plug on her power system, waiting for such innovation? Ratings of such units are quoted as 2-20MW, ideal for a ship's microgrid like those on the QE. This paper discusses and suggests the realistic application of modular micro reactors for the QE, from a size, system integration and decarbonisation perspective.

Containerised, fitted in the hangar, integrated into the power system, slashing the carbon footprint in a weekend, removable if you had a mission to a nuclear-free zone, well capable of providing a large amount of baseline and cruising power, refuellable in a weekend, developed and tested by industry with rapid insertion by a Navy.

Cruise nuclear, sprint conventional, perhaps; parallel operation of conventional and nuclear prime movers are eminently possible. It opens up all sorts of possibilities, which will be explored in the paper, from using excess power on board to manufacture e-diesel for the ship to powering Portsmouth when she is in harbour, rather than the other way around.

Imagine the Queen Elizabeth carbon neutral, reverse-RASing her escorts with e-diesel and telling her hometown, "When the Queen is in town, your bills go down."

Keywords: IFEP; Nuclear; Propulsion; Integration; Marine systems; QE; Micro; Reactor; Container

1. Introduction: Decarbonisation and Density

Decarbonising is hard, decarbonising transport is hard, decarbonising land transport is difficult enough but decarbonising maritime is even harder. Perhaps only aviation is harder still. Maritime transport, for many vessels, has gone through an optimisation phase: can routes be optimised, can speeds be optimised, can vessels be arranged to run on fewer engines, more efficiently, can engine speeds be varied to suit economical engine speeds, rather than speeds required by the propeller.

Electric propulsion has played a key part in this for many vessels: the ability to operate fewer engines, more efficiently, share prime movers, gain even better performance by using energy storage, not to store the voyage energy but to further optimise the operation of the generator sets.

As well as allowing optimisation of the present, ships' electric grids offer a clear ability to host tomorrow's technology on platforms built today, not only new weapons, sensors, and mission systems, but accommodating the changing nature of some of these. There is a rush for directed energy weapons to counter new threats, and a key enabler for these is the electrical energy to power them.

The same is also true for the electrical energy production. Whilst such systems allow prime movers to be optimised, they also allow new power sources to be hosted on existing networks, whether this is new fuels in existing engines, and the ability to cope with any associated transients and different combustion characteristics, or

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whether the new sources are solid state fuel cells or flow cells, or energy storage, kinetic or chemical. It's a compelling argument that many new sources will be integrated and interfaced electrically rather than mechanically.

The other great challenge to the maritime sector is the [lack of] power density of not only energy storage, but cleaner fuels, such as hydrogen. These fuels may make a large impact in decarbonisation, such as hydrogen from renewables, burnt cleanly in turbines, stored in large tanks on land. Short duty-cycle transport, such as buses, cars and taxis, will no doubt benefit, but long-range shipping is a tougher challenge, and warships are tougher still, as they are long range, compact and fast.

They can only be optimised so much, and it may take a while for green fuel energy density to be high enough to compete with diesel. Of course, high performance maritime has struggled with even the energy density of marine diesel, which limits the range of SSK submarines and means replenishment tankers are never far away from warships.

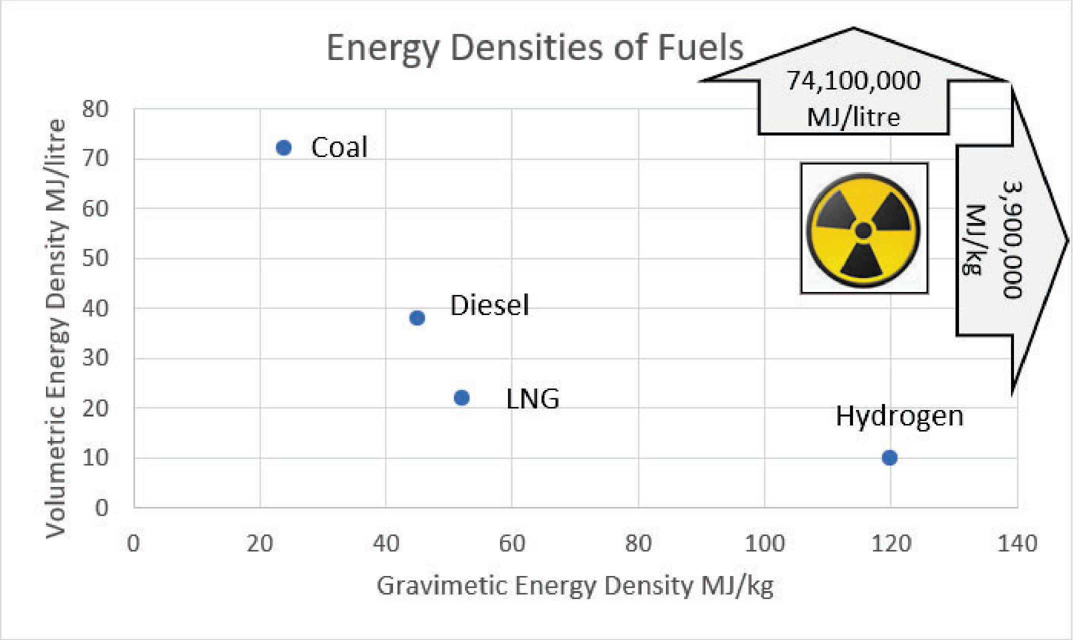

Figure 1: Volumetric and Gravimetric Densities of Marine Fuels

Surprisingly hydrogen is the most power dense fuel you can get, its 3x more power dense than diesel, but unfortunately that's by weight, and hydrogen sits at the light end of the periodic table. If you can liquify it, it's about one third the power density of diesel by volume.

Interestingly from the diagram in Figure 1, as the maritime sector transitions from coal to diesel to LNG and perhaps to hydrogen, it is moving from high volumetric energy density to high gravimetric energy density.

2. Extreme Transport Comparison

Table 1 is a simple comparison, between a 747 and its aviation fuel, the space shuttle and its hydrogen fuel and the QEC carrier and its diesel fuel.

Platform	Litres	Kg	MJ Total
Boeing 747	216,847	165,000	6,600,000
Space Shuttle	1,497,440	105,000	12,600,000
QEC	4,000,000	3,600,000	162,000,000

Table 1: 747 vs Space Shuttle vs QEC Fuel Tanks

https://doi.org/10.24868/11195

The comparison ignores the solid rocket boosters on the Space Shuttle as it's the fuel tank in the middle that's of interest. A 747 in its tiny inboard tanks holds more fuel by weight than is in the Space Shuttles hydrogen tanks, and amazingly almost half the energy, but the shuttle holds more, due to the energy density of hydrogen being much better, by weight. You wouldn't think looking at the fuel tanks below that a 747 carries half the energy of the space shuttles large hydrogen tank in its hidden wing tanks.

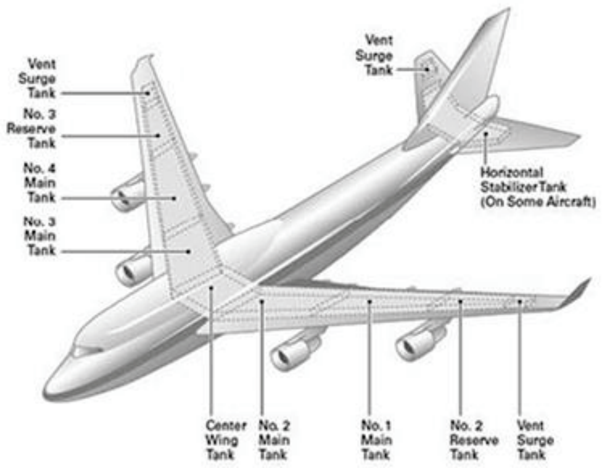

Figure 2 – 747-400 Wing-Integrated Fuel Tank Arrangement

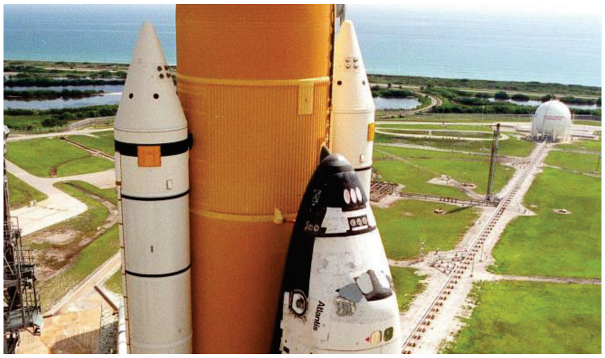

Figure 3 - Space Shuttle (orange) Main Hydrogen Tank. Credit: NASA

If you have never thought about it before, it's one of the reasons why rockets have used hydrogen - so much more power dense than other fuels by weight, which is key for a rocket, and they live with the larger tanks. We don't bat an eyelid when the space shuttle sits on top of its massive fuel tank which dwarfs the orbiter, but of course we would find such a tank curious on a 747.

Shuttle engineers clearly prize weight over volume, and interestingly the huge extra drag of large fuel tanks at hypersonic speeds is tolerated, probably due to the short duration in the atmosphere. This is a simplistic comparison, and of course the space shuttle tank also includes oxygen which the 747 scoops up in its engine intakes.

One would however laugh at such large tanks on a ship, just to accommodate fuel. Normally ship designers worry about displacement being a factor on ships. Interestingly, hydrogen ships, with the same installed energy, would be much lighter, saving displacement and reducing fuel. However, the volume of the tanks would perhaps start to produce more air resistance and windage to the upper decks.

Based on the final values in table 1, the QEC energy comparison, using figures from the Royal Navy's website, is 13x the installed hydrogen energy capacity of the space shuttle, or 25 747s.

3. The Nuclear Ace Card

To be really power dense, you need to look at the other end of the periodic table. The heavyweight elements are where the real volumetric power density lies. Navies have always had an ultimate ace card if you can afford, build and maintain it and live with its special challenges: that's to go nuclear. With an energy density by volume of 39,000,000 compared to diesel, uranium is a clear winner.

So this is the other end of the scale. Now you don't really need a fuel tank as such, you have a fuel tank that is often filled only once at the build of the vessel. Of course filling up with nuclear fuel is an expensive business, hence the emergence of nuclear electric, to allow even the almost limitless energy, be used more efficiently and last longer, so it doesn't have to be refuelled mid-life. So nuclear electric has a future, not just in large thermal power stations, but in smaller and smaller installations.

- Large thermal power stations need electricity to distribute their energy.
- Next generation submarines need electricity to up their efficiency.

4. Nuclear Micro-Reactors

The world is starting to see a huge amount of development by many different countries and companies in small "micro" nuclear reactors. There are an array of different technologies, but these are generally small, "intrinsically safe" micro reactors that can produce for example 0-10MW rather than hundreds of MW. This is not a paper about the different technologies of these reactors, more of the potential basic application of these reactors, whichever technology wins out. There is real commercial momentum to develop and fit these units for distributed generation to act as neighbourhood generating sets that don't need refuelling, or replacing batteries that never need recharging. The expectation is that these reactors will be containerised in a [ISO] standard 40 or 45 feet container; perhaps one or two containers per location.

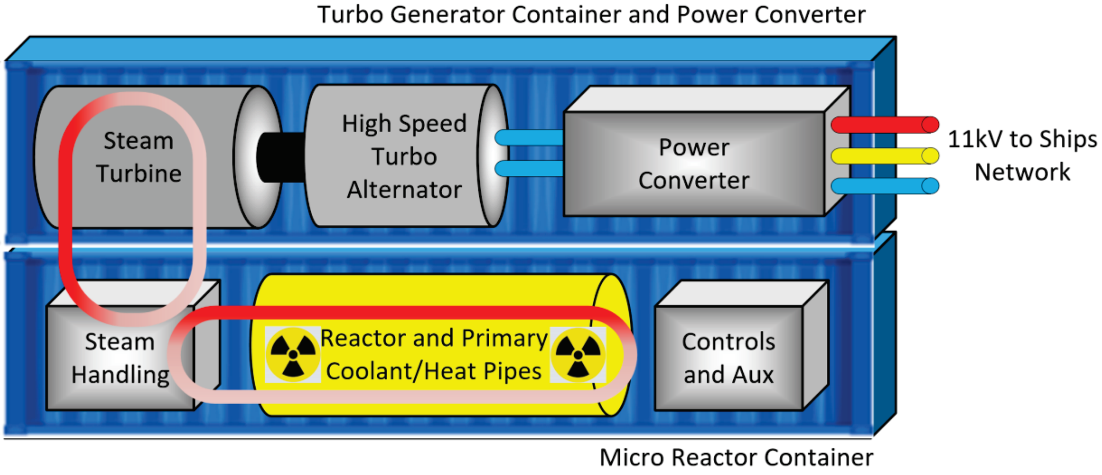

Figure 4 - Basic Layout of a 2 Container Micro Reactor

The expectation is they will consist of self-contained, truck-transportable modular units, probably in pairs. One would probably be a thermal container, containing the reactor, the protection and the steam raising plant, the second would be the steam turbine, high-speed generator and the power conversion machine to produce a voltage suitable for the network.

Almost certainly a high speed genset would be used, these are generators where, due to the uses of a power convertor, the speed of the machine is not determined by the electrical frequency, which allows the possibility of higher speed gensets, producing either DC directly or high frequency AC into the power convertor stage. The expectation is that the safety case and the intrinsic design will make these reactors suitable to be located in neighbourhoods and not requiring a classic large containment vessel. The author does not wish to debate the safety features of individual companies' designs, and the overall safety case, but simply to say that if it gets approved for the neighbourhood, then a more controlled environment such as a naval base or a warship should be justifiable. Clearly neighbourhood units would have to be considered for impact damage, vandalism, and in certain areas in the world, "recreational" gunfire, which convertor, energy storage, solar and wind installations are subject to from time to time.

5. Neighbourhood Nuclear Warships

Fast forward a few years when neighbourhood micro-reactors are available and have been safety-certified in the field. How could these be applicable to decarbonising warships and what do you need to consider for a retrofittable containerised micro reactor on a warship? You need an **electric ship** to interface into, such as the Albion Class, Type 45 or the QE Class. You need space, so that might be a challenge for a Type 45 without sacrificing the hangar, but Albion and QEC have large spaces and flight decks. You also need the requirement for a lot of electrical power. HMS Queen Elizabeth has to be a candidate as she meets all of these criteria.

6. Queen Elizabeth (Class) (QEC) – Not Nuclear…*Initially*

The author was an integral part of the power and propulsion design team for the QEC, and one line in the specification caused the most clarity, as well as the most questions for the next 25 years: "*QEC will not be nuclear powered"*. Associated with this were many facets of cost, performance, refuelling, handling, ports, safety case, etc. The other decision was, if not nuclear, then she should be electric, such as many complex vessels of high tonnage are, for example Queen Mary 2 cruise liner, etc, to maximise flexibility and energy efficiency.

Figure 5 - HMS Queen Elizabeth - A 110MW Power System with a Large Flight Deck and Hangar
(Credit: crown copyright 2020)

Another inherent enabler with electric ships is their upgradability and flexibility to host future power and mission equipment. If you install a full electric grid on a vessel, you can change prime movers and energy sources through life, as well as mission systems, sensors and weapons at the consumption end. This paper outlines the opportunity to consider one of these technologies, the micro/modular reactor, which has an external electrical interface at high power, exactly as QEC has the capacity to receive it.

Figure 6 is the public domain single line diagram for the QE class power system, used in a number of different papers. The system distributes at 11000V AC, with transformers to drop the voltage down to ship services at 440V and propulsion at 4160V. The network was designed with future upgrades in mind, so there are a number of spare breaker compartments around the switchboards.

The high-power connections were also provided for an EMCAT or EMALs[1] system to be fitted as part of a future upgrade, either for full scale jets, after the F35B, or for smaller and more numerous manned or unmanned platforms. So the microreactor containers could readily interface into the ship's power network. Two containers would be required for each system module, one for the reactor, one for the electrical generating plant. As well as the EMCAT feeders there are spare breakers on board and the port and starboard shore connections could also be used as additional power connections at sea. So the system is ready to receive at 11kV-level large amounts of power input or output.

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[1] Electromagnetic catapult or aircraft launch system

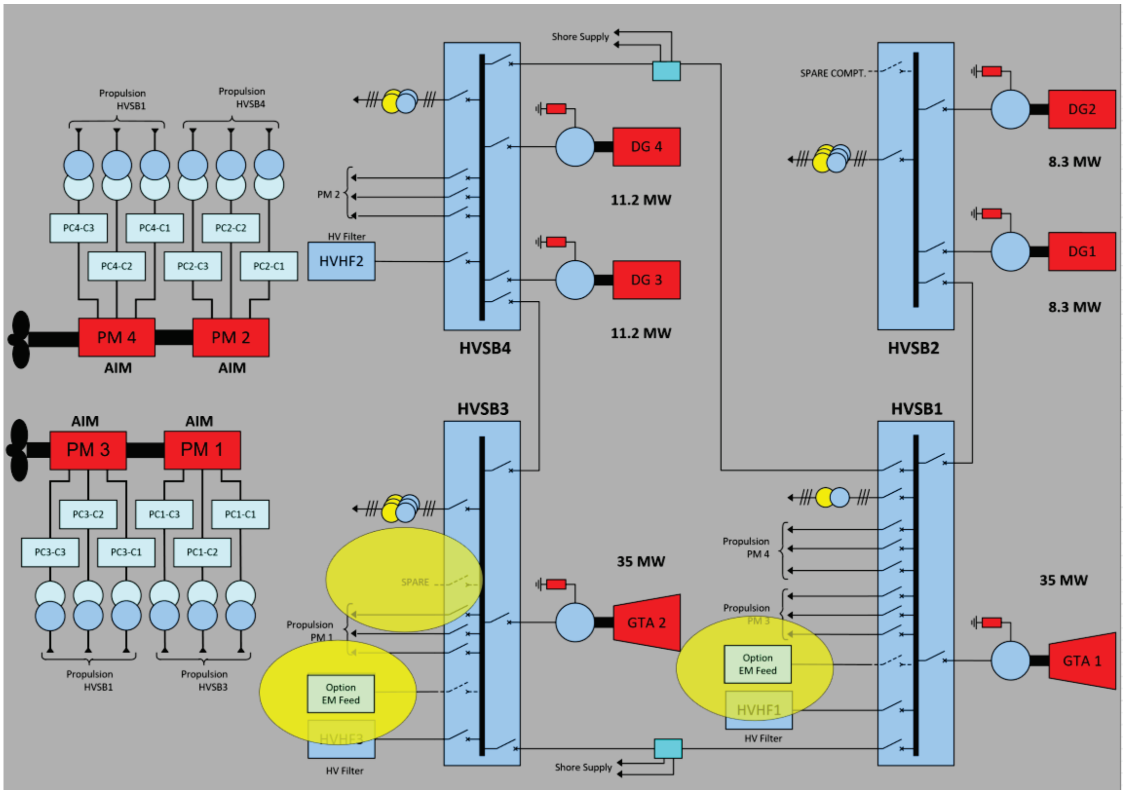

Figure 6 - Existing QE Class Single Line Power Diagram

7. Fitting the Containers Onboard

The units are claimed to be fully self-contained, not requiring any external cooling, but it's not the end of the world if some ship's cooling were required to be made available. It takes two to three days to unload a 10,000 container ship, that's about two a minute. If containership ports can unload two a minute with the right equipment off a cargo ship, even if we add a margin of 2000x, that is still a single weekend to drive some containers onto an aircraft carrier hangar.

Where to put the containers? The hangar is the obvious choice, but they could also potentially be on deck, away from the flight areas. To position and cable up two containers is expected to be undertaken in a matter of hours in the neighbourhood reactors, depending on the cable interface preparation. Trucks could potentially drive the containers straight into the hangar and unload them, like they would in the neighbourhood. Many sea trials have taken place with containers in the hangar or even on the flight deck at times. As far as connection is concerned, the expectation of the neighbourhood containerised solution is that they would be completely self-contained and simply plug in by a power cable into the grid, so the expectation here is the same, an 11kV cable would connect into the ship's power network and other services would not be required. Of course, we will see whether there is local air ventilation required, which may or may not be dissipated within the hangar space, should it be required.

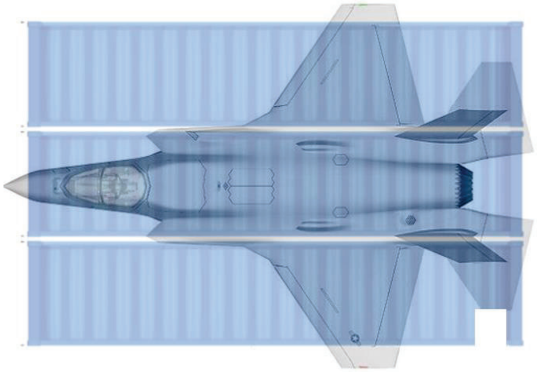

Figure 7:
ISO containers compared to the plan view of an F35

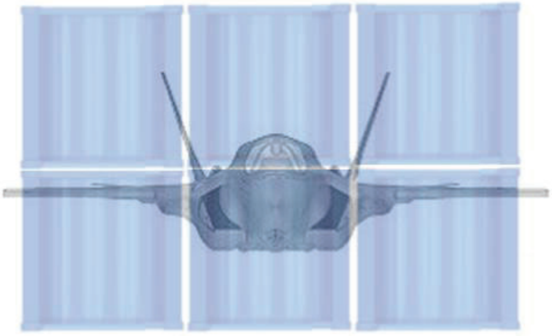

Figure 8:
ISO containers compared to the front view of a F35 aircraft

How much space would they take up? Figure 7 indicates the relative space of three 45-foot standard ISO containers, taking up similar space to a F35C aircraft. The frontal view is also shown in figure 8, a little off the ground to allow for the undercarriage.

Actually, the QEC has a much higher hangar in places than is required for simply parking the F35, so figure 9 is perhaps a bit more relevant, which shows the approximate maximum hangar height declared, and using HiCube taller containers.

So, give or take a little, and notwithstanding considerations such as weight, there is space to fit around nine HiCube 45-foot ISO containers in the footprint of a single F35. The power densities claimed by these reactors vary – one to 10 MW per container. These are large containers, at 45-foot and HiCube, so let's assume a pair delivers 5MW, then for the space of an F35 you could potentially deliver over 20MW. If we take the mid-range estimate of 10MW, that would be 40MW. This is a serious amount of electrical power, even for this large ship, certainly capable of running the ship at cruising speeds without the other prime movers.

The aim would be not to replace the prime movers and fuel tanks, it would be simply to supplement them. It would make the system like a super hybrid vehicle: running around most of the time on zero carbon, full-electric power and, when required, sprint using diesel. The full-electric system on the QEC would allow this seamlessly to happen.

So, in principle, within one parking spot of an F35, installed, or removed in a weekend, the QEC could be made conventional or nuclear, or both, as the mission requires.

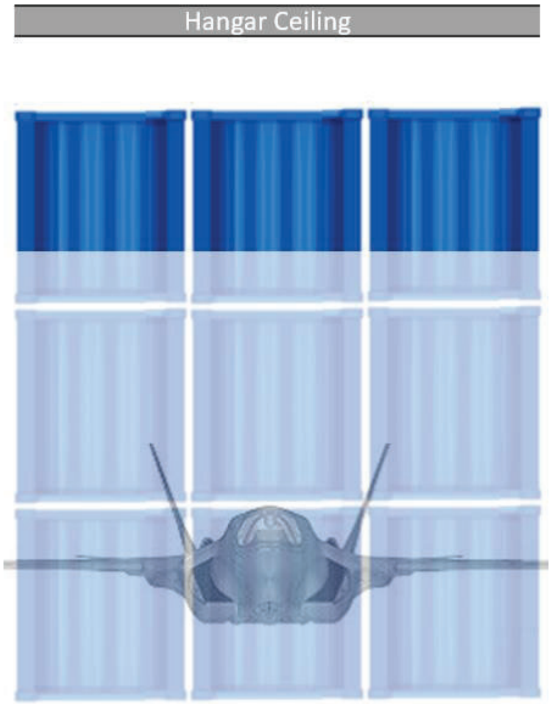

Figure 9 - nine ISO Containers in the QEC hangar footprint of an F35

As with any radical proposal, there are a number of things to consider - logistics, hearts and minds, safety - but the technologies are coming, and fast. It's true to say that soon we will be able to drive a nuclear reactor onto the QEC hangar deck and plug it in, and produce serious power, making the QEC, for large parts of its mission, emission free. This is very different as a proposition compared with existing, expensive, fit-for-life nuclear, such as in submarines and other navies' carriers.

8. Considerations in Warship Applications

They could be “peacetime” nuclear batteries, that could be removed in conflict rapidly if required. They could even be considered ejectable under damage conditions, such as aircraft and bombs have been onboard aircraft carriers after battle damage. Another lesson from Star Trek, in times of trouble they often eject the warp core at early signs of danger.

The ship could run around full of diesel ready for operations, but not consuming it until required, significantly not only reducing emissions, but also removing the requirement to be chased by oilers so closely. Of course the power could be used to charge and recharge drones, available for DEW, propulsion, single engine operation, just like an infinite capacity HV battery.

When the ship goes into port, a shore supply would no longer be required, although you might want to still connect to the shore supply in order to export power into the land-based network. Imagine how popular it might be that whenever the QEC came into port, it halved everyone’s electricity bill in the city?

It also opens up the possibilities of the production of synthetic fuels on board from waste carbon, electricity and water. Fuels such as hydrogen, methane, ammonia or eventually even e-diesel, could be produced and burnt in the existing QEC machinery, some would require space for bunkerage on board, others could use or be mixed in the existing tanks. In the future this could mean that perhaps the QEC could refuel its own tanks, in port or underway. Why stop there? If the ship produced its own liquid fuel, why couldn’t it reverse RAS[2] that to its escorts, pumping fuel to the smaller ships instead of receiving it from the oilers? With electric ships, not only could you transfer fuel, but you could also transport electricity, so escorts such as a Type 45 would be emission free whilst connected to the carrier, a sort of “electric towing”.

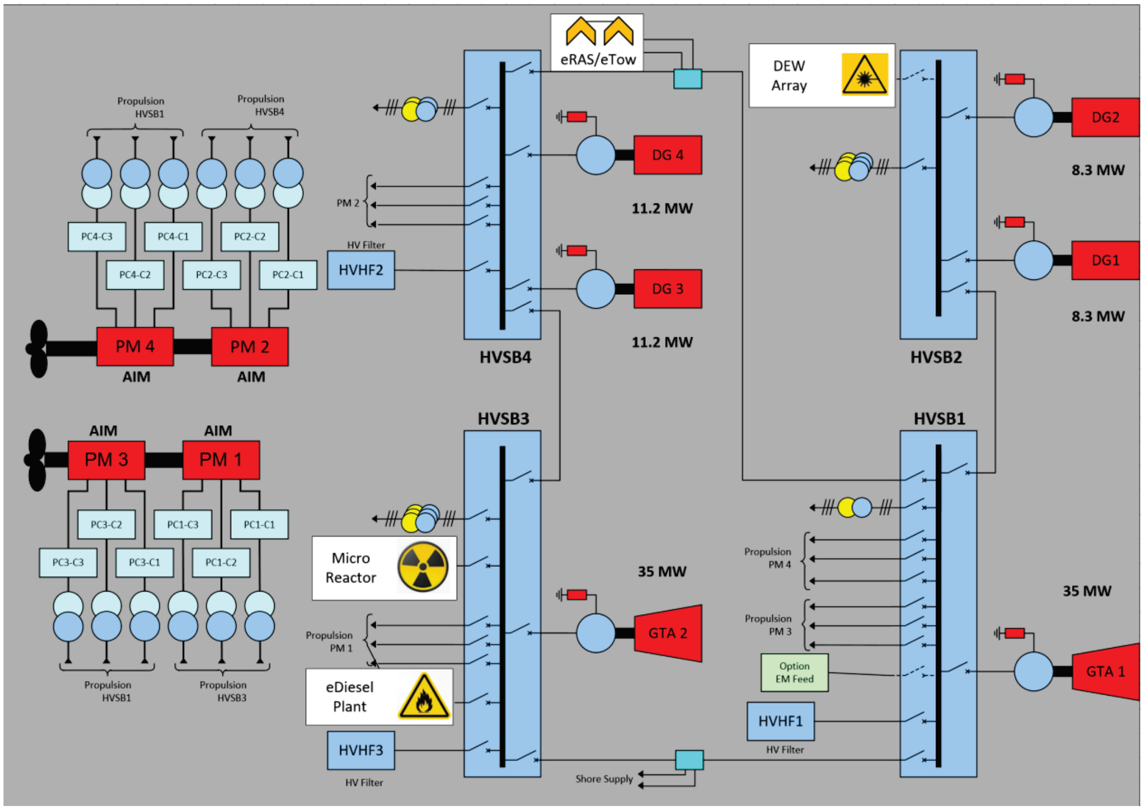

Figure 10 - QE Single Line Diagram with Micro Reactor, eDiesel, eRAS eTow and DEW Arrays

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[2] Replenishment at sea

Figure 10 shows the addition of Micro Reactors, eDiesel Plant, eRAS, eTow and Directed Energy Weapon (DEW) arrays, without any extra breakers or modification to any of the existing power system. It shows the flexibility of the existing IFEP installed network.

Could we devise a system where the carrier could move the containers to an escort if required, at sea? Chinooks can lift 10 tonnes, so it's not impossible. Could we see a system where the carrier can propel its escorts for longer than just RASing? A true mothership. A sort of electric towing."

The micro reactors would be modular; one set could be moved from HMS Queen Elizabeth to HMS Prince of Wales, depending on deployment. Half a set could fit HMS Bulwark. A quarter of a set could fit a Type 45, the electric ships could all take them, even the hybrid-electric configurations of Type 23 or Type 26 could cruise on nuclear if you used the hangar.

It isn't clear at the moment what the costing of the different reactors would be, but as they are aimed at commercial neighbourhoods for use potentially as boost or emergency power supplies to add additional capacity, the expectation would be that they would be compatible with naval fuel costs for ships such as the carriers.

The containers potentially represent ship-sized super batteries, with perhaps a five or 10-year life with no requirement to recharge on board. When expended the containers would be replaced with new ones, that have been refuelled on land. Ships are seeing challenges with conventional batteries' energy density, old nuclear is very expensive and very restrictive, emission targets are getting tighter, hydrocarbons are becoming more expensive. Such small nuclear systems should be seen as super batteries, perhaps not AAA or even D Cells, but perhaps NNN Cells, which could easily be added to ships that are already electric, as much of the UK fleet is. As mentioned previously, they could be shared between ships, missions and could even potentially be passed from one ship to another in local and foreign ports, if required. They are intended to provide emergency support in neighbourhoods if there is power loss due to equipment failure, this could equally be the case here, if a prime mover were lost on an electric warship, the micro reactor containers could be deployed to temporarily replace that prime mover capacity to complete the mission or return to port.

Figure 11 - Cut out the Middle Tanker and Reverse RAS eDiesel from the mother ship to the escorts
Credit: © crown copyright 2019

If the concept were taken to its ultimate conclusion and the ship used the micro-reactors, not only for its own propulsion and electrical power, but used any excess capacity to make eDiesel, then fewer support tankers would be required, and literally we could cut out the middle man and reverse the fuel flow, so the carrier becomes truly a mothership that could download fuel to its escorts by RASing and during this operation could export electrical power too. This could have a fundamental impact on the tanker fleet; clearly aviation fuel and solid provisions would still be required.

9. Pros and Cons

Pros

- Emission-free cruising power
- Huge reduction in carbon footprint possible, whilst maintaining lethality.
- Huge reduction in diesel fuel bill.
- An addition to present capabilities, none are removed. (except one F35 Space)
- Full diesel tank cruising in peacetime, so always at full capacity
- Dramatic reduction in DG set running hours, as well as GT.
- Technology development mostly done by the commercial sector.
- 10-year battery
- Deployed and removed in a weekend on the ship.
- Commonality with neighbourhood nuclear
- Minimal or no modifications required to the ship.
- Opportunities for e-diesel or other fuel production (If/When Available)
- Opportunities for reverse RAS
- Opportunities for no shore power requirements to achieve zero emissions.
- Opportunities to export power in port
- Electric towing
- Silent mode with no DGs or GTs running becomes possible.

Cons

- It’s a mindset change.
- Civilian neighbourhood safety case would need to be transferred/upgraded to a warship.
    - At sea, in port, in peace, at war

10. Conclusion

Decarbonisation is hard, there are no easy options, warships can’t compromise lethality for emission reduction, nor can they afford to be tied to fossil fuels for the long term. The technology is coming, we need to be brave enough to apply it safely sometimes. It’s a mindset shift, but this proposal is not decades away, it’s years away. It’s a great example of the flexibility of electrical warships. When the Author was involved in designing the QEC Power system we fitted a large grid and breakers to attach future tech. We had no idea we might consider a neighbourhood nuclear reactor connecting to one of those spare breakers, but it’s perfectly possible.

It’s an example of the upgradeability that electric ships really give you, the ability to accommodate the future, whatever it looks like and whenever it arrives. As electrical engineers, we don’t have to understand all the detail within the container. It’s interfaced electrically and we know the connections are already aboard HMS QE. As we decarbonise the world, we will aways have to look for technology, there used to be huge gaps, but they are closing. Opportunities like this, the technology is coming, it’s electric and soon the challenge isn’t going to be technical, it’s going to be hearts and minds and getting our heads around what it takes to accommodate the future.

Thankfully, due to its powerful electric grid, HMS Queen Elizabeth can sit and wait in the knowledge in the end, it just might be plugged in over a weekend, sometime in the future.

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The views expressed in this paper are that of the author and do not necessarily represent the views and opinions of GE Vernova’s Power Conversion business.

Application of Quantum Technology for Generation of Green Solar Hydrogen from Sea Water for Naval Applications

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Synopsis

Majority of the present-day technology for production of hydrogen utilizes Electrolysers, which are energy intensive and with a large carbon foot print. In order to provide a cost effective and efficient production process, Green Keplerate Laboratory, at Banaras Hindu University (BHU) in India has developed a novel and sustainable Quantum-derived technology for the bulk production of Solar Green Hydrogen from water through cost-effective photocatalytic based process. This team at BHU, led by Dr. *rer. nat*. Somenath Garai, has designed a Quantum Confinement Technology, wherein the confinement of the reaction systems inside the space with sub-Bohr radius, leads not only an accelerated kinetics but also alters the overall thermodynamics of the reaction. The Quantum Thermodynamics will reign inside the compartmentalized Quantum Containers, also amounting for the unusually high photo-conversion-efficiency.

The authors are effectively simulated the industrial waste material-based electron donor system and through progressive upgradation of the prototypes (from generation-I to generation-III), they have ultimately accomplished the optimum green H_2 generation rate, with a peak production rate of approximately 50 Litres/hr (YouTube Link for Lab-Scale Demonstration: https://youtu.be/uIKdd_5Uzfw). Similarly, they have rigorously tested their technology with saline water, simulated seawater and even artificially polluted water. The authors are confident that with abundance of sea water in the maritime domain, they can cost effectively directly harness sea-water for green hydrogen production, subsequently employing it as a marine and naval fuel, representing a promising and eco-friendly technological endeavour. In addition to the pure solar energy as an input to this process, the authors have also demonstrated production of hydrogen with LED lights as an input, should there be a challenge in availability of direct sunlight in certain circumstances such night time or poor weather conditions or inside closed compartments.

The authors have ensured that the design and assembly of the production unit is carried out in such a manner that they can produce hydrogen with maximum purity, thereby alleviating the need for additional purification. Hydrogen thus produced can be directly injected into the IC Engines, which they have successfully demonstrated in a two-wheeler, portable power generators. They have also successfully adapted the legacy IC Engines, by suitably redesigning the fuel manifold system, adhering to the safety standards, to power a river boat (https://youtu.be/-jLBpJ3GOHk). Notably, the legacy of hydride storage free IC-Engines with minimum modifications have been shown to run on the pure hydrogen produced with this new technology. These engines powered by green hydrogen minimizes energy loss due to heating, thereby elevating performance and durability. In view of the above experiences, the authors feel that this technology can be utilized in the marine and naval sectors.

This paper begins with the general introduction, followed by a brief on the modern Quantum technology application for green routes of energy generation and discusses the challenges likely to be encountered in adapting to the naval /marine environment such as safety, storage, metal-embrittlement etc. and the technologies available for finding solutions.

Keywords: Photocatalytic Green Hydrogen; Hydrogen-fueled Direct IC engine; Hydride Free Hydrogen Storage; Gas Clathrate Hydrates, Maritime Naval Transportation

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1. Introduction:

In this today's shift towards sustainable energy sources, the Quantum Energy Roadmap emerges as a pivotal player amid burgeoning technologies for the sustainable generation of green hydrogen from seawater. This roadmap frameworks an innovative strategy to harness quantum principles and solar energy to directly produce green hydrogen fuel from seawater, offering an eco-friendly alternative to carbon-intensive methods. The depletion of carbon-based non-renewable fuels and subsequent CO_x emissions significantly contribute to global warming and severe climate changes (Cook *et al.* 2010, Chu and Majumdar 2012, Chu *et al.* 2017). Meanwhile, the green hydrogen generation *via* renewable energy resources like solar or wind, proffers a sustainable resolution to curtail carbon emissions and lessen reliance on fossil fuels (Marouani *et al.* 2023).

The vastly expanded global shipping sector contributes around 2-3% of the world's carbon emission (Sharma *et al.* 2021). The growth of green hydrogen is of paramount importance for global transportation, with a detailed examination of EU regulations and regional nuances highlighting its potential as a cornerstone in Europe's carbon-constrained environment (Bader *et al.* 2008). Researchers indicates that future developments in shipbuilding may be shaped by transformative trends motivated by evolving energy sources and technological innovations. The incorporation of green hydrogen as an eco-friendly fuel corresponds with the industry's transition toward sustainable methodologies and diminished C-footprints (Seppälä 2023). According to the IEA, adopting sustainable methods could annually save 830 million tons of CO_2 emitted from fossil fuel-based hydrogen production. Transitioning all global grey hydrogen production to green hydrogen would necessitate 3,000 TWh/year of new renewable energy. Despite concerns over its production cost, advancements in renewable energy and decarbonization efforts are expected to render green hydrogen more economically viable in the future.

Depending on the extraction method employed, hydrogen is classified into three distinct categories as referred in Figure 1. (Phukan *et al.* 2024)

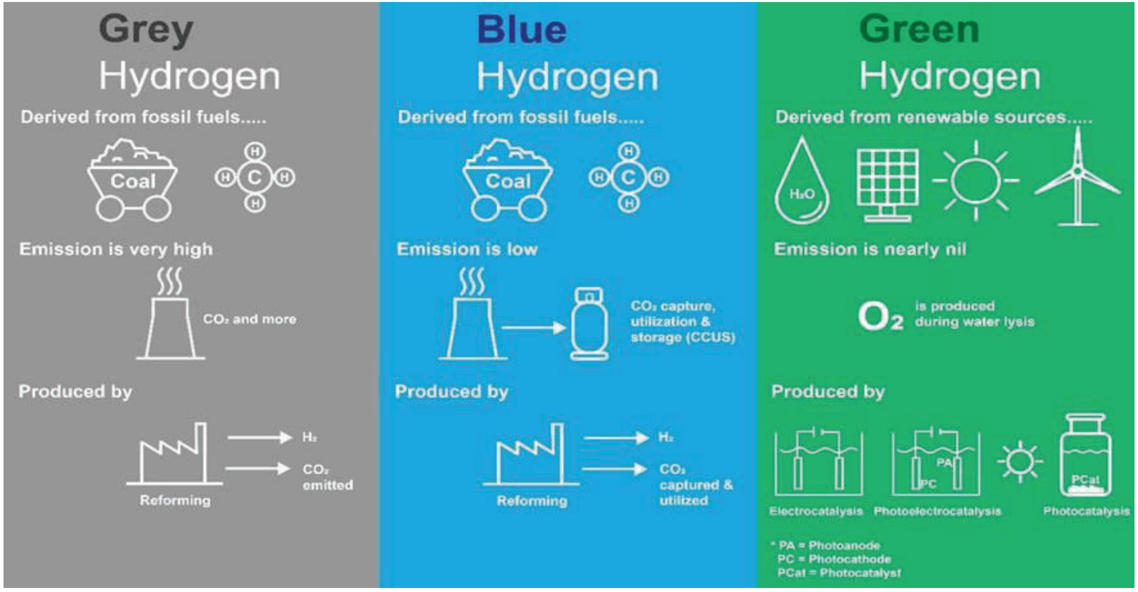

Figure 1: Differentiating by the method of extraction, hydrogen is categorized into three distinct types: Grey, Blue, and Green. Reproduced with permission from *ref.* Phukan *et al. 2024*. Copyright 2024 Elsevier

To address the pollution issues, the Green Keplerate Laboratory (GKL) at Banaras Hindu University (BHU), has pioneered a novel Quantum-derived technology for large-scale Solar Green Hydrogen production. The team has gradually scaled up through three prototype generations to optimize the peak rate of green hydrogen production up to 50 Liters/hour. The technology has been validated with various water sources, envisioning direct seawater utilization for eco-friendly marine and naval fuel production. Adaptability extends to LED-driven hydrogen generation, mitigating sunlight dependency. Production unit design ensures maximum hydrogen purity, obviating additional purification needs.

The succeeding sections explain the Quantum Technology developed for green hydrogen, followed by the progress made in generation and storage of green hydrogen. The redesigning of some parts/sections of the existing legacy IC Engines will then be presented and discuss the challenges (safety, storage, metal-embrittlement *etc.*) before concluding the paper. The graphical roadmap of the technology is depicted in Figure 2.

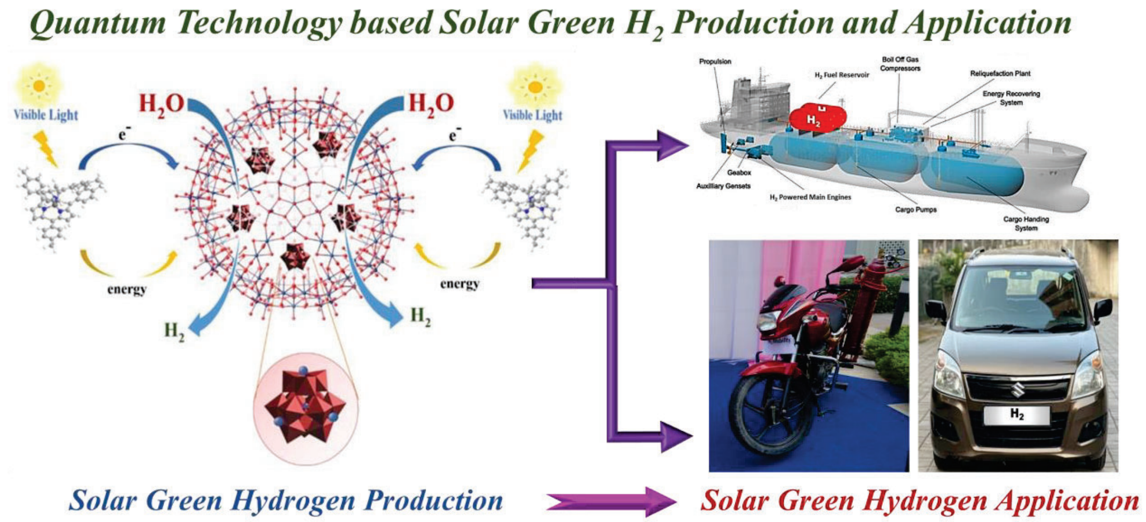

Figure 2: Graphical representation of the technology developed by Green Keplerate Laboratory, BHU, India

Some of the National and International highlights are as shown in Appendix-A. The research group has also demonstrated the “Quantum-confinement powered Bulk-scaled Production of Photocatalytic Green Hydrogen” Technology at the CEM14/MI-8 Ministerial discussions, which took place on 19-22 July, 2023 in Goa University on the side-line of the G20 Energy Transition Ministerial Meeting and also in 9th Smart City India Expo-2024, at New Delhi. The particular links for the above-mentioned events are as follows in the Table 1:

Table 1: YouTube Links for the demonstration of the GKL’s Technologies (Solar Green H_2 production and H_2-Mobility) at different Events.

Particulars	Link
Solar Hydrogen Production Technology Demonstration Set-Up in the G-20 Ministerial Meeting, Goa	**https://youtu.be/dkF3Q-FoJNY** **https://youtu.be/mua3E5yUbGk**
Demonstration by GKL at the 9th Smart Cities INDIA Expo	**https://youtu.be/La9nwOIAnuM**

2. Modern Quantum Technologies for Green Hydrogen Generation

In the paradigm of solar energy transformation, the deployment of Quantum Dots (QDs) has materialized as a promising route for enhancing the efficacy of photocatalytic reactor systems. These nanoscale semiconductor systems demonstrate unique photonic and electronic properties, which can be finely tuned through size, composition, and structure variations (Bajorowicz *et al.* 2018, Mehta *et al.* 2019). The QDs demonstrated high efficiency in solar energy conversion, leveraging quantum confinement to considerably augment photovoltaic performance (Kundu and Patra 2017). Furthermore, the inclusiveness of QDs within solar panels possesses the capability to revolutionize the field of sustainable energy production, leading to an orientation towards increased sustainability and efficiency (Xu *et al.* 2021). Recent investigations manifest advantageous outcomes with optimal photo-harvesting and improved charge carrier separation in QD-based catalyst systems. As the domain of QDs grows, integrating this technology into solar-powered frameworks holds notable potential for systematic renewable energy production.

The conventional photocatalysts exhibits reduced H_2 production rates relatively to the quantum effect powered catalytic systems due to insufficiently accessible active sites. In 2021, Jia *et al*. (Jia *et al.* 2021) proposed leveraging surface autocatalytic effects and quantum confinement of ultrasmall SiC-nanocrystals to augment active site approachability. By anchoring these nanocrystals onto carbon nitride nanosheets, they advanced a non-metallic photocatalyst that substantially enhanced and sustained H_2 generation. The heterojunction band alignment, enabled by quantum confinement, optimized photo-harvesting in the visible range and facilitated optimal exciton pair separation. Meanwhile, Sanjay Apte *et al.* (Apte *et al.* 2014) has also verified the satisfactory functionals of $CdS_{0.5}Se_{0.5}$ and CdSe QD-glass nano-systems induced with quantum confinement characteristics for solar hydrogen production phenomena. Through the alteration in dimensions of $CdS_{0.5}Se_{0.5}$ QDs, the band gap of glass nano-system was adapted from 3.6 to 1.8 eV, and further to 1.68 eV with the growth of CdSe QDs. The facile tunability of band gaps improves light harvesting, boosting the photocatalytic hydrogen generation, with maximum rates attaining 8164.53 and 7257.36 $\mu mol \cdot h^{-1} \cdot g^{-1}$ for $CdS_{0.5}Se_{0.5}$ and CdSe quantum dot-glass nano-systems, respectively.

Quantum materials, owing to quantum confinement and tunnelling effects, shows the competence to produce multiple excitons, enabling up to three electrons per absorbed photon, contrary to conventional semiconductors that predominantly yield a single electron. Additionally, doping QDs with wide-bandgap semiconductors further improves light absorption and photocatalytic hydrogen production (Rao *et al.* 2019). For instance, the co-condensed amorphous carbon/g-C_3N_4 photocatalytic composites was able to demonstrate hydrogen production rate attaining 212.8 $\mu mol \cdot h^{-1} \cdot g^{-1}$ (Xu *et al.* 2017). Whereas, g-C_3N_4 nanotubes embedded with carbon QDs displayed a significantly heightened rate of 3538.3 $\mu mol \cdot h^{-1} \cdot g^{-1}$ (Wang *et al.* 2018), referable to the quantum effects rooted within the latter catalytic system. Advancements in quantum mechanics principles, such as confinement and tunnelling, are being leveraged to augment materials with advanced catalytic performance for water splitting (Attia and Samer 2017). Innovative integration techniques and custom nano-structuring are undergoing assessment to address existing hurdles and encourage the broader application of quantum materials in green hydrogen production.

3. Achievements of GKL in *state-of-the-art* Quantum Confinement (QC) Technology

The Quantum Confinement Technology has been devised by the authors of the GKL to enhance the utilization of renewable energy sources to yield green energy fuels. This technology involves confining reaction systems within spaces smaller than the Bohr exciton radius of given system, which relates to the significant effect in the reduction of the distances over which an excited electron and an ensuing hole are attracted to each other, as depicted in Figure 3. This reduction in radius enhances the kinetics of the reactions, meaning they occur more rapidly. Moreover, the confinement alters the kinetic as well as the thermodynamic properties of the reactions. Quantum Thermodynamics, which governs the behaviour of energy at the quantum level, becomes significant within these Quantum Containers (QCs). This alteration in thermodynamic properties further contributes to the efficiency of processes like photo-conversion, where light energy is converted into other forms of energy with remarkable efficiency.

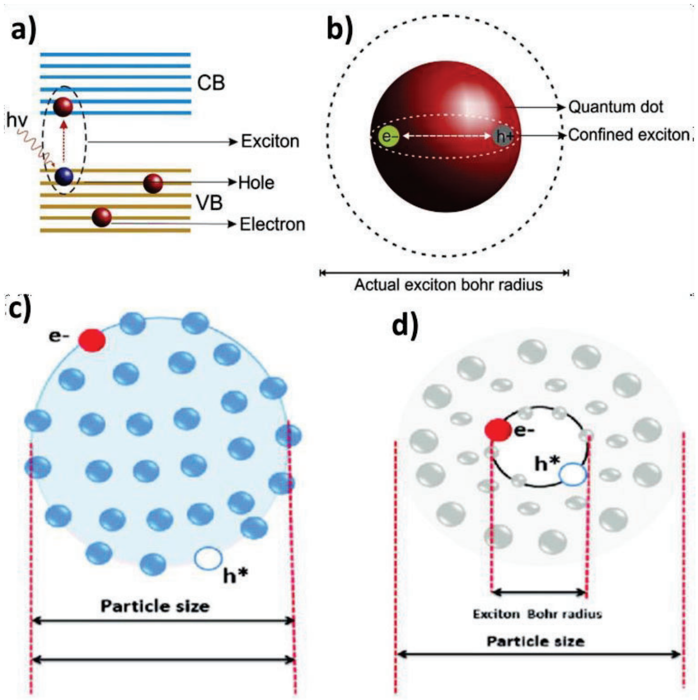

Figure 3: Graphical description of (a) formation of photo-excitons in quantum confined energy band. (b) comparison of exciton radius and quantum dot size. Comparison of (c) excited electron and hole position of conventional particle system and (d) Exciton Bohr radius in quantum dots. Reproduced with permission from *ref.*(Ramalingam *et al.* 2020). Copyright Intechopen.

3.1. Scientific Merits

Recent interest has growing in developing QCs with designed geometries and pore structures to host catalytically active molecules, integrating the properties of diverse nanomaterials for expanded applications. Beyond integrating Keplerates or QCs with metal or semiconducting nanoparticles, assessing their viability in fields such as solar cells and fuel cells needs a deep dive into optimizing charge separation (electron and hole dynamics), modifying valence and conduction bands, enhancing proton conductivity, facilitating electron transport and stabilizing active centers for hydrogen evolution. A. Mueller *et al.* reported the synthesis of Quantum enabled spherical capsules (Figure 4; Size 3.0-3.5 nm as opposed to the Bohr radius of 7.0 nm for molybdenum sub-oxides) based on the robust fundamental skeleton $[\{(Mo)Mo_5O_{21}(H_2O)_6\}_{12}\{Mo_2O_4(ligand)\}_{30}]$ which has sizeable pores, finely sculpturable interiors with Quantum Gating (inner diameter 2.5 to 3.0 nm) and in between, tuneable functionalized channels with unprecedented molecular-scale filter properties (Müller *et al.* 2003). B. Nohra *et al*. has highlighted the synthesis of Polyoxometalate-based metal organic frameworks where they grafted the triangular 1,3,5-benzene tricarboxylate linkers on tetrahedral ε-Keggin polyoxometalates (POMs) capped by Zn (II) ions, formed in situ under hydrothermal conditions. These POMOFs demonstrate potential for an effective electrocatalysts for H_2 generation (Nohra *et al.* 2011). A recent progress in this area is construction of polytantalotungstates by using tri-vacant Dawson- or Keggin-type POTs as supporting and protecting ligands by Shujun Li *et al*. In their work they achieved a higher rate of H_2 evolution by modulating the electronic structure by way of mixing the W5*d* and Ta5*d* orbitals and specifically raising the LUMO level of the polytantalotungstates with respect to Ta-free POTs (Li *et al.* 2012). Another advance in this area is made by Jaramillo *et al*. from Stanford University, to develop surface structure of MoS_2 to preferentially expose edge sites to improve the electrocatalytic hydrogen evolution (Kibsgaard *et al.* 2012). Prof. Lee Cronin, Univ. of Glasgow has been working profoundly on polyoxometalates for oxygen evaluation (Rausch *et al.* 2014, Martin-Sabi *et al.* 2018). The enhanced electrocatalytic activity of this catalyst is mainly due to its high surface curvature, which enhances the exposure of edge sites. This study underlines the significance of polyoxometalates as next-generation hybrid materials.

Although not yet commercialized, the growing interest in these multifunctional materials highlights their potential to address challenges related to cost, design and performance in advanced applications.

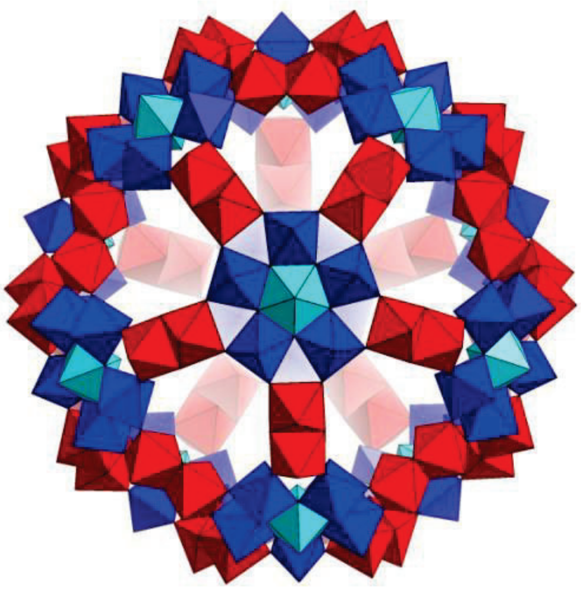

Figure 4: Polyhedral representation of the crystal structure of Mo_{132}-type QC. Reproduced with permission from *ref.* (Lodh *et al.* 2018). Copyright Royal Society of Chemistry.

3.2. Production Technology

By the culmination of the calendar year 2021, the esteemed research cohort hailing from the illustrious GKL, BHU has adeptly pioneered and meticulously engineered sophisticated photochemical energy production methodologies. The authors have designed and fabricated a laboratory-scale photocatalytic reactor possessing the capacity to yield approximately 50 liters/hour of photochemical green hydrogen, leveraging a 200-watt LED illumination source, till *May 2022*. Notably, they have also obtained the peak throughput of their laboratory demonstrator for the evolution of green hydrogen stands at approximately 1.0 liter/minute, even when utilizing saltwater as the feedstock, till *September 2022*. The GKL team has also designed, assembled and fabricated a lab-scaled solar powered-green energy production reactor, installed with concaved solar reflectors for maximum solar light utilization. The solar reactor's development was finalized by *March 2023*. The reactor was assessed in *May 2023*, demonstrating a green hydrogen production rate of ~50 liters/hour (Figure 5). The attached gas chromatography (GC) report is shown in Figure 6, which illustrates the purity analysis of the green hydrogen sample.

Keeping the '*Waste-to-Wealth*' approach in mind, the authors has designed the Quantum Confinement Technology with maximum utilization of the waste materials. The confinement of the reaction systems accelerates the kinetics but also alters the overall thermodynamics of the reaction as Quantum Thermodynamics will reign inside the compartmentalized Quantum Containers, also amounting for the unusually high photo-conversion-efficiency as depicted in Figure 7. The Z-scheme charge transfer pathway for advanced photocatalytic green hydrogen production has been enhanced using quantum confinement technology, which is integrated to a two-dimensional hybrid photocatalytic composite, as shown in Figure 8. The GKL team has successfully simulated an electron donor system originated from industrial waste, attaining an optimized green hydrogen generation rate. They are currently developing a solar-powered salt water-based photocatalytic reactor, which will be able to use both solar and LED lighting depending on solar availability. The reactor is designed to make maximum use of solar radiation and achieves a green hydrogen production rate of around 50 litres/hour with over 95% purity, eliminating the need for further purification and increasing cost-effectiveness.

The authors demonstrate the development of three successive prototypes (as shown in Figure 9) dedicated to green energy production, concluding in the successful development of a lab-scale green hydrogen fuel production unit. This system represents a significant development over existing photocatalytic hydrogen generation technologies, particularly through its direct utilization of seawater. This approach circumvents the need for ultrapure milli-Q water and delivers robust performance across saline, simulated seawater, and polluted water samples. Even under these conditions, consistent and efficient green hydrogen production establishes this technology as a promising, sustainable solution for marine and naval fuel applications.

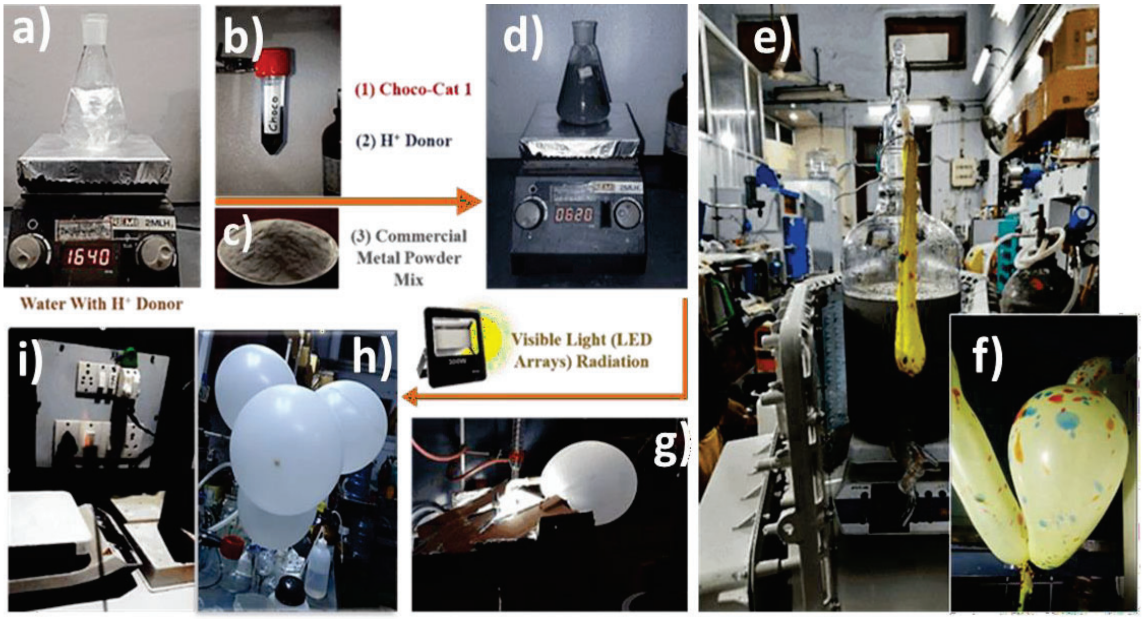

Figure 5: Internal methodology and assembly of the lab-scaled photochemical reactor for bulk Green H_2 production. ((a) Reaction flask containing ground water; (b) Quantum photocatalyst; (c) Mixed metal waste powder; (d) Reaction flask at mixing stage; (e) Lab-scale Green H_2 production reactor; (f) Ballons filled with as produced Green H_2 gas; (g) Execution of Photochemical reaction; (h)Yield of Green H_2 gas from reaction vessel shown in (e); (i) Flame test for H_2 gas.)

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Date/Time: 2024-07-02,18:44:09                                   Analyst:
Data File: C:\Users\Bhu\OneDrive\Desktop\GC Reports\H2.mdy    Date/Time: 2024-07-02,18:53:49
Method File: D:\CS200\TCD.mtd
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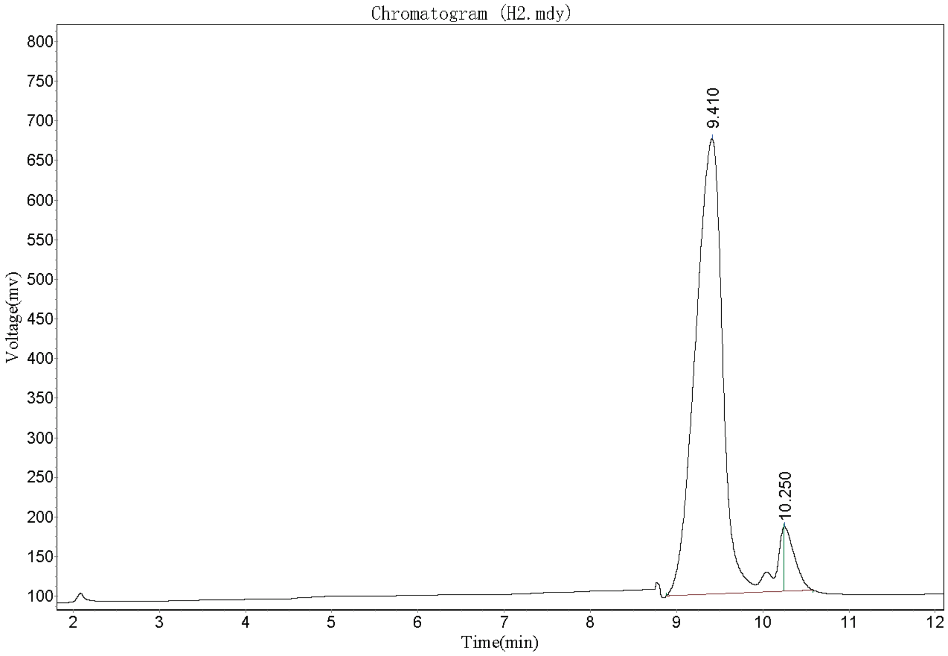


Results

Peak No.	Peak ID	Ret Time	Height	Area	Conc.
1	H2	9.410	574940.625	13121469.000	95.1184
2	N2	10.250	81703.695	673416.750	4.8816
Total			656644.320	13794885.750	100.0000

Figure 6: Gas Chromatography (GC) Report of Produced Green Hydrogen Purity.

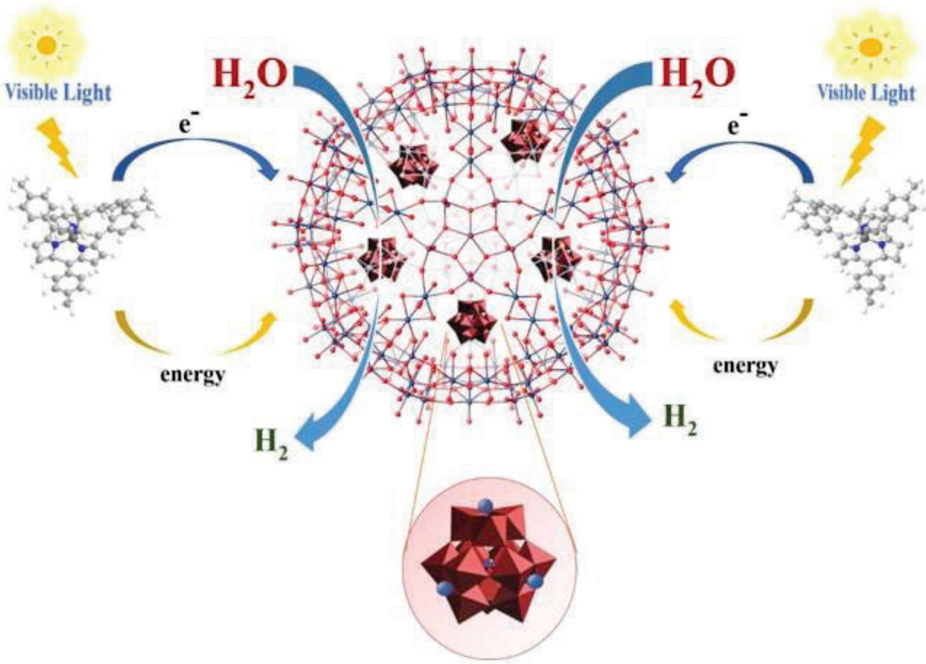


Figure 7: An overall pictorial description of photocatalytic Green H2 production strategy induced with charge transfer route.

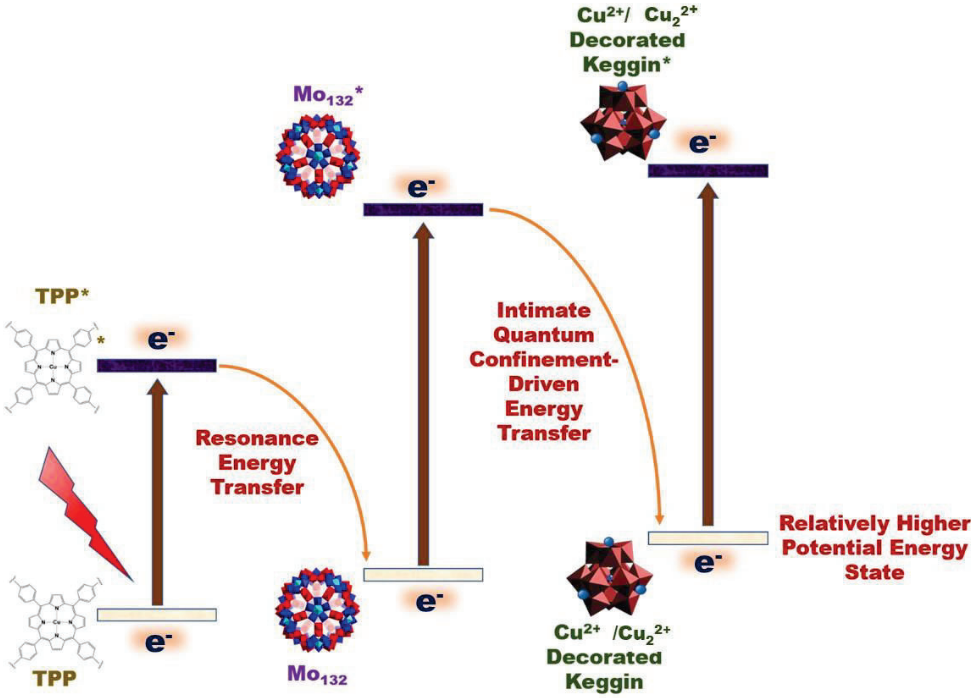


Figure 8: Schematic representation of proposed Z-scheme charges transfer route for effective photocatalytic activities, as a consequence of restrained recombination of photo-excited charge carriers.

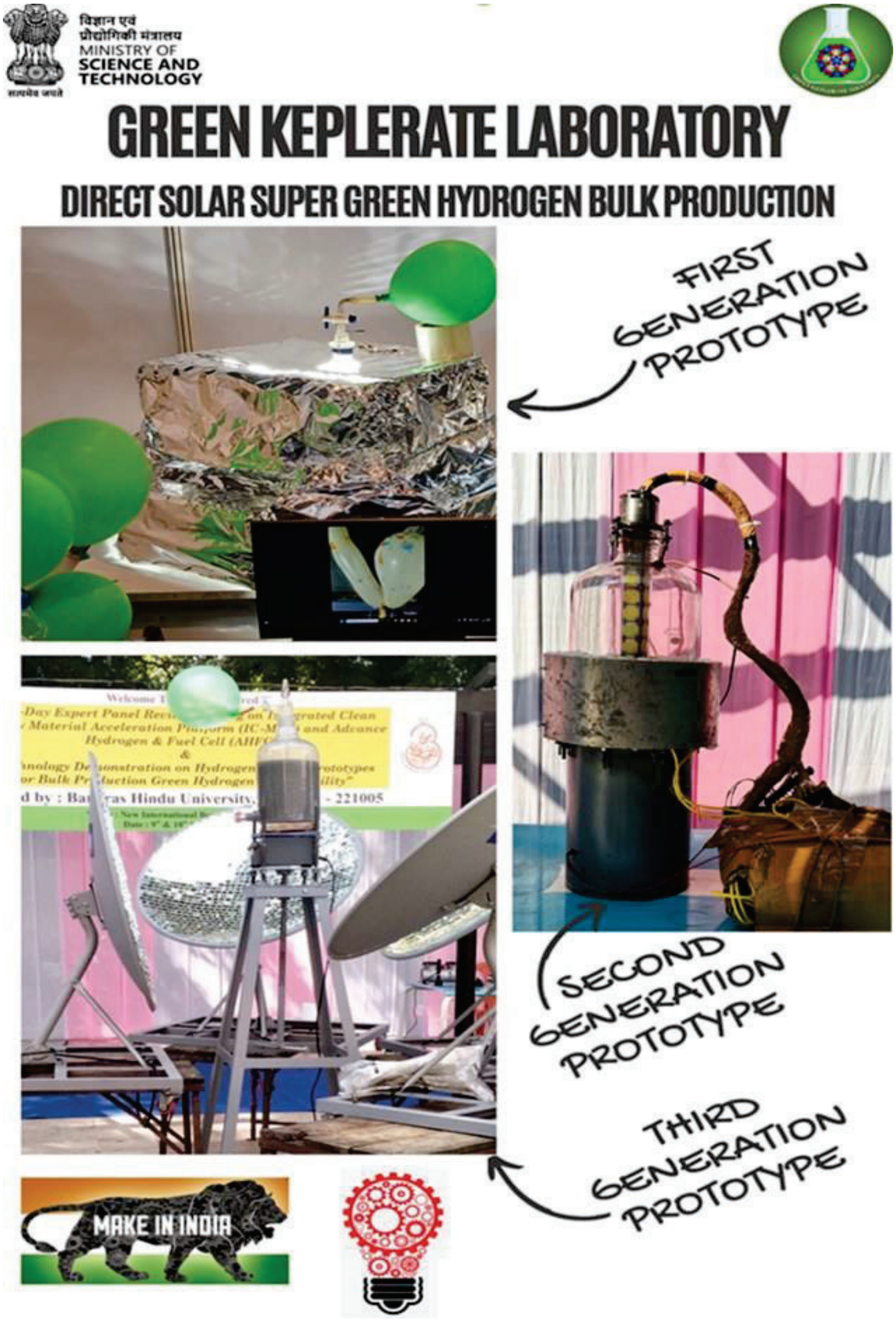


Figure 9: Illustration of the three generation prototypes for green energy generation.

3.3. *Green Hydrogen Storage Technology: A Future Idea*

The research group at the Green Keplerate Laboratory plans to improve energy efficiency by forming clathrate hydrates by employing a hydrogen natural gas blend (HNGB)-based approach for hydride-free H_2 storage. This approach takes advantage of carefully structured, strong hydrogen bonding shells, similar to those observed in clathrate structures, such as the water shells contained within $\{Mo_{132}\}$-Keplerates. The validation behind this method lies in the structural resemblance between water shells in clathrates and the encapsulated water shells within $\{Mo_{132}\}$-Keplerates (Figure 10). Extending this concept for green hydrogen gas storage, the team aims to exploit the beneficial properties of the well-defined hydrogen bonding shell to confine hydrogen gas within the clathrate in the future.

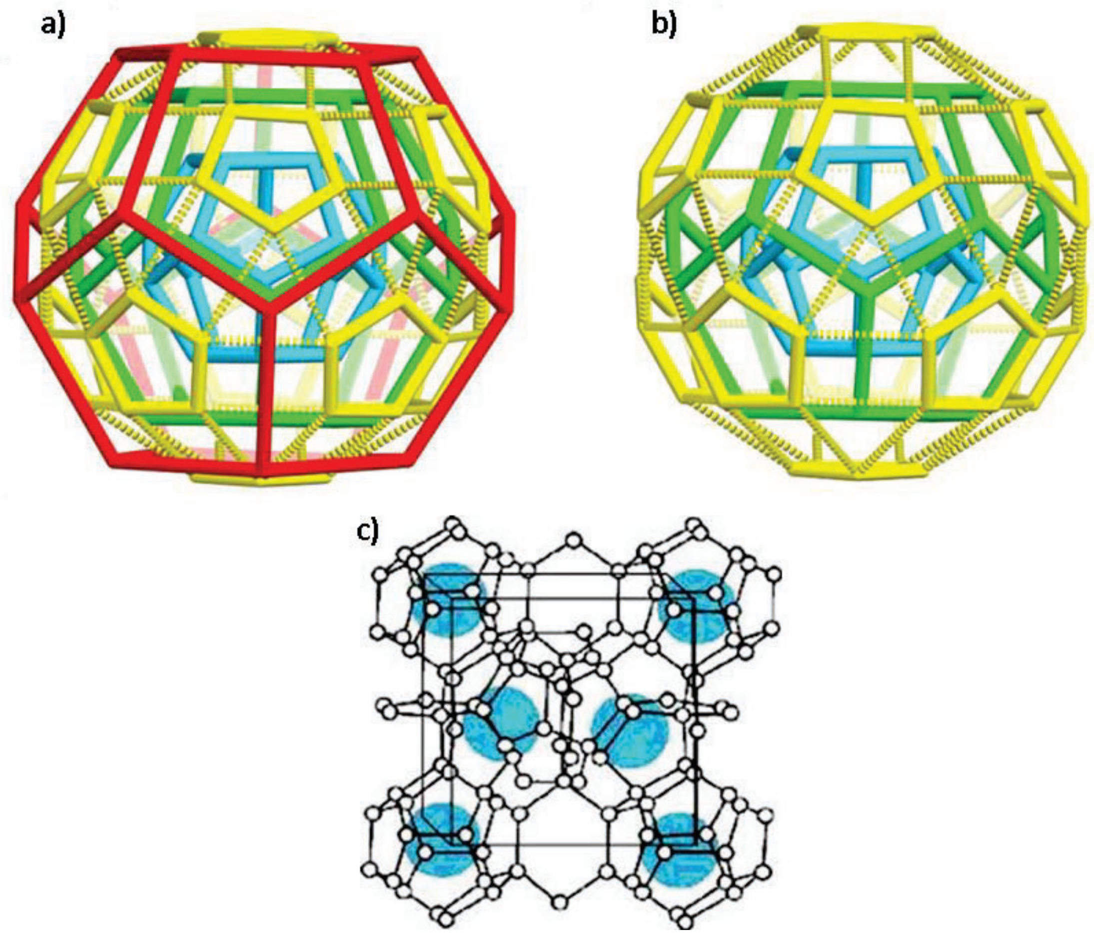


Figure 10: The pictorial diagram of encapsulated $(H_2O)_{100}$ inside the $\{Mo_{132}\}$-Keplerate. Reproduced with permission from *ref.*(Mitra *et al.* 2009). Copyright John Wiley and Sons.

This method takes advantage of the stabilization of hydrogen gas within a clathrate encapsulated by metal oxide clusters, significantly increasing stability and reducing cost and risk. The tunability of clathrate structures and gas encapsulation properties provide a prominent solution for hydrogen storage, especially for direct H_2 ICE-based vehicles. This approach addresses key challenges in hydrogen storage and increases the efficiency and safety of hydrogen-powered transportation.

For the H_2 fuel storing purpose, treating the Keplerate-based Quantum Container assemblies with ammonium sulfate solutions and utilizing the resulting nano-capsules containing the $\{Mo^V{}_2O_4(SO_4)\}$ type linker (Müller *et al.* 2003) as containers offers a promising approach to address the challenge. Upon examination, the authors observed that the significant alteration is undergone by the central water assembly structure within the obtained capsule. The icosahedral supramolecular $\{H_2O\}_{100}$ water nanodroplet (Müller *et al.* 2002) confined within the carefully engineered quantum container mentioned earlier. The structure of this nanodroplet may be derived either by enclosing the two nested $\{H_2O\}_{20}$ dodecahedra within a strongly distorted $\{H_2O\}_{60}$ rhombicosidodecahedron or by inserting an $\{H_2O\}_{20}$ dodecahedron within the two-shell $\{H_2O\}_{80}$ assembly. This geometric arrangement is characterized by relatively short hydrogen bonds, with an average hydrogen bond energy calculated to be 28 kJ/mol and significant anisotropy across the three concentric water molecule shells. Moreover, due to the substantial negative charge of the Quantum Containers, ammonium ions are absorbed into the cavity along with the water molecules. This water-based assembly presents a unique opportunity for direct observation of how its hydrogen-bonding network is perturbed by the presence of foreign cations.

3.4. Integration with the Existing Engines Technology

The endeavors have culminated in the proficient adaptation and integration of H_2-ICE (Hydrogen—Internal Combustion Engine) across a diverse spectrum of automotive platforms- 4-wheeler (Figure 11), two-wheeler (Figure 12) as well as a 7.5 HP diesel engine-based generator (Figure 13), and the Honda ep 2500 CXS petrol-based generator. The adaptive modification for direct hydrogen combustion, on the ICEs of the vehicles was completed by end of year 2023. Additionally, the propulsion systems, tailored for Ganges River boats (as shown in Figure 14), showcased hydrogen power in October 2023.

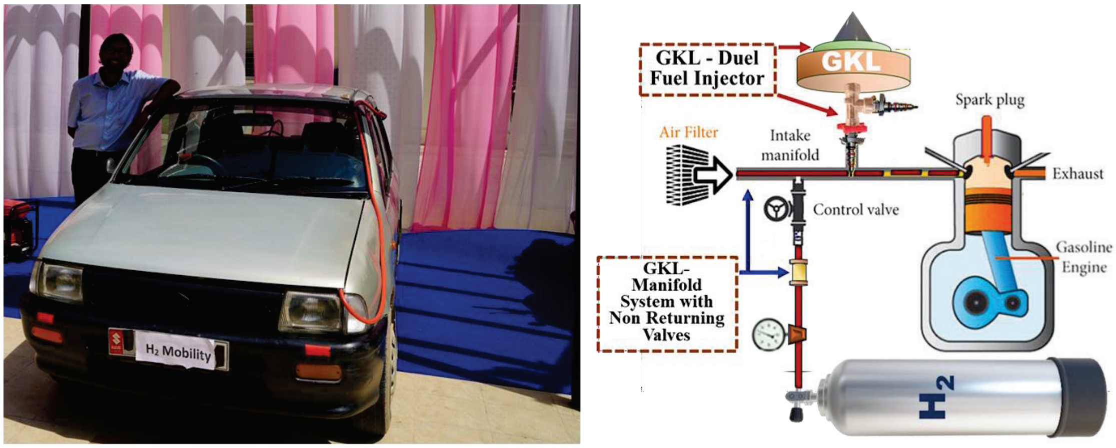
A standard hydrogen gas cylinder, which has a capacity of 50 liters and is pressurized to 200 bars, is capable of delivering energy equivalent to 10 kWh. This implies that the cylinder can sustain a fuel cell producing 1 kW of electrical power for a duration of 10 hours (Cellkraft Fuel Cell Products: Factsheets_Fuelcells n.d.). To supply a 50-kW fuel cell for one hour, you would need around 4,900 liters (4.9×10^3 liters) or approximately 4.375 kilograms of hydrogen gas. For a fuel cell of this capacity, the hydrogen feed rate would be roughly 102 liters per minute (LPM). Therefore, the hydrogen fuel consumption rate can be approximated to be 2 liters per minute per kilowatt (LPM/kW). The authors conducted a test ride using a hydrogen-powered maritime boat, revealing important insights into the fuel requirements for such scaled vessel. This test involved a maritime boat equipped with a 7.5 horsepower (5.6 kW) Honda IC motor, which had a weight of approximately 50-60 quintals. During the test, the maritime vessel achieved speeds of about 8-12 knots. To maintain this speed, the boat required a hydrogen fuel flow rate of approximately 12 LPM.

The experimental results indicated that the hydrogen consumption rate of the maritime boat during the test ride closely matched the theoretical values typically expected from a traditional fuel cell system. This alignment between experimental and theoretical values suggests that the fuel consumption behavior of the hydrogen-powered maritime boat is predictable and consistent with established models. Based on these findings, it is concluded that in order to efficiently power a boat equipped with a 7.5 horsepower Honda internal combustion motor using a high-quality fuel cell system, a hydrogen fuel feed rate of approximately 11-12 liters per minute would be necessary. This rate ensures that the boat operates optimally, providing the necessary power while maintaining efficiency and consistency with theoretical predictions. Meanwhile, the statistics and optimization parameters derived from the testing of hydrogen-powered maritime vessels will be methodically evaluated for potential application in larger-scale naval ships. The implementation of this environmentally sustainable waterborne mobility technology in naval-based operations will necessitate procurement of appropriate regulatory endorsements at both national and international levels. Additionally, it will necessitate access to suitable certified testing facilities and supervision by competent authorities. In spite of the prerequisites, the acquired valuable insights from maritime testing and optimization are decidedly advantageous for advancing to the next phase of scaled-up trials. These exertions are contributory in driving the integration of next-generation IC engine technologies into the naval sector, paving the route for a transformative alteration in naval propulsion systems.

This visionary project integrates green hydrogen gas through a methodically advanced manifold piping system, adhering to stringent safety standards. The modified H_2-ICEs significantly decrease internal acoustic emissions, improving auditory comfort. The major modifications include the inclusion of fuel cylinders with established safety protocols, secure mounting mechanisms, a custom manifold-based hydrogen fuel transition assembly, industrial-grade one-way valves, and hydrogen-compatible fuel control systems. To prevent the accumulation of gas, a special gas injection system secures continuous air flow inside the engine section, thereby preventing the accumulation of hydrogen. Innovating with customized fire-retardant, hydrogen-grade non-return valves using indigenous technology, the system ensures fire and leakage resistance, strategically integrated at junctions and chamber inlets. Figure 13 schematically shows the restructuring of a conventional maritime boat or naval ship engine into a direct H_2-ICE. Relevant technological links are provided in Appendix-B.

https://doi.org/10.24868/11196

Vehicle Name: *Maruti Suzuki Zen* **Engine Type: BS-IV**



Vehicle Name: *Maruti WagonR* **Engine Type: BS-VI**

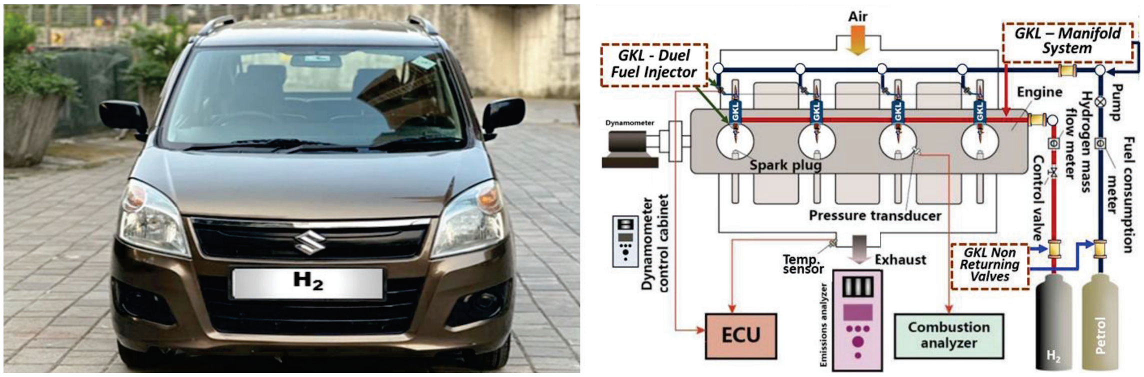


Figure 11: The engine schematic design powering the H_2 fueled four-wheeler vehicles.

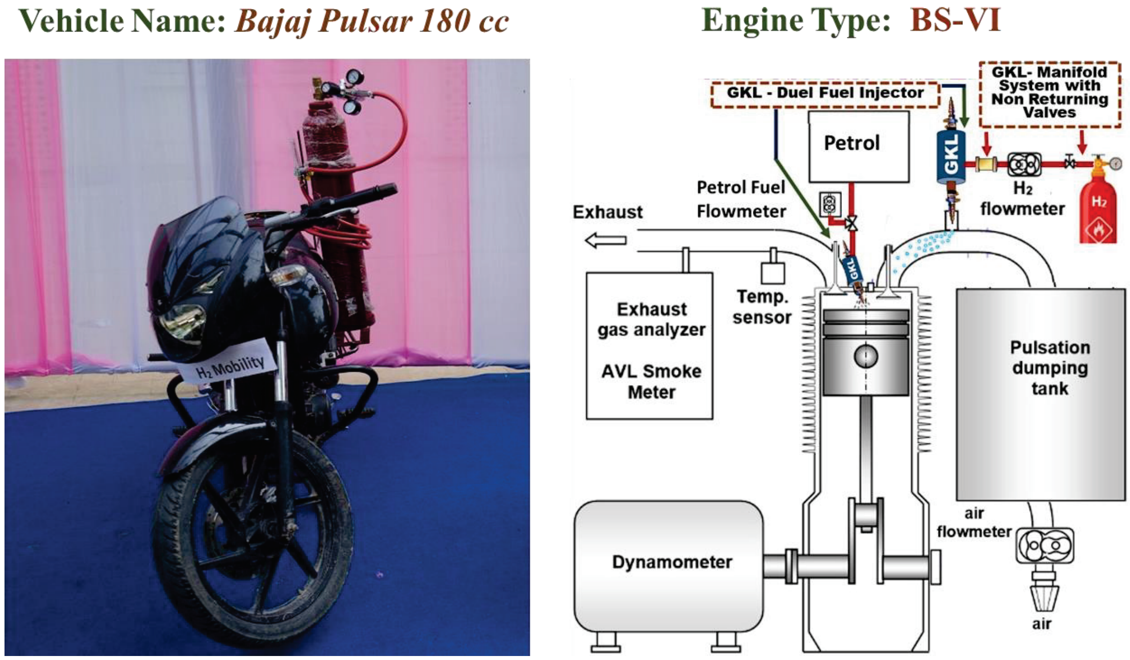


Figure 12: The engine schematic alongside a captivating showcase of the H_2 fueled two-wheeler vehicle.

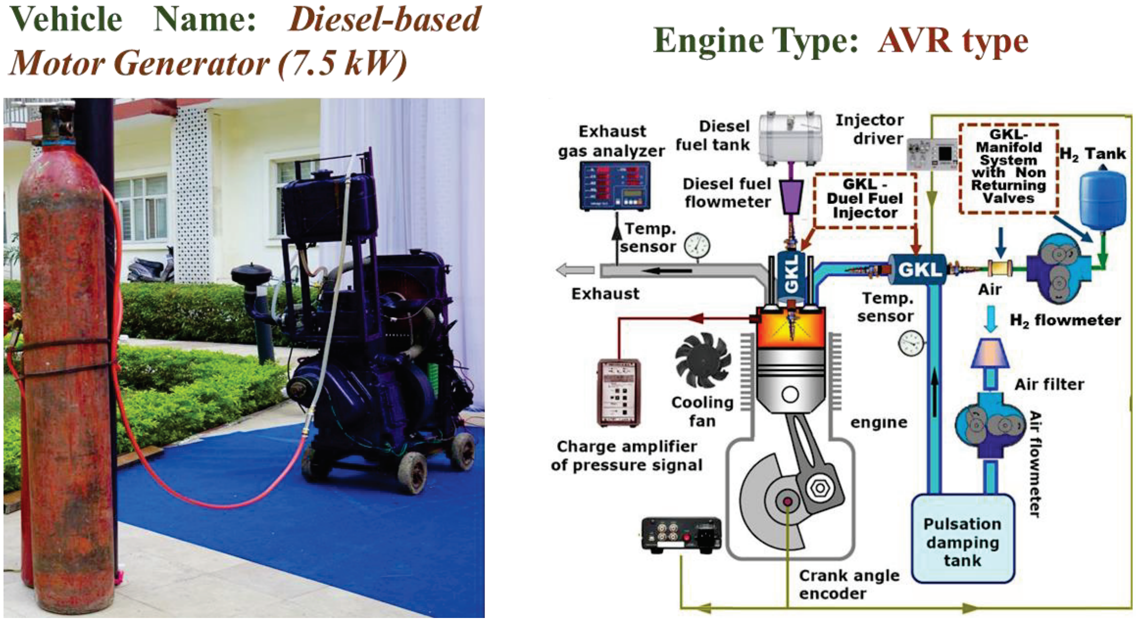


Figure 13: The detailed engine schematic alongside a demonstration of the hydrogen-powered diesel engine

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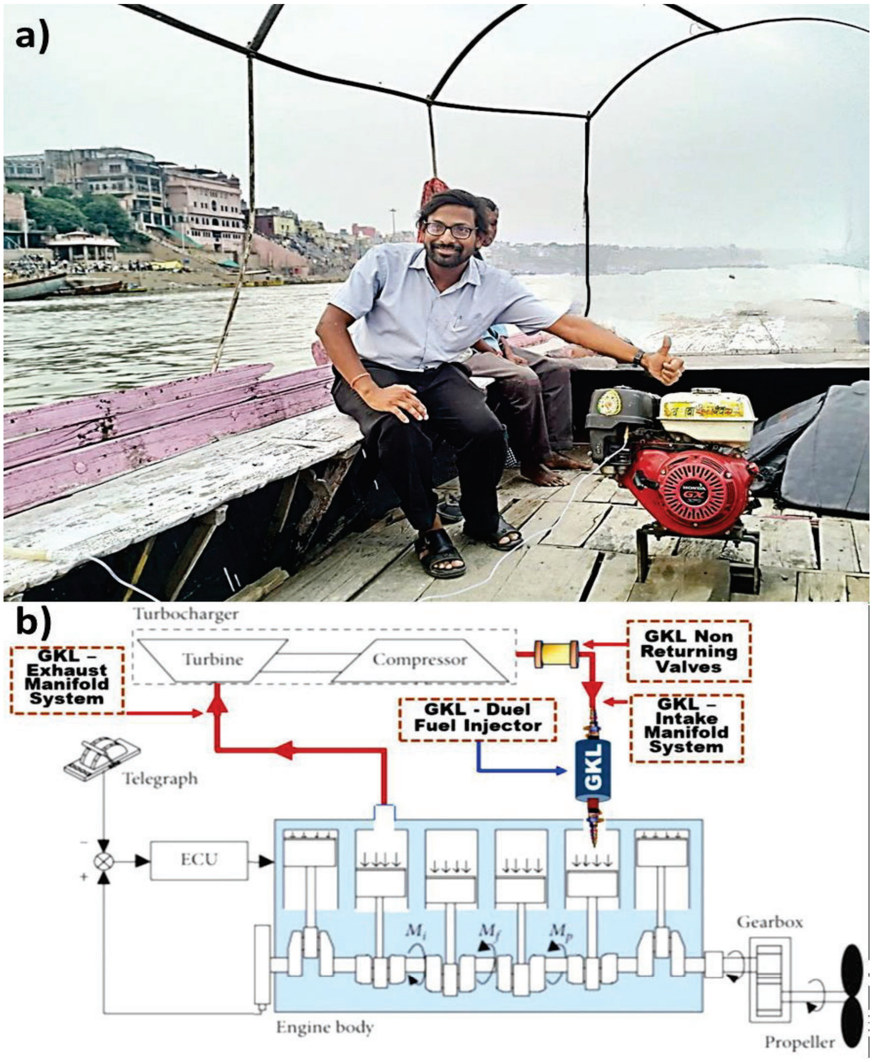

Figure 14: (a) Block diagram of Strategical reconfiguration and assembly of conventional propulsion-based boat engine into direct H_2 –IC Engine; (b) Revolutionizing Waterways: H_2-Powered Boat Navigation on the **Ganges** River.

4. Challenges

4.1. Safety

Liquid hydrogen, with its minuscule molecular structure and high expansion coefficient, undergoes rapid expansion, intensifying its combustible nature. This rapid expansion serves to dilute the concentration of hydrogen in the surrounding air, reducing the potential for danger while increasing the size of flammable clouds. With a surprisingly low energy barrier to combustion in air (0.017 mJ) and wide flammability range (4-74%), hydrogen stands as a prime candidate for being ignited by even the slightest spark (Ratnakar *et al.* 2021). Furthermore, once ignited, extinguishing hydrogen flames proves to be a very difficult task. For safety, the GKL team had implement a specialized gas injection system designed specifically to efficiently disperse any hydrogen gas that might accumulate in the engine chamber (*viz.* section 3.4). This system confirms an unceasing airflow, preventing hydrogen build-up. The GKL team is also using custom-made non-returning valves that are fireproof and leak-resistant, tactically positioned in crucial junctions and chamber inlets.

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4.2. Storage

The shift towards green hydrogen for sustainable energy introduces complex storage challenges that must be addressed for widespread adoption. Effective storage methods are vital, particularly in overwhelming limitations like reactor efficiency and catalyst advancement in solar-driven photocatalytic hydrogen production. Figure 15 structures various hydrogen storage technologies, predominantly remain economically and safely unviable for naval applications. Recent studies have emphasized the need to increase storage capacity through technological advancements, including the enhancement of batteries and capacitors using nanomaterials (Ahmad *et al.* 2023). These revelations elucidate the pivotal role of storage in streamlining the utilization of green hydrogen, notably within domains like maritime and naval applications. Through the incorporation of quantum technology in storage frameworks, remedies can be formulated to counteract safety apprehensions, metal embrittlement predicaments, and heighten overall efficacy in harnessing green hydrogen sourced from marine environments. This comprehensive methodology tackles the multifaceted obstacles linked with hydrogen storage, laying the groundwork for a more sustainable energy terrain.

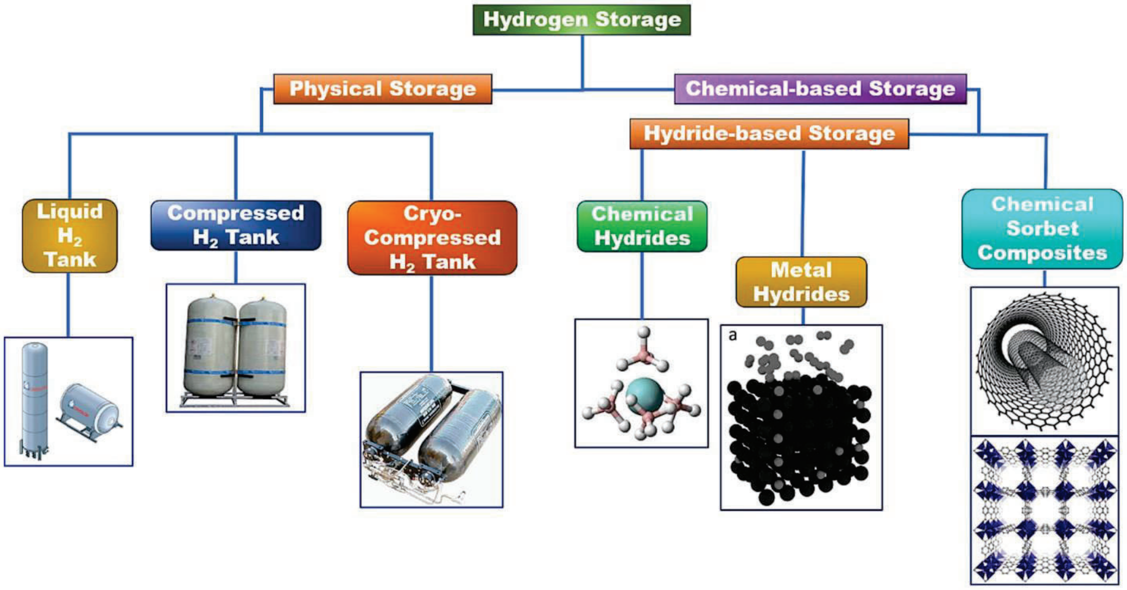

Figure 15: Currently available various methodologies for safe and efficient hydrogen fuel storage. Reprinted with permission from *ref.* Phukan *et al. 2024*. Copyright 2024 Elsevier

The challenge of storing natural gases, encompassing hydrogen, methane, and higher analogues like propane to pentane, persists due to various risk factors. Gas clathrates, a natural storage mechanism, have emerged as a significant methodology, inherently designed by nature. However, replicating these conditions for gas storage presents challenges, requiring lower temperatures and several bars of pressure. Instead of attempting to form clathrate hydrates solely from pure H_2, previous researchers have proposed blending hydrogen with natural gases. This approach has been experimentally validated to facilitate clathrate formation under milder conditions (Ahn *et al.* 2020) and also under Quantum Encapsulation of the QCs as mentioned in the section 3.3.

4.3. Metal Embrittlement

In the field of green hydrogen generation, the issue of metal embrittlement within hydrogen domains emerges as a daunting challenge that requires solutions to maintain the safety and stability of the infrastructure. The invasion of hydrogen atoms into the metal structure causes the metal embrittlement, leading to hydrogen-induced cracks and subsequent breakdown of the material (Sun *et al.* 2024). The maximum embrittlement of metals occurs at the 20 and 100 bar of the partial pressure of H_2 (Barthélémy 2006)). This phenomenon is of utmost significance in the marine and naval sectors where constructions endure ongoing being exposed to extreme environmental conditions. Measures to alleviate this predicament encompass incorporating alloys with elements capable of capturing hydrogen atoms, adopting surface modifications to establish shielding barriers, and enforcing stringent examination and upkeep procedures essential for forestalling catastrophic breakdowns in hydrogen systems. By grasping the intricacies of metal embrittlement mechanisms and carrying out pre-emptive actions, the marine and naval sectors can efficaciously leverage the potential of Quantum technology for sustainable green energy generation while safeguarding operational safety and dependability (*cf.* section 3.3).

4.4. Transportation

Transporting hydrogen is concerned with challenges due to its low density and flammability. Currently, it is mainly transported as a liquid in pipelines or super-insulated tanker trucks, which require cryogenic temperatures (Di Nardo *et al.* 2023). Liquefaction costs more than 30% of the energy content of hydrogen and is expensive (Osman *et al.* 2022). Losses from evaporation during storage are further exacerbated. Another method is to compress gaseous hydrogen to high pressure for transport in tube trailers, which are limited by regulations to 250 bar, but exemptions allow for higher pressures. Recent advances in composite storage vessels have increased carrying capacity. The GKL has also derived a newer Hydrogen injection system for efficient use of the fuel gas used as illustrated in section 3.4.

4.5. Other Naval Challenges

The above sections have discussed, the important challenges that are common to all the domains, However, when one thinks of marine environment one has to factor in many other challenges as enumerated, which will be factored in when one moves from the Pilot Plant to Industrial Scale deployment.

(a) Marine corrosion
(b) Shock
(c) Vibration
(d) Noise
(e) EMI/EMC
(f) Ship motions
(g) Redundancy
(h) Reliability.

Multiple parameters of these factors have been significantly improved by the newer gas injection methodology as derived by the GKL scientists, mentioned in section 3.4; however, further improvements are indispensable to increase the engine agility and operational robustness.

5. Way Ahead and Conclusions

As part of the way ahead strategy, the authors and the respective GKL team feel that they have achieved Technology Readiness Level of 5, and are now planning to build a Pilot Plant that will qualify them to move into producing Green Hydrogen at the industrial scale.

In conclusion, the efforts in sustainable energy production, especially solar and green hydrogen development, represent a significant step forward in addressing the pressing global issues of environmental degradation and energy in the management of sustainability. By integrating cutting-edge quantum mechanics with other engineering techniques, the authors have overcome challenges in various aspects related to safety concerns, storage limitations and metal fragility issues to produce energy-efficient a durable and environmentally friendly technology. The research efforts have yielded promising results, as evidenced from the successful lab-scale demonstrations and real-world applications on various automotive and river platforms.

By integrating solar green hydrogen technology into the maritime industry, the authors want to provide a relatively more efficient system for the running of the naval facilities, emphasizing sustainability and reducing C-emissions. The successfully proven technologies in national and international forums highlight the potential for transformation across sectors, promoting economic growth and environmental stewardship. In essence, the journey exemplifies the power of innovation, collaboration and a strong commitment to meet complex global challenges. As the authors continue to refine and expand the technology infrastructure, their unwavering commitment is destined to build a sustainable and resilient future.

Acknowledgements

Mr. S. J. Phukan and Mr. S. Goswami would like to thank Dr. *rer. nat.* Somenath Garai, Head of Green Keplerate Laboratory (B.H.U., Varanasi), for his support and knowledge support throughout the journey to achieve the Technology Readiness Level 5 (TRL 5) till date. They also appreciate the financial support given to them by the Department of Science and Technology, DST Govt. of India as well as Ministry of Mines and BHU-IoE-SEED Grant. Authors would like to thank Department of Chemistry, Institute of Science, Banaras Hindu University, Varanasi for enabling use of their laboratories and guidance.

Reference

Ahmad, A., Shaheen, S., Majeed, S., Pervaiz, M., Saeed, Z., Younas, U., Javed, M.S., Luque, R., and Gnanasekaran, L., 2023. RETRACTED: Recent developments in metal/metalloid nanomaterials for battery applications; a comparative review. *Fuel*, 340, 127399.

Ahn, Y.-H., Moon, S., Koh, D.-Y., Hong, S., Lee, H., Lee, J.W., and Park, Y., 2020. One-step formation of hydrogen clusters in clathrate hydrates stabilized via natural gas blending. *Energy Storage Materials*, 24, 655–661.

Apte, S.K., Garaje, S.N., Naik, S.D., Waichal, R.P., Baeg, J.-O., and Kale, B.B., 2014. Quantum confinement controlled solar hydrogen production from hydrogen sulfide using a highly stable CdS $_{0.5}$ Se $_{0.5}$ /CdSe quantum dot–glass nanosystem. *Nanoscale*, 6 (2), 908–915.

Attia, Y. and Samer, M., 2017. Metal clusters: New era of hydrogen production. *Renewable and Sustainable Energy Reviews*, 79, 878–892.

Bader, N., Bleischwitz, R., Madsen, A.N., and Andersen, P.D., 2008. EU Policies and Cluster Development of Hydrogen Communities. *Bruges European Economic Research papers*, 14, 1–67.

Bajorowicz, B., Kobylański, M.P., Gołąbiewska, A., Nadolna, J., Zaleska-Medynska, A., and Malankowska, A., 2018. Quantum dot-decorated semiconductor micro- and nanoparticles: A review of their synthesis, characterization and application in photocatalysis. *Advances in Colloid and Interface Science*, 256, 352–372.

Barthélémy, H., 2006. Compatibility of metallic materials with hydrogen. Presented at the Air Liquide.

Cellkraft Fuel Cell Products: Factsheets_Fuelcells, n.d.

Chu, S., Cui, Y., and Liu, N., 2017. The path towards sustainable energy. *Nature Materials*, 16 (1), 16–22.

Chu, S. and Majumdar, A., 2012. Opportunities and challenges for a sustainable energy future. *Nature*, 488 (7411), 294–303.

Cook, T.R., Dogutan, D.K., Reece, S.Y., Surendranath, Y., Teets, T.S., and Nocera, D.G., 2010. Solar Energy Supply and Storage for the Legacy and Nonlegacy Worlds. *Chemical Reviews*, 110 (11), 6474–6502.

Di Nardo, A., Calabrese, M., Venezia, V., Portarapillo, M., Turco, M., Di Benedetto, A., and Luciani, G., 2023. Addressing Environmental Challenges: The Role of Hydrogen Technologies in a Sustainable Future. *Energies*, 16 (23), 7908.

Jia, R., Gui, Q., Sui, L., Huang, Y., Lu, H., Dong, H., Ma, S., Gan, Z., Dong, L., and Yu, L., 2021. Active sites provided by the surface autocatalytic effect and quantum confinement for stable and efficient photocatalytic hydrogen generation. *Journal of Materials Chemistry A*, 9 (26), 14768–14774.

Kibsgaard, J., Chen, Z., Reinecke, B.N., and Jaramillo, T.F., 2012. Engineering the surface structure of MoS2 to preferentially expose active edge sites for electrocatalysis. *Nature Materials*, 11 (11), 963–969.

Kundu, S. and Patra, A., 2017. Nanoscale Strategies for Light Harvesting. *Chemical Reviews*, 117 (2), 712–757.

Li, S., Liu, S., Liu, S., Liu, Y., Tang, Q., Shi, Z., Ouyang, S., and Ye, J., 2012. $\{Ta_{12}\}/\{Ta_{16}\}$ Cluster-Containing Polytantalotungstates with Remarkable Photocatalytic H_2 Evolution Activity. *Journal of the American Chemical Society*, 134 (48), 19716–19721.

Lodh, J., Mallick, A., and Roy, S., 2018. Light-driven carbon dioxide reduction coupled with conversion of acetylenic group to ketone by a functional Janus catalyst based on keplerate $\{Mo_{132}\}$. *Journal of Materials Chemistry A*, 6 (42), 20844–20851.

Marouani, I., Guesmi, T., Alshammari, B.M., Alqunun, K., Alzamil, A., Alturki, M., and Hadj Abdallah, H., 2023. Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future. *Processes*, 11 (9), 2685.

Martin-Sabi, M., Soriano-López, J., Winter, R.S., Chen, J.-J., Vilà-Nadal, L., Long, D.-L., Galán-Mascarós, J.R., and Cronin, L., 2018. Redox tuning the Weakley-type polyoxometalate archetype for the oxygen evolution reaction. *Nature Catalysis*, 1 (3), 208–213.

Mehta, A., Mishra, A., Basu, S., Shetti, N.P., Reddy, K.R., Saleh, T.A., and Aminabhavi, T.M., 2019. Band gap tuning and surface modification of carbon dots for sustainable environmental remediation and photocatalytic hydrogen production – A review. *Journal of Environmental Management*, 250, 109486.

Mitra, T., Miró, P., Tomsa, A., Merca, A., Bögge, H., Ávalos, J.B., Poblet, J.M., Bo, C., and Müller, A., 2009. Gated and Differently Functionalized (New) Porous Capsules Direct Encapsulates' Structures: Higher and Lower Density Water. *Chemistry – A European Journal*, 15 (8), 1844–1852.

Müller, A., Das, S.K., Talismanov, S., Roy, S., Beckmann, E., Bögge, H., Schmidtmann, M., Merca, A., Berkle, A., Allouche, L., Zhou, Y., and Zhang, L., 2003. Trapping Cations in Specific Positions in Tuneable"Artificial Cell" Channels: New Nanochemistry Perspectives. *Angewandte Chemie International Edition*, 42 (41), 5039–5044.

Müller, A., Krickemeyer, E., Bögge, H., Schmidtmann, M., Roy, S., and Berkle, A., 2002. Changeable Pore Sizes Allowing Effective and Specific Recognition by a Molybdenum-Oxide Based "Nanosponge": En Route to Sphere-Surface and Nanoporous-Cluster Chemistry. *Angewandte Chemie International Edition*, 41 (19), 3604–3609.

Nohra, B., El Moll, H., Rodriguez Albelo, L.M., Mialane, P., Marrot, J., Mellot-Draznieks, C., O'Keeffe, M., Ngo Biboum, R., Lemaire, J., Keita, B., Nadjo, L., and Dolbecq, A., 2011. Polyoxometalate-Based Metal Organic Frameworks (POMOFs): Structural Trends, Energetics, and High Electrocatalytic Efficiency for Hydrogen Evolution Reaction. *Journal of the American Chemical Society*, 133 (34), 13363–13374.

Osman, A.I., Mehta, N., Elgarahy, A.M., Hefny, M., Al-Hinai, A., Al-Muhtaseb, A.H., and Rooney, D.W., 2022. Hydrogen production, storage, utilisation and environmental impacts: a review. *Environmental Chemistry Letters*, 20 (1), 153–188.

Phukan, S.J., Goswami, S., Bhowmik, S., Sah, N.K., Sharma, M., Pramanik, P., Pathak, C., Roy, M., Pai, R.K., and Garai, S., 2024. Contemporary Progress on Photo-induced Green Hydrogen Evolution: Potential, Challenges, and Perspectives for the Hydrogen Energy-based Economy -An Updated Review. *Fuel*, 361, 130654.

Ramalingam, G., Kathirgamanathan, P., Ravi, G., Elangovan, T., Kumar, B.A., Manivannan, N., Kasinathan, K., Ramalingam, G., Kathirgamanathan, P., Ravi, G., Elangovan, T., Kumar, B.A., Manivannan, N., and Kasinathan, K., 2020. Quantum Confinement Effect of 2D Nanomaterials. *In*: *Quantum Dots - Fundamental and Applications*. IntechOpen.

Rao, V.N., Reddy, N.L., Kumari, M.M., Cheralathan, K.K., Ravi, P., Sathish, M., Neppolian, B., Reddy, K.R., Shetti, N.P., Prathap, P., Aminabhavi, T.M., and Shankar, M.V., 2019. Sustainable hydrogen production for the greener environment by quantum dots-based efficient photocatalysts: A review. *Journal of Environmental Management*, 248, 109246.

Ratnakar, R.R., Gupta, N., Zhang, K., Van Doorne, C., Fesmire, J., Dindoruk, B., and Balakotaiah, V., 2021. Hydrogen supply chain and challenges in large-scale LH2 storage and transportation. *International Journal of Hydrogen Energy*, 46 (47), 24149–24168.

Rausch, B., Symes, M.D., Chisholm, G., and Cronin, L., 2014. Decoupled catalytic hydrogen evolution from a molecular metal oxide redox mediator in water splitting. *Science*, 345 (6202), 1326–1330.

Seppälä, L., 2023. Futures of shipbuilding in the 22nd century : Explorative industry foresight research of the long-range futures for commercial ship-building, using elements of OpenAI. University of Turku.

Sharma, S., Agarwal, S., and Jain, A., 2021. Significance of Hydrogen as Economic and Environmentally Friendly Fuel. *Energies*, 14 (21), 7389.

Sun, B., Zhao, H., Dong, X., Teng, C., Zhang, A., Kong, S., Zhou, J., Zhang, X.-C., and Tu, S.-T., 2024. Current challenges in the utilization of hydrogen energy-a focused review on the issue of hydrogen-induced damage and embrittlement. *Advances in Applied Energy*, 14, 100168.

Wang, Y., Liu, X., Liu, J., Han, B., Hu, X., Yang, F., Xu, Z., Li, Y., Jia, S., Li, Z., and Zhao, Y., 2018. Carbon Quantum Dot Implanted Graphite Carbon Nitride Nanotubes: Excellent Charge Separation and Enhanced Photocatalytic Hydrogen Evolution. *Angewandte Chemie*, 130 (20), 5867–5873.

Xu, L., Yuan, S., Ma, L., Zhang, B., Fang, T., Li, X., and Song, J., 2021. All-inorganic perovskite quantum dots as light-harvesting, interfacial, and light-converting layers toward solar cells. *Journal of Materials Chemistry A*, 9 (35), 18947–18973.

Xu, Q., Cheng, B., Yu, J., and Liu, G., 2017. Making co-condensed amorphous carbon/g-C3N4 composites with improved visible-light photocatalytic H2-production performance using Pt as cocatalyst. *Carbon*, 118, 241–249.

Appendix-A

This technology has received numerous praises, with one of the most significant recognitions from HPCL. The technological innovations garnered significant acclaim during these events, as the authors unveiled avant-garde green mobility solutions to a discerning audience. Some of the technology highlights are as follows:

National Highlights

- https://ddnews.gov.in/sci-tech/quantum-technology-promises-green-hydrogen-revolution
- https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1966488
- https://timesofindia.indiatimes.com/city/varanasi/experts-discuss-green-h2-fuels-production-utilisation/articleshow/104358063.cms
- https://government.economictimes.indiatimes.com/news/technology/cutting-edge-quantum-tech-backed-green-hydrogen-production-unveiled-to-power-green-future/104336121
- https://sputniknews.in/20231011/india-unveils-cutting-edge-quantum-technology-to-boost-usage-of-green-hydrogen-4737808.html
- https://newsstation.media/latest-news/cutting-edge-quantum-technology-unveiled-for-green- hydrogen-production-paving-the-way-for-a-sustainable-future/
- https://mysuruinfrahub.com/quantum-backed-technology-for-green-hydrogen-production/

International Highlights

- https://www.chronicleindia.in/current-affairs/9805-quantum-technology-promises-a-revolution-in-green-hydrogen-production
- https://opengovasia.com/indias-quantum-powered-green-hydrogen/
- https://carbon-pulse.com/228388/
- https://bwsustainabilityworld.com/bhu-develops-tech-that-can-boost-green-hydrogen-production/

Appendix-B

YouTube Links for the showcasing of the Green H2 production and H2-Mobility technologies.

Particulars	Link
Lab-Scale Green H_2 Production Demonstration	https://youtu.be/uIKdd_5Uzfw
Green H_2 Fueled WagonR (BS6 engine) in the Campus of B.H.U.	https://youtu.be/y59XDwvWWZw
Green H_2 Fueled Boat (BS4 engine) in the Holy River Ganges	https://youtu.be/-jLBpJ3GOHk
Green H_2 fueled Diesel Generator	https://youtu.be/s6aamtAgGXg
Green H_2-Powered Maruti Zen (BS4 engine) car	https://youtu.be/WQJsCqH-7_4
Green H_2 Fueled Bajaj CT100 (BS4 engine)	https://youtu.be/6sjd101fheE
Green H_2 Fueled Bajaj Pulsar 160cc (BS6 engine)	https://youtu.be/Hvqr-pcKh48
Technology Demonstration & Recognition Snapshots	https://tinyurl.com/ysf95nbj
Some Important Technological Details	https://tinyurl.com/meu2xz3w

Driving the Hydrogen Fuelled Boat in the River Ganges

https://www.youtube.com/watch?v=-jLBpJ3GOHk

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Towards a data-driven naval maintenance organisation: the importance of a social roadmap

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Synopsis

The Royal Netherlands Navy (RNLN) aims to bring new platforms into service across its force structure, including a combat support ship (CSS), anti-submarine warfare frigates (ASWF), air defenders, submarines, and various auxiliary vessels. Constant pressure to reduce ships' crews and the increasing complexity of systems aboard naval ships create challenges for the maintenance of these future vessels. This necessitates the development of improved shore support, provided by the Directorate of Materiel Sustainment (DMI). The rise in the number of sensors on board and the emergence of learning algorithms is essential to facilitate this. It offers an opportunity to identify failures at an earlier stage, better plan maintenance, and reduce (corrective) workload aboard ships through data analysis. Consequently, the RNLN is actively transitioning from its traditional approach of planned periodic maintenance with a high corrective workload towards embracing data-driven maintenance. This shift encompasses the increase of condition-based maintenance (CBM) and the adoption of predictive maintenance (PdM) based on advanced condition monitoring and data analysis techniques.

This paper adopts a design science research approach, beginning with the identification and motivation of the problem. We then delve into an examination of the organizational challenges associated with the introduction of data-driven maintenance and explore solutions outlined in existing literature. Within this study, we employ four lenses as guiding design principles for the development of the social roadmap: maturity models, work system approaches, technology acceptance models, and change management models. We then proceed to outline the initial steps towards designing a social roadmap based on six guiding design principles from the four lenses. Furthermore, this paper presents practical examples of developments and challenges encountered in the implementation of data-driven maintenance, shedding light on the social dynamics involved in implementing data-driven maintenance within the RNLN's maintenance organization. By sharing these examples, we aim to provide insights into real-world experiences and considerations for practitioners and researchers. The paper concludes by outlining future steps envisioned for the ongoing implementation of smart maintenance within the RNLN.

Keywords: Organisational transition; Smart Maintenance; Predictive Maintenance; Condition Based Maintenance; Military-Maritime; Royal Netherlands Navy.

1. Data-driven maintenance for the current and future fleet

The Royal Netherlands Navy (RNLN) aims to bring new platforms into service across its force structure, including a combat support ship (CSS), anti-submarine warfare frigates (ASWF), air defenders, submarines, and various auxiliary vessels. With the ongoing pressure to reduce crew sizes aboard ships and the growing complexity of onboard systems, maintaining these future vessels presents significant challenges. Addressing these challenges necessitates the development of improved shore support capabilities, provided by the Directorate of Materiel Sustainment (in Dutch: 'Directie Materiële Instandhouding', abbreviated as DMI).

The integration of an increasing number of sensors onboard ships, combined with the emergence of learning algorithms, offers an opportunity to identify and diagnose failures at an earlier stage, better plan maintenance, and

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Author's Biography

dr. Wieger Tiddens has extensive experience and knowledge on the implementation and development of predictive maintenance. His passion is to achieve the maintenance of tomorrow. Within the Royal Netherlands Navy's Data for Maintenance group, he works on data driven asset management and Predictive Maintenance for the current and future fleet.

Lt (ME) Sophie ten Zeldam MSc has a background as an engineer officer on board of various naval vessels. She has a master's degree in maintenance engineering and operations. Within the Royal Netherlands Navy's Data for Maintenance group, she bridges the gap between operations and development, paving the way for innovative maintenance solutions in the military-maritime domain.

Cdr (ME) ret. Bart Pollmann has fulfilled a lifetime military career in various marine engineering jobs, both at sea and in support and policy roles. From a maintenance perspective, his passion is to develop and implement solutions to improve the maintainability of future navy ships, allowing for trends of increased system complexity and reduced crew sizes.

Dennis Curvers BSc is an experienced Information Management Professional with a background in Chemistry and Quality Management. Complemented with keen analytical skills and a practical approach, he finds his way in getting reliable information to the right people at the right time. Within the Royal Netherlands Navy's Data for Maintenance group, he puts his experience into practice with a focus on Data Acquisition, -Infrastructure and -Governance for the current and future fleet.

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reduce (corrective) workload aboard ships through data analysis. Consequently, the RNLN is actively transitioning from traditional periodic maintenance, characterized by a high reliance on periodic checks and corrective actions, towards a more proactive approach. This shift entails a greater emphasis on condition-based maintenance (CBM) and predictive maintenance (PdM) strategies, based on advanced condition monitoring and data analysis.

Data-driven maintenance offers the opportunities to radically change the view on the RNLN's maintenance process. The application of these approaches of data-driven maintenance is however rather limited in the maritime industry (Tiddens, Braaksma, *et al.*, 2022). Many organisations have a high ambition to accurately predict failures of individual systems in their fleet, but this ambition does not match with the low quality of failure data and the very limited availability of machine (condition or sensor) data.

This also holds for the RNLN. Aiming for a data-driven maintenance organisation triggers the RNLN to collect and store more and more data from its ships. Data has traditionally been stored on-board for only days or weeks. Nowadays, the value of long term (onshore) storage is recognized, not only for maintenance but also as input for the design of new ships. The Defence Vision 2035 (Netherlands Ministry of Defence, 2020) recognizes this and indicates that efforts should be made to prevent the risk of drowning in a sea of information. The defence organisation needs to modernise. This, however, should be achieved from a base that has suffered from years of cutbacks combined with a shortage of personnel for the way the NLMOD (Netherlands Ministry of Defence) is currently organised. Change is therefore needed, both in the RNLN's maintenance organisation, the DMI, as well as in the procurement of new naval ships, which is carried out by the Command of Materiel and IT (COMMIT). The RNLN aims to orchestrate maintenance, new construction projects and maintenance knowledge within the military-maritime domain. Adequate maintenance and close cooperation with civil partners should guarantee the continuity of maritime maintenance. It is therefore essential that COMMIT as designer and the RNLN as user and maintainer work closely together.

The 'Data for Maintenance' (in Dutch: 'Data voor Onderhoud', abbreviated as DvO) initiative therefore set out in 2019 to develop a structured programme to introduce data driven maintenance within the RNLN. Setting up such a structured programme is required since it takes time to identify the technology's potential performance with targeted experiments, to integrate the technology into the existing hardware and processes, and to further improve the quality of analyses via processes of learning-by-doing (van de Kerkhof, 2020).

Figure 1: Artist rendering of a Holland-class ocean-going patrol vessel.

While a significant amount of research has concentrated on the development of data-driven models and techniques (Lee *et al.*, 2014) the successful implementation of data-driven maintenance remains elusive for many organizations (Grubic *et al.*, 2011). Achieving successful implementation of data-driven maintenance necessitates addressing both technical as well as organizational barriers.

On the one hand, there are the technical barriers. These challenges range from sensor techniques for data acquisition and the required data infrastructure to the development of validated (machine learning) algorithms to process this data. In earlier work, Tiddens, Pollmann, et al. (2022) presented the technical roadmap of the DvO-programme. This paper presented how one of the Holland-class ocean-going patrol vessels (Figure 1), the HNLMS

Groningen, has been the 'DvO fieldlab' from day one. The fieldlab is used to develop the DvO programme in five strategy lines: data acquisition, data infrastructure, data governance, data analysis and asset management.

On the other hand, there are organisational (and human) barriers to consider. These challenges seem understudied in current literature. Most research studies within the field of data-driven (or predictive) maintenance predominantly emphasize technical dimensions, often disregarding organizational considerations (Garg and Deshmukh, 2006; Kerkhof *et al.*, 2016; Tiddens, Braaksma, *et al.*, 2022; Veldman *et al.*, 2011). Organizational and human factors involve getting support from top management and creating an environment where change is welcomed in the organization (Bokrantz *et al.*, 2017; Lundgren *et al.*, 2023). They also include dealing with changes in culture and behaviour (Akkermans *et al.*, 2016), managing knowledge and helping employees develop their skills (Akkermans *et al.*, 2016), making sure decision-makers are open to using predictive maintenance technologies (Shafiee, 2015) and designing these technologies with people in mind to improve their well-being (Neumann *et al.*, 2021).

These social and technical implementation barriers cannot be seen in isolation since the interdependencies between the implementation issues are important (Burton *et al.*, 2020). This suggests that the implementation of data-driven maintenance innovations has a greater impact on the interaction between technology and knowledge rather than solely on the technology itself. This dynamic interplay, termed social innovation, accounts for up to 50-75% of the success of innovation initiatives (Volberda *et al.*, 2013).

In the current paper, our focus is on developing an implementation strategy to effectively introduce and promote the adoption of data-driven maintenance within the RNLN organization: a social roadmap. Developing an implementation strategy to effectively introduce data-driven maintenance within the RNLN organization requires identifying relevant criteria and steps. Research on data-driven maintenance implementations recall the importance of including the interdependencies between various implementation issues (Burton *et al.*, 2020). The social roadmap should therefore include all relevant implementation issues and their interdependencies. Most importantly, it should align with the RNLN's technical roadmap for implementing data-driven maintenance (Tiddens, Pollmann, *et al.*, 2022). The development of a social roadmap can be guided by a design science research (DSR) approach. DSR seeks to create innovative artefacts that are useful for coping with human and organizational challenges by following an iterative process of development and testing (Hevner *et al.*, 2004).

Our paper is structured following a DSR approach. Above, the problem is identified and motivated. Section 2 examines the organizational challenges related to the introduction of data-driven maintenance and explores solutions outlined in existing literature. We then proceed in Section 3 to outline the initial steps towards designing a social roadmap. These will be accompanied by practical examples illustrating the challenges and social dynamics associated with implementing smart maintenance within the RNLN. Finally, we conclude by outlining the envisioned future steps for the ongoing implementation of data-driven maintenance within the RNLN.

2. Organisational challenges in the introduction of data-driven maintenance

The implementation of new technology within organizations can be examined through various lenses. In this study, we focus on four lenses: maturity models, work system approaches, technology acceptance models, and change management models. These lenses offer different perspectives on organizational change and technology adoption. By applying these lenses to the specific context of the RNLN, we derive design principles that guide the development of a social roadmap tailored to the specific context of the RNLN. These design principles encompass strategies for assessing organizational readiness, optimizing work systems, understanding user acceptance, and managing organizational change effectively.

2.1. Maturity models

Maturity models are structured frameworks that offer organizations a simple but effective possibility to assess and evaluate their capabilities and practices. Maturity models help to pinpoint crucial elements within a company that are vital for successful implementation and establish a set of criteria necessary to reach a specified level (Wendler, 2012). While these models are valuable for fully integrating new technology throughout an organization by identifying improvement opportunities, they often lack adequate validation (Wendler, 2012). Within the RNLN's technical roadmap, the DvO-programme encompasses four maturity levels: concept development on HNLMS Groningen, concept evaluation on HNLMS Den Helder, concept realisation on the ASW-frigates, and concept optimalisation on the future submarines. Kerkhof et al. (2016) developed a descriptive maturity model consisting of five steps for the implementation of CBM, which can be extended to data-driven maintenance, by asset owners like the RNLN. Their model underscores eight categories of organisational aspects crucial for data-driven maintenance implementation: strategy and goals; decisions, structure; budget and capacity; processes and documentation; governance; knowledge and skills; and culture.

Mooij (2023) conducted a preliminary maturity scan within the RNLN's maintenance organisation using the descriptive maturity model of Kerkhof et al. (2016). The RNLN has a long history of structured use of condition monitoring technologies, including vibration monitoring and oil analysis conducted by a specialized department. This established practice has played a pivotal role in laying the groundwork for the introduction of data-driven maintenance within the organization. Mooij's scan showed that CBM is perceived as a proven technology but is not yet structurally embedded in all maintenance decisions. Further, Mooij posited that the RNLNL's maturity can be described on the continuum between 'reactive CBM' (level 2 out of 5) and 'planned CBM' (level 3 out of 5) since a significant part of the maintenance is still focused on corrective maintenance. To integrate data-driven maintenance, Mooij (2023) identified a clear need for a structured work process embedded within the organisational structure. This process should clarify the new maintenance decision-making process, integrating traditional indicators like calendar time and running hours with (near) real time condition indicators from data-driven models.

2.2. Work-system approaches

As the organization advances along the maturity ladder, the adoption of data-driven maintenance brings about transformation within the maintenance organisation. These evolving organizational characteristics should be incorporated into the implementation strategy (van Oudenhoven *et al.*, 2023). To identify factors influencing the acceptance of data-driven maintenance, Van Oudenhoven et al. (2023) utilize an adapted work system approach (Carayon, 2009). Their approach considers five domains: technology, focusing on data-driven decision support; individual, encompassing one's physical and psychological characteristics; tasks, relating to the job at hand; organization, encompassing the organizational conditions under which tasks are performed; and environment, pertaining to the physical surroundings. The interplay among these domains influences an individual's behaviour and performance, which can be influenced by the introduction of new tools and technologies, such as data-driven maintenance. Van Oudenhoven et al. propose four key support factors: establishing an appropriate level of human control for decision-making, fostering trust between decision-makers and the model, providing adequate cognitive resources to handle the system's high cognitive demands, and assigning decision-making responsibilities and capabilities to the appropriate organizational unit.

Berket (2023) applied van Oudenhoven et al.'s work system approach to study how the five domains influence the acceptance of the decision support tool that is developed within the DvO-programme. Berket found that the domains 'individual', 'organisation', and 'tasks' have a negative effect on the usage of the application and outweigh the positive loads in the work system. Berket suggests that the most effective way to facilitate usage within engineering sections in the DMI organisation is to introduce a data analyst role within each engineering section and provide training to improve technological competence within the organisation. These interventions reduce demands in three domains: 'task', due to a high workload, data-driven maintenance and learning to work with a new application is currently seen as an extra activity; 'individual', engineers do not often have a high affinity with data and are not digital literate; and finally 'technology', data-driven maintenance is still immature and a new decision support tool is therefore experienced as incomplete and difficult to use.

Vermeulen (2023) also applied van Oudenhoven et al.'s work system approach to change agents that are used within the DvO-programme. Alike Mooij (2023) and Berket (2023), Vermeulen recognizes the pitfalls of a bureaucratic organisation that suffered from long-term budget cuts, which has a high average workforce age and a high perceived workload. Vermeulen (2023) gestured towards the idea that little knowledge about how to use data seems available within the organization and data ambassadors are still divided when looking at their attitude towards data usage. Some really see the potential where others are not yet convinced that right now is the time to start working data driven. Vermeulen (2023) concludes that the concept of data ambassadors can be better supported by improving the selection process of potential ambassadors. This can be realised by including middle management in the selection process, selecting persons that fit the role and only apply the concept to departments with a high data availability. Finally, these ambassadors should be better supported by middle management and the DvO-programme should better support them in specific post-intervention meetings or training activities.

2.3. Technology acceptance models

Technology acceptance models are among the most extensively utilized frameworks for understanding IT adoption and have demonstrated high predictability in IT adoption and usage (Venkatesh and Bala, 2008). The

Unified Theory of Acceptance and Use of Technology (UTAUT) posits that performance expectancy, social influence, and effort expectancy influence an individual's behavioural intention to use a technology (Venkatesh *et al.*, 2003). Subsequently, behavioural intention and facilitating conditions determine technology usage, while individual difference variables such as age, gender, experience, and voluntariness moderate the relationships within the UTAUT model.

Brus (2022) used the UTAUT model to identify social barriers for implementing data-driven maintenance within the RNLN. Based on 12 interviews, he found that employees seem generally sceptic about new innovations and seem to question whether the RNLN's organisation is suitable for implementing data-driven maintenance. Further, since the programme is relatively new within the organisation, many employees are unacquainted with the programme and have a large variety of expectations of data-driven maintenance. Finally, employees view data-driven maintenance as a new addition to their current work activities, instead of a tool that is integrated in their current work processes.

2.4. Change management models

Kotter's (1995) eight-step process for achieving successful organizational change provides a structured approach to overcoming organizational difficulties. This process emphasizes creating a sense of urgency and vision for change within the organization. Effective implementation relies on strong leadership and motivation to overcome resistance, with top management playing a pivotal role. Following Kotter's approach, to enhance acceptance of data-driven maintenance and reduce scepticism, organizations should focus on achieving incremental successes through small projects and communicate these short-term wins throughout the company. Kotter's eight sequential steps include creating a sense of urgency, building a guiding coalition, forming a strategic vision, enlisting a volunteer army, enabling action by removing barriers, generating short-term wins, sustaining acceleration, and instituting change.

Additionally, Maali et al. (2022) modeled the relationships between key change management strategies and the level of successful change adoption. Their study underscores the importance of implementing five change management strategies concurrently: change agent effectiveness, establishing a realistic timeframe, communicating benefits, setting measured benchmarks, and senior leadership commitment. Among these strategies, change agent effectiveness and a establishing a realistic timeframe are identified as the two most effective organisational change management strategies (Maali *et al.*, 2022).

3. The development of a Social Roadmap for the adoption of data-driven maintenance within the RNLN

Six guiding design principles have been derived from the four perspectives on organizational change and technology adoption discussed in Section 2. Table 1 illustrates how elements from these four perspectives are integrated into the six guiding design principles. This section outlines the initial steps towards developing a social roadmap based on these principles.

3.1. Principle 1: Combining vision and urgency for change with opportunities to create an overall strategy

The DvO-programme originated from a convergence of opportunities that coincided in a specific starting moment in time: April 2019. This convergence included technical opportunities in data storage and analysis within the RNLN, a visionary outlook from top management regarding the utilization of these technical capabilities in an organisational programme, a halt on budget cuts allowing for innovation within the RNLN and allocating budget, and, most importantly, the formation of a multidisciplinary leading team, bypassing the usual organizational formalities (such as a formal place in the organization and job positions).

The first step of the DvO-programme has taken an integrated approach by creating a vision for implementing data-driven maintenance within the organisation. This aligns with Kotter's (1995) principles by creating a sense of urgency and shaping a strategic vision for organisational change. This resulted in a broadly accepted technical roadmap of the DvO-programme (Figure 2) serves as an instrument to promote the adoption of data-driven maintenance tools. The implementation timeframe, spanning from 2019 to 2035 as depicted in the roadmap, is crucial for setting realistic expectations and ensuring progress aligns with organizational goals. This timeframe, outlined by Maali et al. (2022), corresponds to the maturity steps illustrated in the roadmap.

The roadmap is utilized in presentations aimed at maintaining commitment from senior leadership, in line with Maali et al.'s change management strategy, and move from top management support to top management engagement. Additionally, it facilitates the dissemination of information within the organization, fostering a sense of urgency and a shared vision for change, consistent with Kotter's principles.

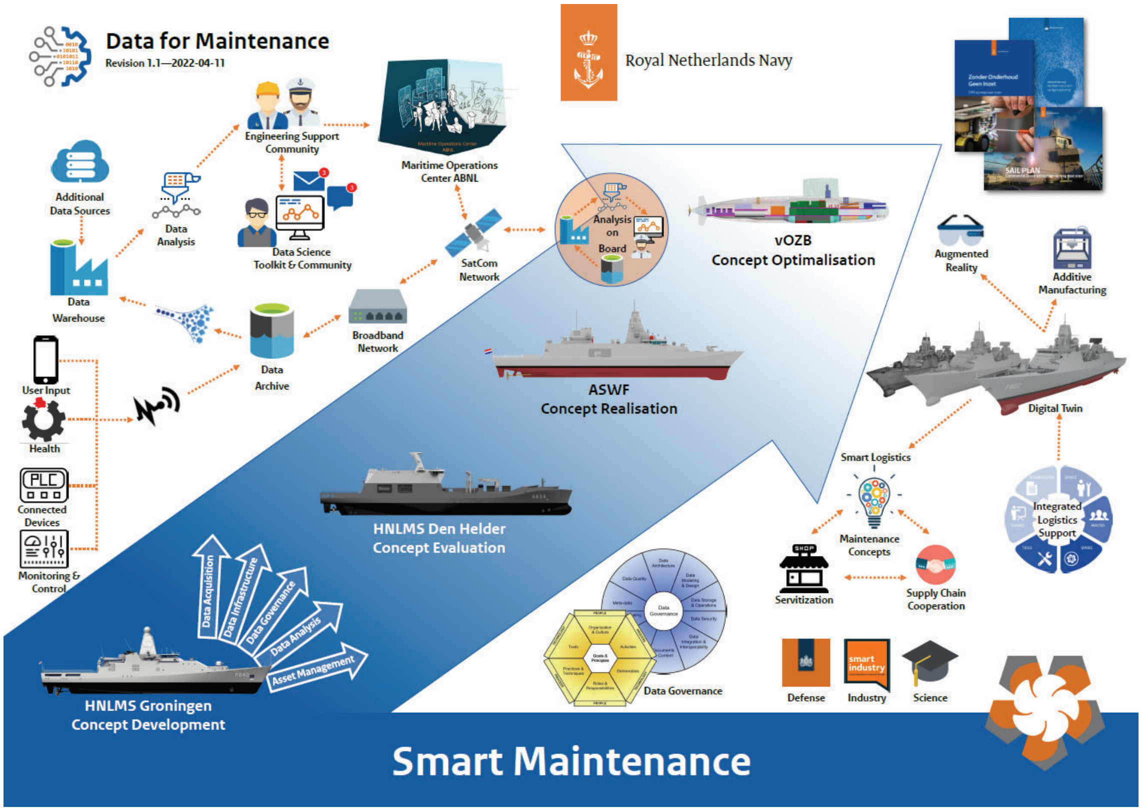

Figure 2. The RNLN's Smart Maintenance technical roadmap of the DvO-programme, see Tiddens, Pollmann, et al. (2022) for a detailed description.

3.2. Principle 2: Tailoring implementation strategies to target user groups and supporting stakeholders

The objective is to direct the implementation initiative towards potential users of data-driven solutions while ensuring continued stakeholder involvement. The UTAUT theory underscores that technology usage is determined by behavioural intention and facilitating conditions, with individual differences moderating these relationships. Potential users include maintenance engineers overseeing the how, when, and why of maintenance activities within the DMI and technical specialists within COMMIT (offering advice on modifications and the application of knowledge for future fleet design), and technical personnel aboard ships (at the organic maintenance level),

Supporting stakeholders, on the other hand, are individuals who do not directly benefit from data-driven tools but are needed to contribute to and facilitate the program. These stakeholders are primarily found within industry partners involved in developing new solutions, standardisation, data exchange, and service-based contracts, COMMIT (providing specifications for new build ships and facilitating design for data-driven maintenance), management overseeing maintenance processes, and IT partners within the organisation.

Different implementation strategies are employed for these user groups and supporting stakeholders. The initial phase of the program has primarily targeted maintenance engineers ashore within the DMI, who are the early adopters of data-driven tools. Subsequently, a specific software tool has been developed to provide insights into the collected data, featuring timeseries plots, descriptive analytics offering insights into system usage aboard ships, and offers the possibility to integrate predictive analytics.

Users: Maintenance engineers within DMI and technical specialists within COMMIT

The initial phase of the program has predominantly concentrated on onshore maintenance engineers within the DMI, primarily with a use-case driven approach (Principle 3), followed by the development of an internally developed decision-support tool. This tool aids maintenance engineers in fault-finding processes utilizing available data, providing descriptive and diagnostic analyses and technical specialist in providing insights in usage of equipment primarily. The primary objective has been to engage early adopters and incorporate their feedback into the DvO-programme. A key takeaway has been the importance of exercising caution in making commitments to ensure sustained engagement of these engineers in the programme: moderation.

Users: Technical personnel aboard naval vessels

For technical personnel onboard ships, a collaborative effort with industry partners is underway to develop an adaptable, comprehensive, and automated analysis solution. This solution is primarily designed to facilitate short-term operational responses and offer detailed system insights using a real-time data archive, in a disconnected environment. Crucially, these data-driven tools are integrated into existing software systems to ensure a seamless user experience. An additional requirement is to ensure that these tools offer similar functionalities to their onshore counterparts to make sure that maintenance engineers that assist in maintenance or fault finding aboard can work with these systems.

Supporting stakeholders: Industry

The transformation towards data-driven maintenance positions within original equipment manufacturers (OEMs) and service providers (SPs) increasingly need to offer services and performance-based contracts, instead of fixed maintenance contracts and selling spare parts, a concept known as servitization. The increasing trend towards servitization underscores the growing importance of facilitating the sharing of relevant data subsets among stakeholders.

Middelbrink (2023) delved into the role of legal and administrative mechanisms in facilitating data exchange between the RNLN, OEMs, and SPs. Middelbrink revealed that barriers to data exchange often stem from misconceptions, particularly regarding the legal framework. Moreover, there exist several unfounded fears surrounding data sharing, intensified by varying perceptions and interests both between and within organizations, leading to a tendency to share less data than possible and/or needed for optimal product support. Middelbrink (2023) emphasizes the necessity of a clear legal framework and open dialogue among parties to establish concrete agreements on data exchange. Such measures not only mitigate uncertainties but also foster trust, a critical component for successful data exchange and collaboration.

Supporting stakeholders: COMMIT (design authority)

The role of COMMIT is critical in defining data-driven requirements for new-build ships and significant modifications, particularly in the context of design for data-driven maintenance. Engineers and project teams must have a realistic understanding of the potential of data-driven technologies. Data-driven tools can facilitate the development of innovative crew and maintenance concepts, while fostering new modes of collaboration with OEMs and SPs, such as through servitization concepts.

Supporting stakeholders: Management overseeing maintenance processes

Management within the DMI plays a crucial role in facilitating the DvO-programme by providing the necessary space for innovation to flourish. This entails ensuring that their organizational structure and work processes are transitioning towards data-driven decision-making practices (Principle 6). One potential approach is to incorporate a dedicated data analyst role within each section, while also making data-driven operations a central theme. Additionally, management serves as a link between the DMI and supporting stakeholders within COMMIT. This ensures alignment and collaboration across different organizational levels, further fostering the success of the innovation initiative.

Supporting stakeholders: IT- partners within the organisation

IT partners within the organization, both in COMMIT and the RNLN play a crucial role in supporting the programme by providing robust solutions for data exchange (e.g., ship-to-shore), data storage and processing, a data analysis platform, and an IT platform capable of running data-driven tools. These technological infrastructures are essential to enable seamless data-driven operations and decision-making.

3.3. Principle 3: Starting small and showing the benefits using small use-cases

Since the start of the programme, use-cases have served as the primary means of addressing organization-submitted challenges. Resolving these use-cases has significantly contributed to the DvO-programme's success in achieving short-term wins, which is in line with Kotter (1995). Resolving use-cases creates a form of merchandise that can be used within the programme or by top management to demonstrate the value of data-driven maintenance. Initially, typical use-cases focused on resolving relatively straightforward fault-finding issues, such as understanding the behaviour of an installation leading up to a failure. However, over time, the focus has shifted towards providing deeper insights into naval ship operations, operational profiles, and insights like optimal settings to minimize fuel consumption (e.g., trim settings).

Collaborating with universities and offering graduate positions has been instrumental in addressing more complex use-cases. Graduates are well-suited to tackle complex problems, as they often have sufficient time available and are required to demonstrate their ability to solve complex issues to obtain their diploma. The DvO-programme provides them with a unique opportunity to work in an innovative department within the RNLN. To date, more than 25 students have contributed to creating data models, solving questions from the organization, and shaping the innovation programme.

3.4. Principle 4: Creating involvement of change agents

To ensure the RNLN has enough maintenance engineers well-versed in using the capabilities of data-driven models, a dedicated course has been established. This course aims to educate engineers from DMI and COMMIT about the DvO-programme and various aspects of data-driven maintenance while enhancing their digital literacy. By equipping engineers with knowledge, attitudes, insights, and basic skills, they can effectively utilize digital solutions. The provision of digital literacy through such courses is an iterative learning process, improving with each iteration. As highlighted by Berket (2023), individuals within the organization appear to have limited familiarity with data and seem to have low digital literacy. Given the embryonic stage of data-driven maintenance, new support tools are often perceived as challenging to use.

In the realm of change management, the significance of change agents is well-recognized. Kotter (1995) suggests the establishment of a volunteer army, while Maali et al. (2022) emphasize the effectiveness of change agent roles as a crucial strategy. They argue that successful change agents should assume responsibility for leading, supporting, communicating goals, and engaging in all stages of the implementation process. We refer to our change agents as data ambassadors, with the aim of having at least one ambassador in every engineering section within the DMI. These ambassadors are tasked with communicating the programme's objectives and assisting colleagues in utilizing data-driven tools. To become an ambassador, individuals are required to complete the DvO-course. However, the voluntary nature of participation in the course was sometimes unclear, which adversely affected its success. Nevertheless, data ambassadors have proven effective in promoting the programme's objectives and supporting the movement especially in sections where data is already available.

Initially, the course heavily focused on data-driven model development, based on perceived interest from participants. However, it became apparent that this approach was overly complex for the audience, necessitating a shift towards emphasizing the practical application of these models. Consequently, the course has evolved to centre around participants' specific use cases, providing them with directly applicable learning experiences within their own work environments.

As highlighted by Vermeulen (2023), future efforts should prioritize the improved selection of potential candidates and enhanced support for these ambassadors throughout their journey.

3.5. Principle 5: Bridging the gap between start-up and scale-up

The first four principles establish the groundwork for transitioning from a start-up phase to a scale-up phase, marking a crucial step in the evolution of the DvO-programme. During the start-up phase, emphasis was mainly placed on experimentation and demonstrating value through use-cases. However, as the program progresses, it must evolve into a more mature organization, where data governance and internal processes are in order. This shift is essential for bridging the gap between change agent involvement (Principle 4) and organizational implementation (Principle 6), fostering trust within the organization by delivering reliable and reproducible results.

Data-driven maintenance within the RNLN is built upon an established foundation of condition monitoring. Nevertheless, Mooij's maturity scan indicates that current practices lean towards reactive or planned CBM. To fully leverage the potential of condition monitoring and data-driven models, a significant organizational shift is required. Using the innovation funnel is thereby important. The DvO-programme is gradually steering the organization in this direction by seizing opportunities as they arise and prioritizing the exploration and development of promising initiatives. This funnel approach is crucial in a resource-constrained programme. The programme proves to be essential in taking proactive steps to initiate the transition, even if the organization and its IT infrastructure are not yet fully prepared for the transition.

One key guiding principle learned within the DvO-programme is moderation. It is essential to encourage creativity and engagement while addressing concerns to prevent disengagement. Moderation is important to temper unrealistic expectations. Moderation is also important as not every department may have access to sufficient data or data-driven models. Adopting a gradual approach, starting from descriptive to diagnostic methods, aids in overcoming challenges and building upon the existing foundation of condition-based maintenance.

3.6. Principle 6: Instituting change by developing a work process for data-driven maintenance

The final principle of Kotter (1995) is instituting the change in the organization. Mooij (2023) argued that embedding condition indicators derived from data-driven models in the way of working of the RNLN is essential. A structured work process should be embedded within the organisational structure. This is also in line with Van Oudenhoven et al. (2023) who argues from a work-system approach that focus should be laid on creating trust between decision-makers and the data-driven models. Moreover, Van Oudenhoven et al. stress the importance of assigning decision-making responsibilities and capabilities to the appropriate organizational unit. Further, similar as discussed for Principle 5, documentation must be established regarding decision-making processes and finding the right balance between relying on a monitoring system and the judgment of engineers.

Presently, analyses derived from condition monitoring, serve as supplementary input for scheduling maintenance activities or providing instructions to limit or optimize usage, typically in consultation with installation managers within DMI. In the future, maintenance decisions such as repairs or replacements should not merely be supported by these new models but be entirely dependent on them. This requires abandoning traditional plans based on factors like calendar time or running hours in cases where effective data-driven models are available, necessitating a mindset shift. Consequently, the implementation of data-driven maintenance demands effective change management, as it entails replacing existing methods with novel, yet incompletely understood, technologies. This change may impact employee engagement, responsibilities, and necessitate a mindset shift that may not be readily accepted by all individuals within the organization.

In our vision, this transition necessitates painting a realistic picture by explaining how it works and clearly stating what is already achievable and what remains to be accomplished. It involves creating practical solutions that deliver results. Work-system approaches provide valuable insights into positively influencing people's behaviour towards data-driven maintenance. These approaches teach us that it is crucial to strike the right balance between relying on a monitoring system and the judgment of engineers. The presence of maintenance engineers who understand the capabilities of data-driven models is essential for assessing current risks associated with assets, while data professionals are needed to develop digital solutions capable of performing monitoring tasks. Integrating these individuals and systems into the organizational structure is particularly important in an organization like the RNLN, where current maintenance strategies are deeply entrenched in tradition.

In the current first steps towards a full integration of data-driven maintenance, maintenance engineers primarily depend on relatively straightforward, descriptive, and diagnostic data-driven analyses. However, with the introduction of more advanced data-driven models in the near future, factors such as human control for decision-making, trust between decision-makers and the model, and adequate cognitive resources to handle the system's demands need to be carefully addressed within the program.

To integrate data-driven decision making in the organisational structure, Mooij (2023) conducted design sessions within the DMI. By involving decision-makers from various organisational layers, she worked in an iterative design science process towards a widely supported work process for data-driven maintenance within the RNLN (Figure 3). This process shows how a measure-analyze loop is conducted before a notification is made that will consequently be allocated to either the ship’s crew or a maintenance engineer ashore. Note that this measure-analyze-notify-allocation sequence can either be conducted in-person, for example in the case of a manual inspection or measurement, or automatically by an accepted and verified data-driven model. Mooij (2023) argued that next to a straightforward maintenance execution process based on data-driven models, a work-process should entail knowledge-building improvement loops to improve data-driven models (the algorithm improvement process of Figure 3).

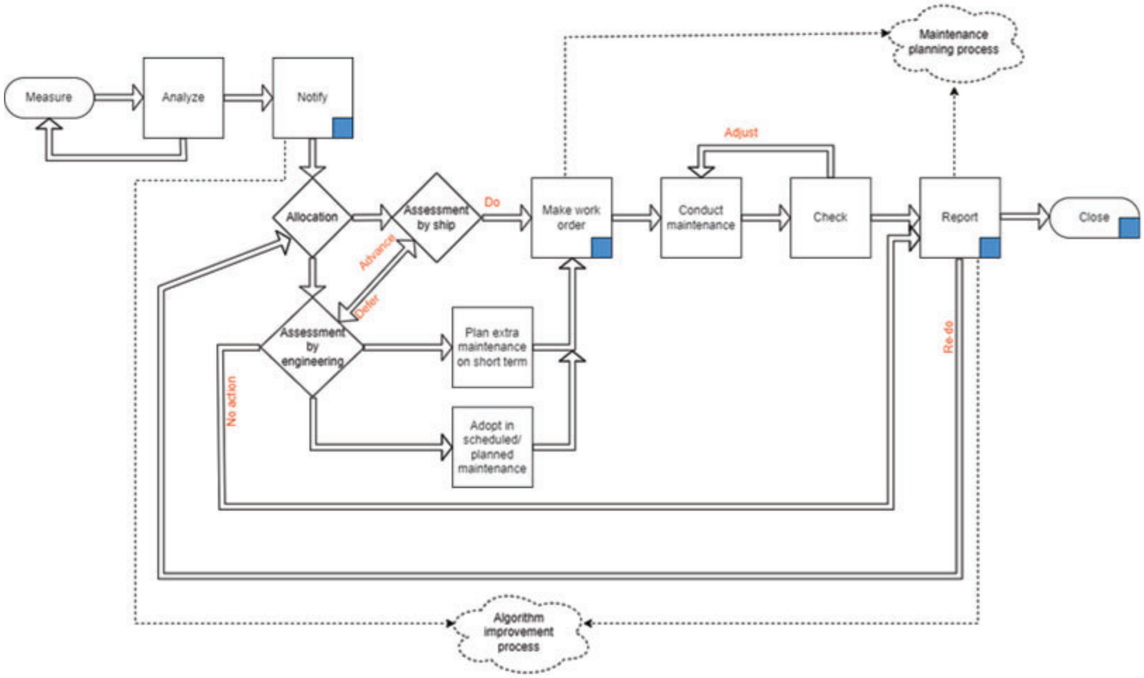

Figure 3. Proposed work process for data-driven maintenance within the RNLN (Mooij, 2023). The blue squares indicate activities in the company ERP system.

4. Conclusions and further directions

The current paper presented the foundation for the development of a social roadmap that complements the implementation programme of DvO with the earlier presented technical roadmap. Through a structured approach, derived from four perspectives on organizational change and technology adoption, six guiding design principles have been determined for the transition towards data-driven maintenance specific to the context of the RNLN. This paper showed that key principles such as moderation, trust-building, and targeted implementation have proven successful in overcoming challenges and driving momentum.

The successful adoption of data-driven maintenance requires careful consideration of human factors, organizational culture, and change management strategies. The engagement of maintenance engineers, management, technical specialists aboard naval vessels, engineers within COMMIT, and industry partners is essential for ensuring the effective implementation.

Moreover, the development of data-driven tools to support maintenance decision making and the use of use-cases as a vehicle for problem-solving and generating short-term wins has proven to be effective in demonstrating the value of data-driven approaches. Collaboration with universities and the involvement of graduate students have enriched the program by addressing more complex use-cases and bringing fresh perspectives to the table.

Looking ahead, continued focus on education and training, developing data-driven tools, stakeholder engagement, and iterative improvement will be crucial for advancing the DvO-programme and realizing its full potential. Further research should be conducted, using work-system approaches, to study optimal implementation strategies of data-driven tools for technical people aboard ships and integration of the six proposed design principles in a complete social roadmap.

Design Principle	Maturity models		Work-system approaches			Technology acceptance models	Change management models	
	van de Kerkhof (2020)	Mooij (2023)	van Oudenhoven et al. (2023)	Berket (2023)	Vermeulen (2023)	UTAUT analysis Brus (2022)	Kotter (1995)	Maali et al. (2022)
1: Roadmap for vision and urgency	strategy and goals;					managing expectations, employees are unacquainted with the programme	creating a sense of urgency, building a guiding coalition, forming a strategic vision, sustaining acceleration	establishing a realistic timeframe, setting measured benchmarks, and senior leadership commitment
2: Differentiate in users and stakeholders						performance expectancy, social influence, and effort expectancy		
3: Show benefits with use case							generating short-term wins	communicating benefits
4: Data ambassadors	knowledge and skills; culture.			provide training to improve technological competence	improve selection process of ambassadors, better support ambassadors		enlisting a volunteer army	change agent effectiveness
5: Trust and digital literacy			human control for decision-making, trust between decision-makers and the model, cognitive resources to handle the system's cognitive demands.	low affinity with data, low digital literacy, concept is still immature, and support tool is experienced as difficult to use.		behavioural intention and facilitating conditions determine technology usage (UTAUT)		
6: Instituting change	decisions, structure, processes and documentation, governance.	structured work process embedded within the organisational structure	assigning decision-making responsibilities and capabilities to the appropriate organizational unit.	introduce a data analyst role within each engineering section,	only apply the concept to departments with a high data availability	integrated in their current work processes, organisation is suitable for implementing data-driven maintenance	instituting change, enabling action by removing barriers	

Table 1. Analysis showing the origin of the six guiding design principles for the social roadmap based on the four perspectives of Section 2

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References

Akkermans, H., Besselink, L., van Dongen, L.A.M. and Schouten, R. (2016), “Smart moves for smart maintenance: findings from a Delphi study on’Maintenance Innovation Priorities’ for the Netherlands”, World Class Maintenance.

Berket, J. (2023), *The PdM Work System at the RNLN: Stimulating the Usage of Decision Support Tools for Smart Maintenance in 2028*, Eindhoven university of technology.

Bokrantz, J., Skoogh, A., Berlin, C. and Stahre, J. (2017), “Maintenance in digitalised manufacturing: Delphi-based scenarios for 2030”, *International Journal of Production Economics*, Elsevier, Vol. 191, pp. 154–169.

Brus, D. (2022), *The Social Impact of Implementing Predictive Maintenance at The Royal Netherlands Navy*, Eindhoven University of Technology.

Burton, J.W., Stein, M. and Jensen, T.B. (2020), “A systematic review of algorithm aversion in augmented decision making”, *Journal of Behavioral Decision Making*, Wiley Online Library, Vol. 33 No. 2, pp. 220–239.

Carayon, P. (2009), “The balance theory and the work system model… twenty years later”, *Intl. Journal of Human–Computer Interaction*, Taylor & Francis, Vol. 25 No. 5, pp. 313–327.

Garg, A. and Deshmukh, S.G. (2006), “Maintenance management: Literature review and directions”, *Journal of Quality in Maintenance Engineering*, Mechanical Engineering Department, Indian Institute of Technology Delhi, New Delhi, India, Vol. 12 No. 3, pp. 205–238, doi: 10.1108/13552510610685075.

Grubic, T., Redding, L., Baines, T. and Julien, D. (2011), “The adoption and use of diagnostic and prognostic technology within UK-based manufacturers”, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 225 No. 8 LB-99, pp. 1457–1470.

Hevner, A.R., March, S.T., Park, J. and Ram, S. (2004), “Design science in information systems research”, *MIS Quarterly*, Vol. 28 No. 1, pp. 75–105.

van de Kerkhof, R. (2020), *It’s about Time: Managing Implementation Dynamics of Condition-Based Maintenance*, CentER, Tilburg University.

Kerkhof, R.M. van de, Akkermans, H.A. and Noorderhaven, N.G. (2016), “Knowledge Lost in Data: Organizational Impediments to Condition-Based Maintenance in the Process Industry”, *Logistics and Supply Chain Innovation*, Springer, pp. 223–237.

Kotter, J.P. (1995), “Leading change: Why transformation efforts fail”, *Harvard Business Review*, Vol. 73 No. 2, pp. 59–67.

Lee, J., Kao, H.-A. and Yang, S. (2014), “Service innovation and smart analytics for industry 4.0 and big data environment”, *Procedia Cirp*, Elsevier, Vol. 16, pp. 3–8.

Lundgren, C., Berlin, C., Skoogh, A. and Källström, A. (2023), “How industrial maintenance managers perceive socio-technical changes in leadership in the Industry 4.0 context”, *International Journal of Production Research*, Taylor & Francis, Vol. 61 No. 15, pp. 5282–5301.

Maali, O., Kepple, N. and Lines, B. (2022), “Strategies to achieve high adoption of organizational change initiatives within the AEC industry”, *Journal of Management in Engineering*, American Society of Civil Engineers, Vol. 38 No. 4, p. 04022021.

Middelbrink, I. (2023), *Data-Uitwisseling in Het Kader van Datagedreven Onderhoud*, Rijksuniversiteit Groningen, Groningen.

Ministerie van Defensie. (2020), *Defensievisie 2035*.

Mooij, Q.J. (2023), *Building a Knowing Maintenance organization by Introducing a Knowledge Improvement Process for Predictive Maintenance at the Royal Netherlands Navy*, University of Twente, Enschede.

Neumann, W.P., Winkelhaus, S., Grosse, E.H. and Glock, C.H. (2021), “Industry 4.0 and the human factor–A systems framework and analysis methodology for successful development”, *International Journal of Production Economics*, Elsevier, Vol. 233, p. 107992.

van Oudenhoven, B., Van de Calseyde, P., Basten, R. and Demerouti, E. (2023), “Predictive maintenance for industry 5.0: behavioural inquiries from a work system perspective”, *International Journal of Production Research*, Taylor & Francis, Vol. 61 No. 22, pp. 7846–7865, doi: 10.1080/00207543.2022.2154403.

Shafiee, M. (2015), “Maintenance strategy selection problem: an MCDM overview”, *Journal of Quality in Maintenance Engineering*, Vol. 21 No. 4, pp. 378–402.

Tiddens, W., Braaksma, J. and Tinga, T. (2022), “Exploring predictive maintenance applications in industry”, *Journal of Quality in Maintenance Engineering*, Vol. 28 No. 1, doi: 10.1108/JQME-05-2020-0029.

Tiddens, W., Pollmann, B., Curvers, D., Teunisse, M., Shanez Saz, S. and Zegers, J. (2022), “Smart Maintenance for Modern Naval Ships”, *Conference Proceedings of INEC*.

Veldman, J., Klingenberg, W. and Wortmann, H. (2011), “Managing condition-based maintenance technology: a multiple case study in the process industry”, *Journal of Quality in Maintenance Engineering*, Vol. 17 No. 1 LB-86, pp. 40–62.

Venkatesh, V. and Bala, H. (2008), “Technology acceptance model 3 and a research agenda on interventions”, *Decision Sciences*, Wiley Online Library, Vol. 39 No. 2, pp. 273–315.

Venkatesh, V., Morris, M.G., Davis, G.B. and Davis, F.D. (2003), “User acceptance of information technology: Toward a unified view”, *MIS Quarterly*, JSTOR, pp. 425–478.

Vermeulen, S.H.J. (2023), *On the Way to Effective Data Ambassadors: A Post-Intervention Analysis*, Eindhoven University of Technology.

Volberda, H.W., Commandeur, H.R., Van den Bosch, F.A.J. and Heij, C. V. (2013), “Sociale Innovatie als aanjager van productiviteit en concurrentiekracht”, *M & O: Journal for Management and Organisation*, Vol. 5, pp. 5–34.

Wendler, R. (2012), “The maturity of maturity model research: A systematic mapping study”, *Information and Software Technology*, Elsevier, Vol. 54 No. 12, pp. 1317–1339.

Is Regulation really the barrier? Exploring the Opportunities and Challenges in Certifying Maritime Systems with Increased Automation and Autonomy

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Synopsis

In recent years there has been a huge drive to apply new and novel technologies across industry and in the maritime sector, centred around the application of automation and autonomy. The potential applications are far and wide and cover every type of maritime vessel. The application of these new technologies challenges the conventional adherence to some of the fundamental maritime conventions, specifically International Regulations for Preventing Collisions at Sea 1972. In an industry that is traditionally underpinned by prescriptive regulations, the ability of the Regulations to keep pace with the evolving technical landscape is continually tested. But is it fair to blame Regulations for the constraints on certifying vessels with ever increasing levels of automation and autonomy? This paper looks at the current commercial approach, which typically takes a more traditional prescriptive approach and compares it to the defence industry that operates in the same environment and undertakes similarly complex operations, but has goal-based regulations and utilises risk based methodologies to demonstrate compliance. The authors' are not advocating any one solution, but comparing two differing approaches to look at opportunities and to examine the question "is Regulation really the barrier".

Keywords: Automation, Autonomous, Regulations, Assurance

1 Introduction

The potential application of new and novel technology in the maritime domain, specifically automation and autonomy, is progressing at a pace rarely seen with regards to technology development/ insertion. The use of automation and autonomy is pushing the technical boundaries and hence regulatory frameworks with a concurrent requirement to understand how their adoption can be assured robustly and consistently.

Development of regulations always takes considerable time, and technology exploitation will always outstrip development of regulations in timescales. As a result, regulations often get blamed for hindering technical development, but is this fair?

It is important to note that the paper is agnostic of vessel size; the challenges posed are common and thus the paper's question is equally applicable. It is also worthy of note that where we discuss safety "...and environment" is implicit.

Great care needs to be taken in the use of terminology, both in terms of ensuring a common/ pan industry understanding, but also to ensure a true reflection of the capability without inadvertently being misleading. The paper does not go into variations on Remote Control or Autonomy, but uses the following core definitions, Remote Control "the vessel is controlled and operated from another location by a person" and Autonomous "the vessel assesses its environment, makes decisions and determines actions by itself to fulfil its mission".

This paper asks the question "Is Regulation really the barrier?" to the adoption of novel technology specifically in the context of automation and autonomy. To examine this question the authors, draw on their respective

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Mr Adrian Payne trained as a Ship Scientist at the University of Southampton. He has work across a variety of sectors within maritime, but predominantly in Defence. He has been specialising in safety management within the defence sector for over 25 years. He is currently the Chief Technical Officer for Safeguard Engineering Ltd, supporting a team of over 50 safety and environmental consultants.
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Mr Ashley Stehr qualified with a master's in mechanical engineering and a seasoned consultant with extensive experience across various sectors, including both commercial and defence. Formerly an Assistant Director at the MCA, where he established and led the Maritime Future Technologies team, focusing enabling the safe adoption of novel technologies within regulatory frameworks. Currently, he serves as Director and Principal Consultant at Stehr Consulting Ltd.

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experiences in the commercial and defence maritime sectors to compare differing approaches to the challenges posed by the adoption of such novel technologies.

The authors are not suggesting that any one model is the answer, but by comparing two industries that both operate in the same environment, both undertaking similarly complex operations and both pushing the adoption of new and novel technology in automation and autonomy, useful comparisons can be made.

2 Sector Landscape

To be able to draw comparison between Commercial and Defence industries, it is first important to understand where the respective regulations have come from, how they have developed and their current status. This section provides that overview.

2.1 Current Industry Landscape

There has been a significant increase in interest and uptake of remote control and autonomous surface and subsurface vessels in recent years across both Commercial and Defence applications, both internationally and within the UK. The press is full of new and novel applications, from the small, sub 6 metres, to the full-scale ships, e.g. 200 meters plus.

This paper considers the application of new and novel technology in the round to the maritime environment and does not focus on any particular example.

2.2 Current Regulatory Framework Context

2.2.1 Commercial Context

The regulatory and standards landscape in the commercial maritime sector is complex and continuously evolving. Traditionally, maritime regulations have been inherently prescriptive, consisting of a broad array of international and national rules, conventions, guidelines, and standards. These are primarily designed to ensure safety, security, and environmental protection. The International Maritime Organization (IMO) plays a pivotal role in creating and implementing these international standards, with member states adopting these standards on a multilateral basis. This top-down regulatory approach details the obligations and rights of Flag States, vessels, and seafarers, setting minimum technical and operational standards that dictate ship design, operation, and performance.

Compliance with these regulations varies significantly across different regions, with some areas showing high levels of compliance and others much lower, partly due to the existence of Flag States that impose less stringent requirements.

Nationally, countries like the UK have their own domestic maritime regulations, overseen by the Maritime and Coastguard Agency (MCA) (an executive Agency of the Department for Transport (DfT)).

The prescriptive regulatory model faces increasing pressure as the maritime sector enters an era marked by rapid technological change and diversity, where traditional prescriptive approaches often fall short. The current regulatory framework, although effective for incremental changes, struggles to accommodate the fast evolution and complexity of new systems, leading to significant regulatory barriers and gaps for emerging technologies.

To address these challenges, regulatory bodies are adopting more tailored, case-by-case approaches for vessel certification. These make use of existing mechanisms like Exemptions, Equivalence, or Alternative Design and Arrangements (AD&As) to facilitate the introduction of new technologies, though they are traditionally intended for minor deviations and the processes are not designed for more substantial, system-wide changes. Within the UK, the MCA has just recently updated the Workboat Code Edition 3 (WBC3) [Ref. 1] to cater for Remote Controlled vessels, and has also published Marine Guidance Note (MGN) 664 ‘Certification Process for vessels using Innovate Technology’ [Ref. 2] which is a goal-based approach and has only relatively recently been introduced.

Similarly, industry via the various trade bodies is also developing supporting information to contextualise how to demonstrate compliance for autonomous platforms. For example, Maritime UK have developed the Maritime Autonomous Systems (MASS) UK Industry Conduct Principles and Code of Practice [Ref. 3].

There is, however, due to commercial nature of projects, little publicly available to allow industry to understand “what good looks like” or what has been successful in seeking certification, a common theme across commercial and defence industries. To be able to rapidly develop, sharing knowledge, is key.

2.2.2 Defence Context

As with the commercial maritime space, defence maritime has its roots very much in the prescriptive regulatory space. Similarly, whilst this approach has allowed it to embed lesson learnt into the regulations and standards applied, it can struggle to keep pace with evolving technology application.

In 1996 the UK Ministry of Defence (MOD) issued, what can be considered by today's standards to be the first Safety Management System, Joint Service Publication (JSP)430 [Ref. 4]. This was developed and issued as a result of various reviews and parliamentary investigations into a series of accidents ranging from the Piper Alpha Oil Rig Fire 1988, to the capsize of the Herald of Free Enterprise 1987 and the Clapham Rail Disaster 1988. The various investigations, inquiries and Coroners Court findings associated with these events led to changes in the law, the creation of the Corporate Manslaughter Act and the specific requirements for Safety Cases. The then UK MOD Ship Safety Maritime Office (SSMO) developed and issued JSP430 [Ref. 4] in response, to provide initial regulation and guidance to the UK Defence Maritime Sector.

JSP 430 Issue 1 [Ref. 4] set the overall objective of "*The overall MOD Ship safety objective is that levels of risk of accident death or injury to crew or other third parties and damage to property and the environment due to MOD shipping activities are as low as reasonably practicable*."

Importantly the forward of JSP 430 [Ref. 4] was signed by the then Secretary of State for Defence, establishing a clear commitment from the very top of government with respect to establishing a robust Safety Culture. Promoting policy at the highest level creates the working environment and conditions individual behaviour [Ref. 5].

JSP 430, also set out two important fundamental concepts for the application of safety management within defence:

1. "…*that where MOD has been granted exemption from specific regulations, health and safety standards and arrangements will be, as far as is reasonably practicable, at least as good as those required by statute*"; and
2. "*Safety management is to commence at the first consideration of a new design*…".

These points still remain extant today, and whilst they have been developed further within the current set of Defence Regulations, DSA02 – DMR [Ref. 6], the fundamentals remain the same; simply put demonstrate that the platform/ system is "Safe to Operate" and is "Operated Safely". As noted, the basis of defence safety is demonstration via a risk-based approach. This poses a number of challenges:

- what is an acceptable level of safety when it is assessed subjectively?
- how do you maintain consistency in approach? and
- how do you maintain consistency in level of rigour and fidelity in analysis?

Whilst the Defence Maritime space might have been applying a risk-based approach for circa 28 years, these concerns remain at the forefront of thinking and result in a body of guidance and training. They are similarly applicable to the commercial space as it embarks on risk based methodology.

The UK Defence industry adopts the As Low As Reasonably Practicable (ALARP) principle, Edwards v. National Coal Board in 1949. MOD generally adopts a Risk Class Matrix approach, which in the majority of cases, takes due regard for the risk tolerability levels defined in the Health and Safety Executive (HSE) guidance document Reducing Risk and Protecting People (R2P2) [Ref. 7]. .

Since the inception of the risk based approach in 1996, there has been a development in internal guidance to support a common baseline of what should typically constitute a Safety Case, for Defence Maritime, most notably the pan defence Acquisition Safety and Environmental Management System (ASEMS) and various supporting publications supporting the Naval Authority Regulations, in effect "Defence Codes of Practice", for lack of a better collective term.

In addition, the UK MOD has developed and applied structured training, accredited to professional institutions to ensure consistency in understanding and application. This with a use of forums to assess risks with relevant stakeholders, the application of a Suitably Qualified and Experience Person (SQEP) forums supports the provision of consistency in risk assessment.

The UK MOD Regulator has evolved from the early days of the SSMO and JSP430 [Ref. 4] into the Defence Maritime Regulator (DMR), within the Defence Safety Authority (DSA) with an aligned set of regulations in DSA DMR 02 Defence Maritime Regulations [Ref. 6] that dovetail with the HSE and the MCA. This evolution started in 2016 post the Haddon Cave Report [Ref. 7] that reset the whole of UK Defence's approach to regulation. That change created the Defence Regulators, aligned to the UK Government's Regulators Code and empowered those regulators to drive and shape the regulatory framework across the domains. For DMR that led to a much closer relationship with the MCA and HSE and endorsement from both of those statutory bodies for the DMR Regulations. The regulator's intent was and remains to provide a sensible handrail to allow defence to deliver its outputs and develop new equipment and technologies in a way that achieves legislative compliance within a safe operating envelope.

The International Naval Safety Association (INSA), responsible for the development and maintenance of the North Atlantic Treaty Organisation (NATO) Naval Ship Code, Naval Boat Code, and NATO Naval Submarine Code, has established a working group focused on unmanned and autonomous systems. This group is working to update the Naval Boat Code to incorporate unmanned and autonomous functionalities under the 'Special Functions' provisions. Furthermore, the group is developing a goal-based performance standard for Autonomous Navigation Systems that could be implemented on remotely controlled or autonomous naval vessels of various sizes. This initiative is cognisant of the IMO MASS Code (to be issues), the UK WBC3 [Ref. 1], and other navy and industry standards, and strives to align with these standards where suitable for naval vessels.

The UK Naval Authority & Technology Group (NATG) have also published, amongst others, the Maritime Acquisition Publication (MAP) No. 01-151 Certification of Autonomous Vessels [Ref. 9] in October 2023. This embeds the provision of a risk-based approach, whilst ensuring compliance with statutory regulations the defence objective of "...at least as good as..." mentioned earlier. In addition to this, it provides consideration and a framework to support progressive proving on novel technology.

Other areas within the MOD are also looking at what safety case models could look like to provide a standard construct for the demonstration of the remote control and autonomous vessels. As with the commercial space, there is considerable work being undertaken, and due to the structure of UK MOD and the complexities of commercial and security arrangements, not necessarily visible to all parties, thus restricting knowledge sharing.

3 Regulation vs Assurance

Through time the application of rules and legislation to systems and activity has evolved and methods of assessment and measurements of compliance have evolved with them, often leading to sustained debate about what is regulation and what is assurance. Regulation is simply the controlling of an activity or process, usually by means of rules, while assurance is simply a positive declaration intended to give confidence. The key difference being that regulation requires adherence, while assurance focuses on the provision of a body of evidence to provide confidence that an activity can be undertaken safely.

The critical challenges in the maritime sector associated with remote control and autonomous platforms has primarily evolved around adherence to International Regulations for Preventing Collisions at Sea (COLREGS) in enabling the vehicle to act in a way appropriate to the maritime condition, establishing and identifying the role of the "Master" in an autonomous vehicle and developing appropriate emergency equipment fits for autonomous vehicles. The situation awareness challenge for over the horizon activities and the understanding and identification of other vessels around an unmanned/ autonomous vessel conducting activities has presented significant challenges to the community as a whole, both within commercial and defence sectors.

The risk-based model adopted can be represented as depicted in Figure 1. The application of prescriptive requirements, whether embedded in regulations, or standards, is a key control to hazards and risks identified. Where novel aspects are considered, either in operations that don't fall under any standards, or the application of novel technology, the risk based model allows consideration of safety from first principles; but importantly building on a sound body of initial assessment against prescriptive standards, ensuring the inherent lessons learnt are captured and not lost. This approach also identifies and addresses any emergent risks that may not have previously been present.

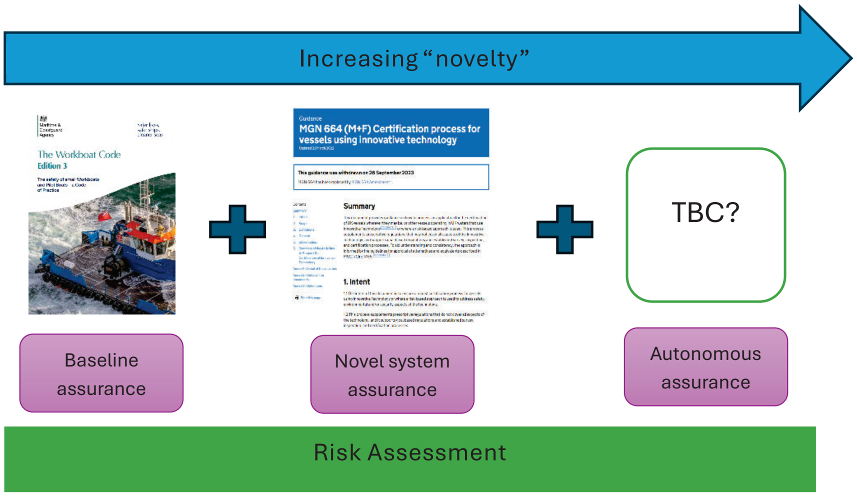

Figure 1 – Risk Based Safety Assurance Model

This approach allows the regulator to seek assurance within a defined construct, which does not stifle innovation, but is cognisant of the activity and how novel technology/ operations are intended to be applied. With this understood, a measured risk-based framework can be developed that enables the development of appropriate assurance for novel systems.

With a thorough understanding and engagement from the community, the regulator can also provide assurance to the accountable persons that all reasonable precautions are in place and applicable procedures developed to allow ALARP to be achieved in activities. This reflects a unique set of conditions that are not necessarily present within the commercial maritime environment, specifically a community with a common understanding and acceptance of tolerability of risk, as baselined in R2P2 [Ref. 8], and environmental with defined training.

However, whilst it may be argued that 28 years of application of a risk based approach within the defence maritime industry generates a community with common understandings and expectations on assessment methodologies and fidelities, the challenges of personnel churn within a small, relatively speaking, community cannot be underestimated.

It is the authors' experience that it is widely acknowledged that the commercial maritime industry as a whole (industry and regulators) are struggling to transition from what is a traditional prescriptive approach, e.g. guardrails shall be a minimum of 1000mm above deck level, to a risk based approach considering controls to mitigate the Hazard of "personnel fall overboard" or "personnel fall from height". In addition to defence, other industries have made, or are making this transition, e.g. O&G initiated by Piper Alpha, and UK building industry is current progressing as a result of Grenfell Towers. The commercial maritime industry has already made some strides in this area with the introduction, at the international level of the ISM Code as a result of the Zeebrugge disaster. Whilst this does not progress a risk-based safety assessment methodology, it does introduce aspects of subjectivity and assurance of the process rather than the product, e.g. what level of fidelity should be in an Emergency Response Plan? Whilst at the national level the UK has MGN 664 [Ref. 2], for novel technologies predicated on a risk-based approach.

The authors propose that there is substantial learning from the risk-based approach, adopted by defence (and other sectors) that can be utilised within the commercial space to alleviate the challenge of lag in regulation/ standards development, whilst maintaining a robust assurance oversight. The fundamentals to allow this to be achieved are already in place, e.g. MGN 664 [Ref. 2]. There are however a set of challenges, which we have characterised as "challenge themes" to the adoption of the risk-based approach. These "challenge themes" span both the Regulator and Industry alike, and thus in answer to the papers question "Is Regulation really the barrier?" the answer is no, it is a shared responsibility with the sector overall, both Regulator and Industry.

Challenge Theme 1 – Necessity for a consistent understanding and connection of the regulation to the hazards and risks being managed.

Commercial maritime regulation is characterised by a complex array of codes, each designed to manage specific risk profiles. These regulations, predominantly prescriptive and technical, have evolved over time, often in response to lessons learned from past incidents and accidents. There is a notable absence of goal-based regulations, and the existing technical requirements frequently lack a clear connection to the hazards and risks they aim to mitigate. This disconnect poses significant challenges when assessing novel technologies. To evaluate such technologies, it is necessary to first understand the original intent of the regulatory requirements. Only then can consideration be given to exploring alternative compliance methods, such as equivalence, or Alternative Design and Arrangements (AD&A). This will also allow for the consideration of any potential emergent hazards and or risks being introduced by the novel technology. A more effective regulatory framework could be achieved by structuring future requirements to highlight overarching goals, with prescriptive measures serving as acceptable means of compliance. This approach would simplify the integration of novel technologies into the maritime sector by making it much easier to demonstrate and articulate alternative means of compliance.

Challenge Theme 2 - Clear safety benchmarks defined in maritime regulation.

In addition, for the need for clear and consistent goals, Theme 1, there is also a need for a consistent understanding of the acceptable level of safety. The importance of defining 'how safe is safe enough', where proportionality is essential and consistent application is fundamental. Commercial maritime lags in adopting such baselines for risk tolerability as those proposed in R2P2 [Ref. 8] prevalent in other sectors. Whilst this can be applied in a national context, due to the common acceptance of risk levels, application on an international basis will pose considerable challenges, as evidenced by the application of varying degrees of rigour in the prescriptive standards. Transitioning to a risk-based approach necessitates an evaluation of risks - from well-understood to emergent - using first principles to establish a baseline of safety. This process involves either deducing the level of safety provided by existing controls and requirements (which are not often apparent or clearly defined) or applying the principles of ALARP. Variations have been adopted in some other countries noting there can therefore be differing interpretations of "reasonably practicable”, thus posing particular challenges for adoption worldwide.

Challenge Theme 3 – Specific challenges with assuring high degrees of autonomy

In addition to the challenges with more bespoke assurance of novel and complex systems, there are some additional specific assurance challenges presented by introducing higher degrees of autonomy. Many of these are not unique to maritime, and other arguably more advanced and well-funded sectors are also trying to grapple with these challenges. These challenges range from needing to consider the shift from product to the inclusion of process based assurance, and operational risk versus system risk. An example are the specific challenges with assuring Machine Learning which can be used as a key enabler for some autonomous systems (e.g. for processing and understanding Electro Optical/Infrared Imagery which can be used in contact classification). Industry wide, established baselines are required to define acceptable levels and methods of assurance to demonstrate the robustness of non-deterministic methods such as Machine Learning. This includes, what tests scenarios and methods are required and how many iterations are necessary to demonstrate that a Machine Learning autonomous system will behave as expected?

Challenge Theme 4 – Increase in SQEP capability and capacity required to implement a risk-based approach.

The transition from a prescriptive to a risk-based approach to safety assurance marks a significant shift in the maritime industry. This change offers greater flexibility, but also presents considerable challenges in terms of the technical skills and capabilities required to manage increased subjectivity, including the need for Suitably Qualified and Experienced Personnel (SQEP). Traditionally, the commercial industry has relied on a model where specialists develop technical standards for generalists to implement. However, a risk-based approach demands the involvement of these specialist skills in every project, posing challenges for both industry and regulatory bodies. Furthermore, the adoption of highly adaptable systems that allow significant post-manufacture modifications through software updates necessitates the need for more comprehensive through-life safety management. This includes oversight through life of the design, construction, maintenance, and modifications, with a demand for ongoing expert involvement and oversight.

Challenge Theme 5 – Shift in safety culture and approach.

The shift from a prescriptive to a risk-based approach in maritime safety assurance represents a fundamental change in the regulatory paradigm, notably transferring more risk management responsibility from regulators to the industry (and other third parties). This alteration significantly impacts the required safety culture and the level of trust between these entities. In a risk-based framework, the industry assumes greater responsibility for identifying hazards and risks and for identifying appropriate controls to either eliminate these risks or mitigate them to ALARP levels. Establishing trust in the industry’s commitment to safety is crucial, yet challenging, given the diversity of stakeholders and a safety culture that will be subject to considerable change from prescriptive to risk based. This transition demands a robust, collaborative effort, by all stakeholders to reinforce trust and ensure a shared commitment to safety excellence, knowledge and good practice.

4 Conclusions

At the start of this paper, we asked ourselves the question "is regulation truly the primary barrier to innovation?". While recognising specific regulatory challenges - which we do not intend to diminish - we believe that many of the core issues extend beyond mere regulatory frameworks. Instead, they are closely linked to the complexities of demonstrating safety assurance in an efficient and effective manner. Thus, the answer to our initial question is no, but it is not straightforward.

The paper identifies that the primary hurdle involves demonstrating safety and environmental assurance of novel and complex technologies through ensuring effective risk management within an existing and inherently prescriptive regulatory environment. This paper has explored various dimensions that transcend traditional regulatory challenges, extending into broader 'assurance' issues that require attention and resolution.

Anecdotally, industry often hastily blames regulatory bodies for obstructing the adoption of innovative technologies. However, many of the challenges we have highlighted are as significant for the industry as they are for regulators, who are tasked with maintaining appropriate safety and environmental standards. It is crucial to acknowledge that regulatory functions vary across different contexts. In the commercial maritime sector, many technical requirements are positioned at a higher level within the regulatory ecosystem than in other industries.

Key challenge themes identified in our paper include:

- 1 – Necessity for a consistent understanding and connection of the regulation to the hazards and risks being managed;
- 2 - Clear safety benchmarks defined in maritime regulation;
- 3 – Specific challenges with assuring high degrees of autonomy;
- 4 – Increase in SQEP capability and capacity required to implement a risk-based approach; and
- 5 – Shift in safety culture and approach;

In conclusion, while Regulation is often perceived as a barrier, our view is that often the real challenges lie in the broader context of assurance and the readiness of industry as a whole to meet these challenges. Moving forward requires a collaborative, balanced approach that not only reevaluates regulatory frameworks, but also enhances industry practices and the collaborative dynamics between regulators and the industry.

5 Acknowledgements

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References

1. The Workboat Code, Edition 3, The Safety of Small Workboats and Pilot Boats – A Code of Practice, 27 November 2023.
2. Marine Guidance Note (MGN) 644 (M+F) Certification Process for Vessels using Innovative Technology, latest version.
3. Maritime Autonomous Ship Systems (MASS) UK industry Conduct Principles and Code of Practice, version 6, November 2022.
4. JSP 430 Ship Safety Management Systems Handbook, Volume 1, Issue 1, January 1996.
5. Safey Series, No. 75-INSAG-4, Safety Culture, A Report by the international Nuclear Safety Advisory Group, International Atomic Energy Agency, Vienna, 1991.
6. DSA02-DMR – Defence Maritime Regulations for Health, Safety and Environmental Protection, 2024 Edition.
7. The Nimrod Review, An Independent review into the broader issues surrounding the loss of the RAF Nimrod MR2 Aircraft XV230 in Afghanistan in 2026, Charles Haddon-Cave QC, ISBN: 9780102962659.
8. Reducing Risks, Protecting People, 2001, ISBN 0717621510.
9. Maritime Acquisition Publication (MAP) 01-151, Certification of Autonomous Vessels, Issue 1.1 October 2023.

Conceptual design and verification of the power, propulsion, and energy system for a future surface combatant

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Abstract

Although it is debatable to what extend Naval Vessels will have to comply with strict regulations concerning exhaust emissions, concerning fuel supply there is a unanimous consensus about the need for independence from countries in conflict areas. Alternative fuels might provide this independence along with a reduction of in radiated noise. In this paper a concept design of a Power, Propulsion and Energy (PPE) System of a Surface Combatant with the focus on significant reduction of greenhouse gas emissions is composed and simulated. Following the Model-Based System Engineering (MBSE) approach a user needs analysis resulted in a logical and physical PPE system design, focusing on four different military mission types. The design is a combined solution of Dual Fuel Methanol Internal Combustion Engines and Fuel Cells that run on compressed hydrogen. It shows advantages in efficiency, emissions and radiated noise. It can run in different modes, including a Zero Emission mode. To verify the design a time-dependant Simulink model of the PPE system was built and coupled with a model of the propeller and hull in MARIN's eXtensible Modelling Framework *(XMF), which includes sea-states and ship motions. A particular Test Case was performed for a highly dynamic military operation involving a turning circle at high speed, while repetitively firing a railgun. The simulation shows the PPE system is capable to deliver and control the required power, at the edge of stability of the implemented DC distribution system. Following the W-model, a future iteration of the virtual model cycle can further improve system behavior.*

Keywords: Conceptual Design, Digital Models, MBSE, Simulation, Methanol, Hydrogen

1. Introduction:

The use of fossil fuels in the maritime sector contributes considerably to pollution and emission of greenhouse gasses (GHG); about 2.5% of the total worldwide GHG emission has a maritime origin. In order to prevent further climate change, both the IMO and the EU have defined ambitious and compulsory targets for the reduction of emissions in the near future. For the maritime sector the transition from fossil fuels to cleaner and more sustainable fuels and alternatives implies a big challenge.

In addition to the ambitions to reduce exhaust emissions, new energy carriers and their associated Energy-to-Power converters, like fuel cells can create independency of fossil fuels coming from countries in conflictual area's. Further, new Energy-to-Power converters have great potential for reduction of the signatures of combatants.

In the maritime energy transition there are many unknowns. Making a ship sustainable is not as simple as only changing the fuel, or electrifying the complete Power, Propulsion and Energy (PPE) system. Which fuels to choose? Which power & energy system are suitable for my operation? How reliable are these new systems and what emission reductions can we achieve?

To answer these and many more questions, MARIN initiated the ZERO JIP [1]which started Q4 2020. It is a Joint Industry Project lead by MARIN with 23 participants, three research partners (TNO, TUD, HAN) and two stakeholders (NMT, KVNR). The aim of the ZERO JIP is: *to design, build and test the prototype Engine Rooms of the Future to assure reliable future operations in realistic conditions while meeting functional and emission requirements.* This is done for 8 Use Cases (ships with their specific missions). Those 8 Use Cases were defined with all participants at the start of the project. The start point for each Use Case was the compilation of user needs; what is required from the ship? Based on this a suitable concept design was made. After making a digital model of the concept, simulations show if the design matches the requirements.

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This paper describes the results of the conceptual design of the PPE system of a Surface Combatant and simulates a Test Case to verify the capabilities of the designed system for highly dynamic military operations. An artists impression of the surface combatant is shown in Figure 1-1.

Figure 1-1 Artists impression future Surface Combatant

For understanding the power needs and creating architectural design of the future Surface Combatant, the Model Based System Engineering (MBSE) method is applied as explained by Veldhuis et. al in [2]. It uses a coherent model to come in multiple steps from user needs to a validated design. This new way of working can be represented by the W-model, a new age addition to the well-known V-model as shown in Figure 1-2. The W-model introduces two additional legs between the 'Component Design' and 'Manufacture and Assembly' steps. These are the model verification and design specification legs. The use of model-based verification testing allows designs to be checked against requirements. This can be started at an early conceptual design stage, thereby reducing project risks through the early identification of issues. This virtual model cycle is the focus of this paper. For the surface combatant design the left leg was executed in the MBSE tool Capella, while the second leg is a combination of dynamic Simulink models, and MARIN's proprietary wave, propeller and ship models. The developed models can be extended with real-world measurement data through the testing, commissioning and operational phases of the vessel to create digital twins of the vessel. These can then be used to optimise operations.

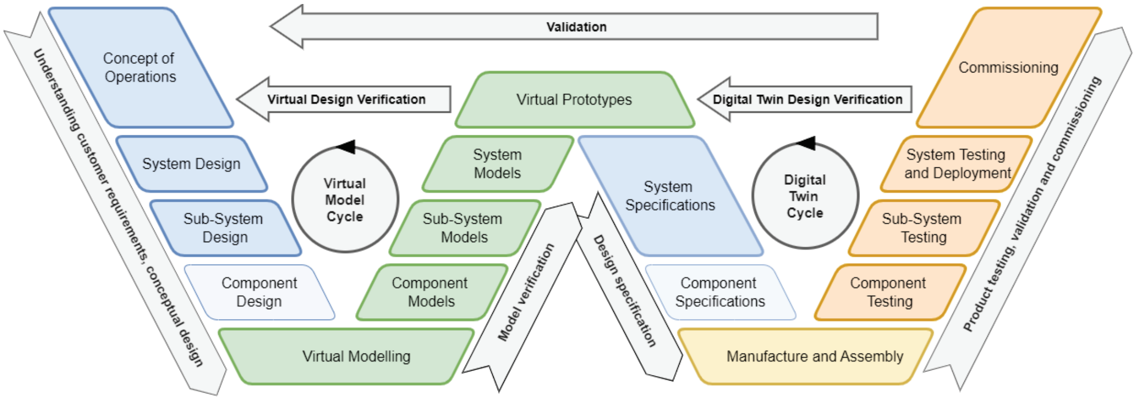

Figure 1-2 W-model for the Life Cycle approach

2. Needs Understanding, Technology Selection, and Concept Design

Before a concept design can be created, it is necessary to have a clear view on the requirements of the PPE system. For this the user-needs must be understood, for which an operational analysis is performed. Based on this a system analysis can make clear which functions the PPE system has to perform and what the system boundaries are.

2.1. Needs Understanding

2.1.1. Operational Analysis

The operational analysis identified the role of the vessel as being - air-defence with advanced weaponry. For the design of the PPE system, the focus of the operational analysis was the energy requirement for different mission types as well as the identification of challenging dynamic operational conditions that the vessel is expected to perform in.

Four representative typical mission types were drafted by MARIN. Those were assessed, improved, and finally approved by the ZERO participants. The resulting four different mission types are summarized, as shown in Table 2-1.

Table 2-1 Summary of the Operational Analysis

Reference Vessel	**Max Vessel Speed**	**Military Service Scenario**	**Max Crew size**	**Mission Types**	**Autonomy/ Endurance**	**Exhaust Emissions**
Successor Air Defence Frigate Δ = 5200 [MT]	25 [Kts]	The Ship shall be capable of sailing at 18 [Kts] in heavy seas (Sea State 6) while intermittently re-charging Electro-Magnetic and Optical Sensors and Weapons with a frequency of 0.2 [Hz]	50	I – Intercontinental Transit	3500 [NMi]	70% Climate Neutral and IMO Tier III
				II – Short Military Voyage	4.5 [Days]	
				III – Long Military Voyage	14.5 [Days]	
				IV – Zero Emission Transit	120 [NMi]	Zero Emission

The main difference between BIO II and BIO III is that BIO III has a longer endurance, making the operational profile of BIO II more dynamic. Both BIOs contain the task “Perform Military Operations”. The two BIOs are shown in Figure 2-1.

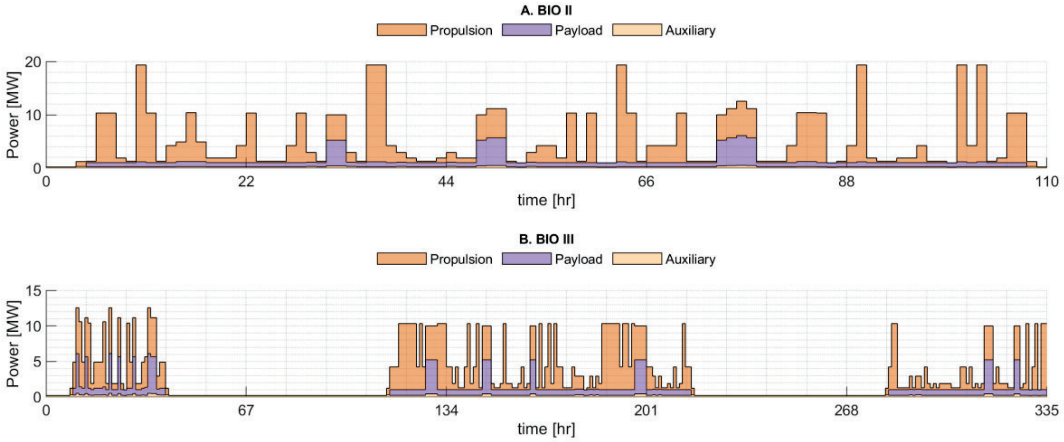

Figure 2-1 Bunker Independent Operations II and III

Additionally, it was concluded that the capability concerning conditions of military service scenario detailed in Table 2-1 is the most challenging for the PPE system and simulation testing should demonstrate its capability to meet these conditions. This challenging condition is translated into an operational requirement:
“The Ship shall be capable of sailing at 18 Kts in sea state 6 while intermittently re-charging Electro-Magnetic and Optical Sensors and Weapons with a frequency of 0.2 Hz”

2.1.2. System Analysis

The second part of Understanding the Stakeholder Needs consists of the System Analysis. This analysis answers the questions ‘Which functions should the system perform?'; 'What is required of those functions?’, and ‘What are its interactions with the Actors lying outside the system boundary?’ Answering these questions also means setting a strict system boundary.

The system analysis identified three main functions for the PPE system – providing propulsion power, providing payload (military systems) power, and providing auxiliary power. The test case that is described in this paper covers specific requests for propulsion, payload and auxiliary power. Doing a high speed turning circle while intermittently re-charging Electro-Magnetic and Optical Sensors and Weapons, means the PPE system should be able to provide the requested propulsion power for the sailing manoeuvre, and at the same time the payload power for sensors and weapons.

The results of the System Analysis are summarized in Table 2-2. The left part shows the data per service (Payload, Propulsion, Auxiliary), the right part of the table shows the data per Mission Type.

Table 2-2 Summary of the results System Analysis

Max Consumed Power [kW]					**Total Consumed Energy [MWh]**	**Exhaust Emissions**	
Per Service			**Per Mission Type**			**GHG**	**Pollutants**
Payload	**Propulsion**	**Auxiliary**	**Mission Type**	**Total**			
8000	18162	800	I – Intercontinental Transit	12547	1512	70% Climate Neutral	IMO Tier III
			II – Short Military Voyage	19362	575	70% Climate Neutral	IMO Tier III
			III – Long Military Voyage	12547	1039	70% Climate Neutral	IMO Tier III
			IV – Zero Emission Transit	2202	27	Zero Emission	

Since the services do not peak simultaneous, maximum power per mission is lower than the sum of maximum service powers. The total consumed energy at this stage does not include efficiency losses and bunker margin.

From Table 2-2 it can be concluded that Mission Type I - Intercontinental Transit has the highest effective energy and is therefore determinative for the amount of climate neutral energy carrier. The PPE system has to meet 70% Climate Neutrality and IMO Tier III emissions requirements for Mission Types I, II, and III. Mission Type IV - Zero Emission Transit is determinative for the amount of zero emission energy carrier.

While future weapon systems like railgun have a wide range of energy requirements ranging from hundreds of kilojoules to hundreds of megajoules [3], [4], [5], this paper considers a 10 MJ railgun modelled on the PEGASUS [4]. It is assumed that the capacitor modules within the railgun system deliver the required pulsed power and the role of the PPE system is the recharging of these capacitors. To meet a firing frequency of 0.2 Hz, the railgun system is charged with 2.5 MW for 4 seconds allowing the system to be operated every 5 seconds. While the charging profile can be controlled to reduce the dynamic load on the power system, in this case a step power profile is used to simulate an extreme scenario.

2.2. *Architectural Design of the PPE System*

2.2.1. Selection of suitable Technologies

After the Needs were clear and registered, an exploration of possible PPE-system technologies and configurations was done. This step typically answers questions, like which technology solutions meet the requirements? What are the expected total size and weight of those solutions and do they, in theory fit into the ship? For this MARIN's Ship Power & Energy Concept (SPEC) tool was used. The result of this analysis was the selection of a hybrid power and propulsion system with DF-methanol ICEs, Fuel Cells supplied with compressed hydrogen, and Batteries.

The Methanol (CH_3OH) ICE solution complies with the requirement of climate neutrality for mission types I, II, and III. The Dual Fuel variant is allowed because of the 70% climate neutrality and preferred by the stakeholders for having fuel flexibility. The Compressed Hydrogen (Comp H_2) Fuel Cell solution complies with requirement of Zero Emission for mission type IV. The battery (Electric Storage) is selected for Dynamic Support of the Fuel Cell, but can also provide power equalization to the DF Methanol Generator Sets. Hybrid Propulsion, i.e., a propulsion system with a DF Methanol ICE and an Electrical Machine connected to each shaft, was mainly a CapEx and volumetric consideration as the maximum propulsion power is not requested simultaneous with the maximum payload power, the main ICEs can also provide payload power in the propulsion mode ‘Shaft Generation’.

2.2.2. *Logical Architecture*

The PPE solution, as described in Section 2.2.1, was worked out in more detail as Logical System Architecture. In the Logical Architecture the system functions were refined into subfunctions and assigned to logical components. The result is the system topology as shown in Figure 2-2.

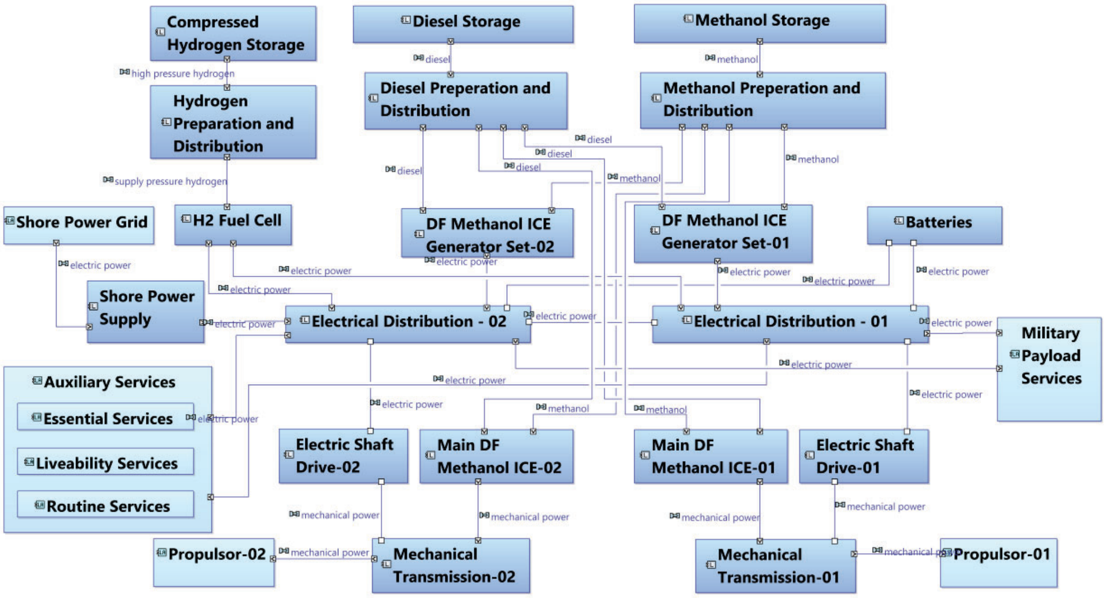

Figure 2-2 Logical Architecture of the Power, Propulsion and Energy system of the Surface Combatant

The architecture contains multiple operating modes, like Mechanical Propulsion, Electric Propulsion, Cross-Shaft Propulsion, and Shaft Generation. While the cross-shaft operation is considered for economic cruising, in this paper we focus on the propulsion mode shaft-generation. At a ship speed of 18 [Kts] the Internal Combustion Engines are not yet at their maximum power. The architecture of how the engines, electric shaft machines and the electrical distribution system are coupled enables the remainder of the available power of the main Internal Combustion Engines to be used as Payload Power (electro-magnetic and optical sensors and weapons).

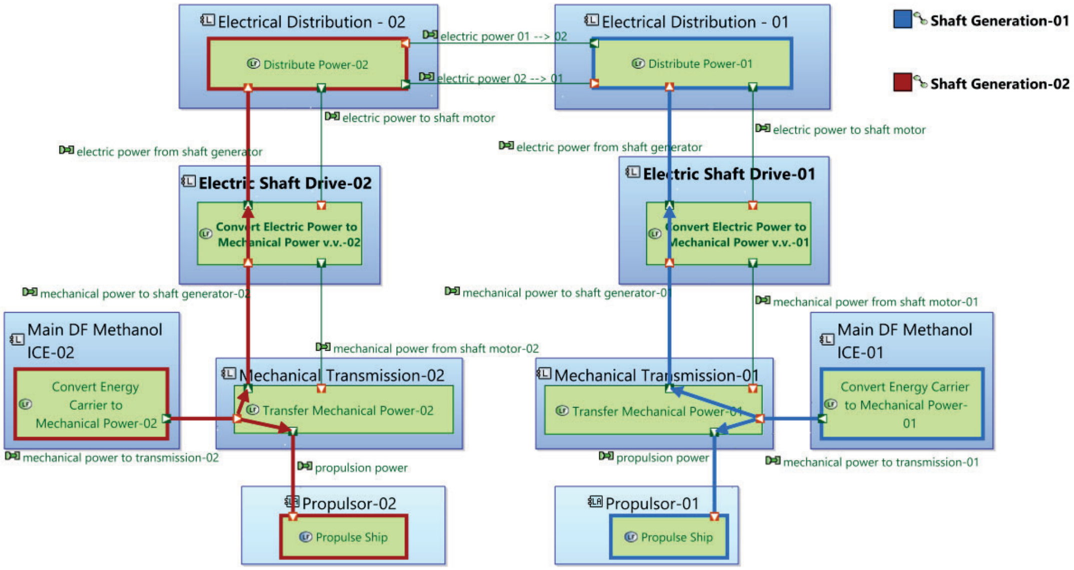

Figure 2-3 Logical Architecture of the Electric Shaft Drives. The Functional Chains of the Shaft Generation mode are shown.

2.2.3. Physical Architecture

The topology of the Logical Architecture was designed and extended into a Physical Architecture, as shown in Figure 2-4. Power of the propulsion engines was chosen such that the vessel can reach its maximum speed on these engines only, allowing a diesel-only sailing fallback scenario. Sizing of all other components was chosen by balancing the required size, weight and resulting bunker volume. Distributing the requested power as shown in Table 2-2 over multiple smaller power sources increases efficiency during operation.

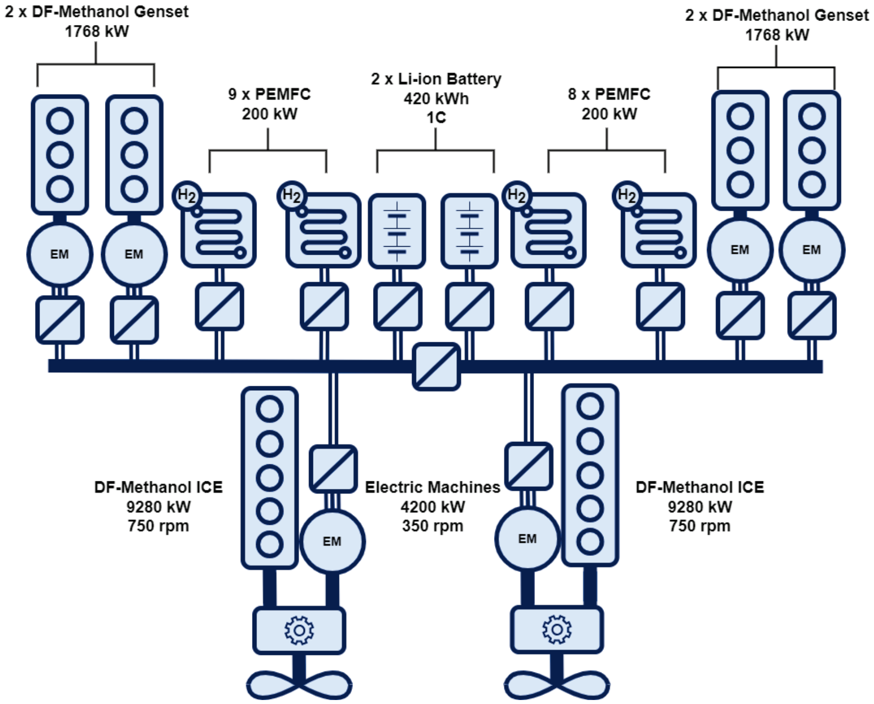

Figure 2-4 Physical Architecture of the Power, Propulsion and Energy System of the Surface Combatant

The Geometrical Arrangement of the PPE system is shown in Figure 2-5. The Building Groups that are arranged correspond to the Physical Architecture as shown in Figure 2-4.

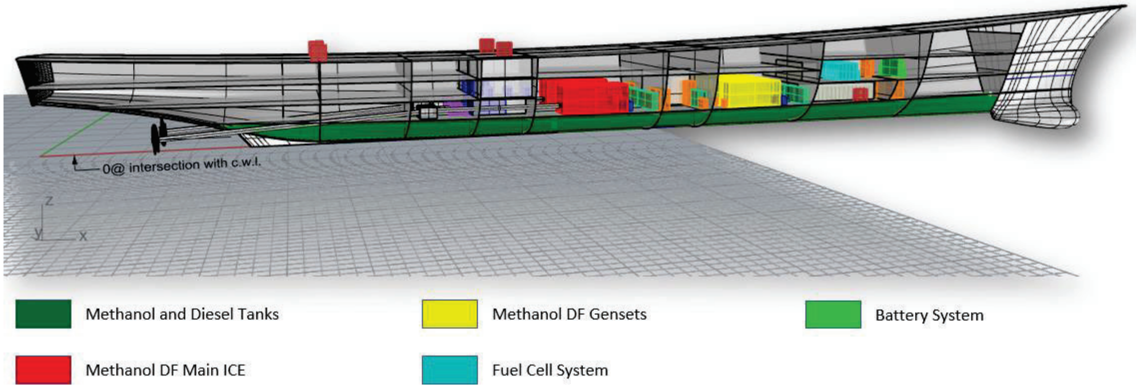

Figure 2-5 Geometric Arrangement of the PPE system

Mission Type I “Intercontinental Transit” has been determinative for energy storages sizing since it is the most energy demanding one. The autonomous design range has been set at 3500 nmi which corresponds to an endurance of 328 hours, including a 10% bunker margin. The ICEs in the design run on a blend of 5% in volume of Diesel (pilot fuel) and 95% in volume of methanol (main fuel). Considering the energy densities of the different fuel, the resulting energy fraction is given in Table 2-3.

Table 2-3 DF-Methanol ICE Energy Fractions

	Unit	**Diesel**	**Methanol**
Energy density	MJ/kg	42	19.7
	MJ/l	35.8	15.60
Contained Energy density	MJ/kg	29.6	14.50
	MJ/l	33.2	13.60
Density	kg/m3	840	792
Volume fraction		5%	95%
Energy fraction		**11%**	**89%**

When examining the developed power to consumer efficiency of the Main Internal Combustion Engine (ICE), a weighted average efficiency has been computed to determine the energy consumption during Mission Type I. This efficiency was calculated by factoring in the developed power to consumer efficiency of the Main ICE's for each individual task that takes place throughout the mission, with each task's contribution weighted based on its duration. The resulting weight and volume of the fuels are given in Table 2-4.

Table 2-4 Fuel storage sizing

Fuel	**Total Required Energy Carrier**	**Weight**		**Volume**	
		Uncontained	Contained	Uncontained	Contained
	MWh	tonne	tonne	m^3	m^3
Diesel	463	40	56	46.5	50
Methanol	3744	684	930	864	991

3. Simulation of the concept

As described by the W-model in Figure 1-2, the virtual model cycle is used to test that the designed Power, Propulsion and Energy (PPE) system meets the developed requirements. For this, a number of virtual vessel models are created of varying fidelity levels according to the questions to be answered. This paper addresses the dynamic performance of the PPE system, hence, the dynamic models for the PPE system and the ship-propeller are briefly described in the section.

3.1. The PPE system

The virtual model of the PPE system is constructed based on the Physical Architecture shown in Figure 2-4. However, as the simulated test case considers the Operational Task “Perform Military Operations,” the Fuel Cells have not been included as they are not operated in these tasks. The remaining components are modelled in Matlab-Simulink using approaches that have been widely reported in literature[6], [7] and are not repeated in this paper .

The architecture of the designed PPE system includes a hybrid propulsion system with a Controllable Pitch Propeller (CPP). The operating chart of this system is shown in Figure 3-1.

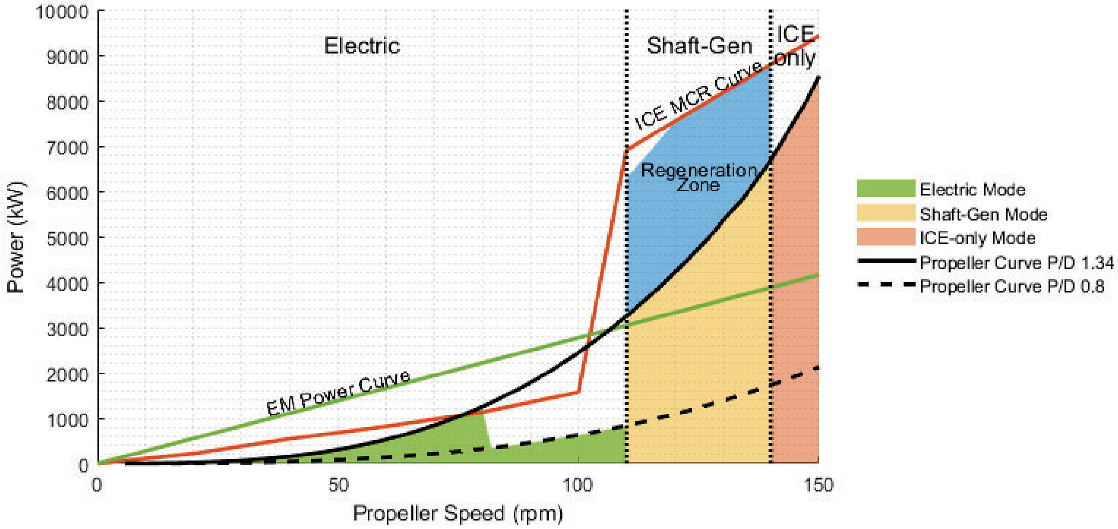

Figure 3-1 Propulsion Operating Modes. Three modes of operation are possible – electric mode, between 0 and 110 rpm, shaft generation mode between 110 and 140 rpm, and ICE-only mode. In the Shaft-Generation mode, the main propulsion ICEs deliver the propulsion power while the excess available power is fed to the distribution system by the electric shaft machines.

The propulsion system can be operated in four modes – electric, shaft-generation, cross-shaft, and ICE only. For the simulations presented in this paper, only electric, shaft-generation, and ICE only are considered. In the electric mode, the propulsion power is provided by the electric machines alone, this propulsion power along with auxiliary and payload power is provided via the DC distribution system by the connected DF-Methanol Gensets, Fuel Cells and Batteries. In the Shaft-Generation mode, the main DF-Methanol ICEs provide the propulsion power, and the electric machines feed the excess power back to the DC distribution system for the auxiliary and payload services. In the ICE-only mode, the propulsion and power systems are decoupled, with the main DF-Methanol ICEs providing all the propulsion power and the gensets and batteries providing the auxiliary and payload power for the services connected to the distribution system. To achieve operation with the constraints of the power curves of the electric machine and the ICE as well as the available power on the DC distribution system, the pitch of the CPP is actuated between P/D ratio of 1.34 (the design ratio) and 0.8 when the propeller speed is between 80 and 110 rpm. The propulsion system is operated in torque control, with the torque and pitch setpoint generated by the combinator curve.

The power system is managed by the Energy Management System (EMS) and the Power Management System (PMS). The EMS generates power setpoint advice for the available power sources on the distribution system and the PMS ensures stable operation by converting this advice to control commands to be followed by the lower control layers. The lower control layers operate using droop control to achieve the operating point decided by the

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EMS and PMS. The EMS used in these simulations is a simple rule-based system that acts on the load on the distribution system to allocate power amongst the different power sources. The operation of the EMS and PMS is shown in Figure 3-2.

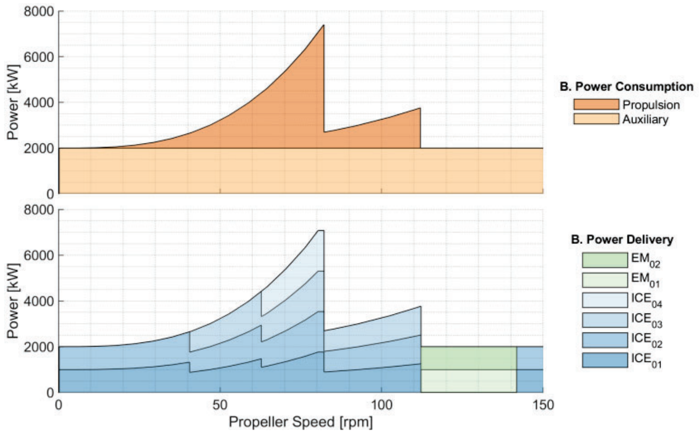

Figure 3-2 Example of the operation of the EMS and PMS. The EMS uses a simple rule-based approach to advice the power allocation between the sources on the DC distribution system.

In the electric mode, the power system (comprising of 4 DF-methanol gensets and 2 batteries) provides all the power demand. The gensets are turned on according to the load with the constraint of a spinning reserve of 50% of the nominal power of a single genset in addition to the batteries to allow fast ramp-up of payload power during military operations. The operated gensets share power equally and the battery is used as a peak-shaver and power ramp support along with its role of providing spinning reserve. When the system transitions to the Shaft-Generation mode, the electric machines provide power to the power system loads (i.e., the auxiliary and payload services) from the excess power available in the propulsion lines. This can be seen in Figure 3-2, where between the propeller speeds of 110 and 140 rpm, the complete auxiliary power of 2 MW is provided by the electric machines. In the ICE-only mode, the propulsion and power systems are decoupled and the load on the DC distribution system is delivered by the combination of DF-methanol gensets and batteries with identical rules as in the electric mode.

There are three separate services that the PPE system must provide power for – propulsion, auxiliary and payload. The propulsion services are modelled using a complete ship-propeller-environment model as described in Section 3.2. The auxiliary and payload services are modelled as power consumers on the DC distribution system. The power consumed by these services have been identified in the Needs Analysis, as explained in section 2.1. Additionally, as the test case demonstrated in this paper involves intermittently re-charging Electro-Magnetic and Optical Sensors and Weapons (as noted in Table 2-1), additional power consumption for this sensor and weapon system is considered in the payload services.

3.2. Ship and propeller simulation method

The manoeuvring while sailing in waves is simulated using MARIN's time simulation framework XMF. The ship and propeller simulations predict the load variations for the PPE system, while the effects of any limitations of the PPE system are taken into account (2-way coupling). A more elaborate description of the ship propeller simulation method can be found in Moulijn et al. [8].

3.2.1. *Two-timescales method*

The ship and propeller are modelled using a two-timescales method that was first introduced by Yasukawa & Nakayama [9]. The manoeuvring motions and the motions due to low frequent wave drift forces are solved by a time domain simulation method. The wave frequent motions and propeller inflow variations are calculated by means of a linear frequency domain seakeeping method which are superimposed on the (low frequent) results of the time simulation method.

The wave forces (and moments) acting on a ship that is sailing in waves can be split in two components: first order (wave frequent) forces and second order drift forces. The first order forces have a zero mean value, the variations happen at frequencies that are equal to the ship-wave encounter frequency, and the magnitude is proportional to the height of the waves. The second order forces, also called drift forces, are proportional to the wave height squared (at least up to moderate wave heights, hence second order). The drift forces have a non-zero mean value. When the ship sails in irregular waves, the drift forces are varying at a much lower frequency than the wave frequency. These low frequent variations are related to the occurrence of wave groups. Sometime the ship is encountering several high waves. This results in large drift forces. A little later the sea is more quiet and the drift forces are low. The mean value of the drift force component in sailing direction is often called *added resistance due to waves*.

The basis of the ship and propeller simulation model is a calm water manoeuvring time simulation model. An additional force is introduced that represents the (mean and low frequent) drift forces. This force causes low frequent ship speed variations and consequent propeller inflow variations. The wave frequent ship motions and propeller inflow variations are calculated by means of a 3D linear frequency domain seakeeping code. This method calculates the disturbed wave pattern around the ship, which appears to be crucial for an accurate prediction of the propeller inflow variations. The wave frequent motions and inflow variations are simply superimposed on the low frequent motions and inflow that are predicted by the time simulation method. The seakeeping method also predicts the drift forces.

3.2.2. Propeller load variations

The propeller model in the simulations is based on open water characteristics. A 4 quadrant form of the open water characteristics is used [10], which has the advantage that the model always provides an adequate solution (also for off-design conditions like backing or a non-rotating propeller). The load variations are caused by the inflow variations to the propeller due to manoeuvring and/or ocean waves.

Special attention was paid to the propeller inflow model in the manoeuvring simulation method. When a ship is sailing under drift and/or in a turn, the inflow to the propellers is very different from the inflow when the ship is sailing straight. Figure 3-3 shows a visualization of a CFD prediction of the flow around a naval surface combatant that is sailing under 25° of drift to port.

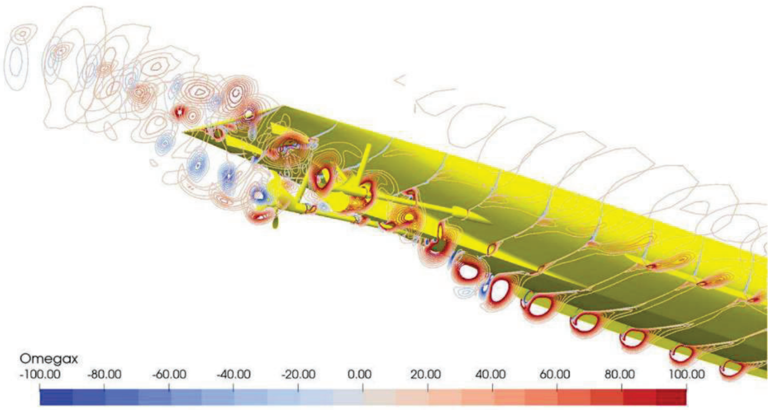

Figure 3-3 Vortex flowing through the starboard propeller of a naval surface combatant

The effect of the resulting swirl (i.e. averaged inflow rotation) in the wake fields on the effective RPM of the propellers is included in the manoeuvring simulation model. It can cause a strong difference between the load on the inside and the outside propellers of a ship that this sailing a turn. More details about this inflow model can be found in Moulijn et al. [8].

The effect of the ocean waves on the propeller model is predicted by means of the linear frequency domain seakeeping method named SEACAL. This is a 3-dimensional method (unlike strip-theory). This method accurately predicts the waves and water motions around the ship due the undisturbed incoming waves, the diffracted waves and the radiated waves due to the motions of the ship. The effect of forward speed on the waves is included.

3.2.3. Validation

The two-timescale simulation method to predict the propeller loads and ship motions of a ship that is manoeuvring in waves was validated against an extensive dataset for the DTMB 5415M naval surface combatant. The results are presented in Moulijn et al. [8]. Main conclusions are that this method gives reasonably good results for head and bow quartering waves. In stern quartering waves the agreement is less good, yet useful.

3.3. Coupling of the Ship and propeller to the PPE simulation

The ship and propeller simulation is running in co-simulation with the time simulation of the PPE system. This implies that information between the two simulations is exchanged at fixed common time steps, typically at the time step of the simulation that is running at the lowest frequency, which is the ship/propeller simulation in this case. The hydrodynamic torque that acts on the propeller is send to the PPE simulation. The shaft rotation is solved in the PPE simulation, where the rotational inertia of the propeller and its entrained water are taken into account. Subsequently the resulting propeller RPM is send back to the ship/propeller simulation.

With this method the effect of the propeller load variations on the PPE system are predicted. The method also predicts the effects of any limitations of the PPE system on the manoeuvring behaviour of the ship. When the PPE system cannot maintain the required RPM this will result in a lower thrust and the speed and heading keeping capabilities of the ship will reduce.

4. Test Case 'Highly dynamic military operation, involving a turning circle at high speed, while repetitively firing a railgun'

To demonstrate the use of virtual models for design verification and refinement, a test case involving a military manoeuvre is simulated using the models described in Section 3. The turning circle manoeuvre is performed sailing at an average speed of 18 knots in sea state 6 while the pulsed power weapon system is recharged for operation at a frequency of 0.2 Hz. The environmental conditions for the simulation are derived from NATO definitions. This is a significant wave height of 5 m, and a wave period of 12.4 s. The test case description is summarised in Table 4-1.

Table 4-1 Test Case Description

Description	unit	Value
Operational Task	-	Military Operations
Manoeuvre	-	Turning Circle
Sea State	-	6
Significant Wave Height	m	5
Wave Period	s	12.4
Required Average Ship Speed	kts	18
Auxiliary Services Power	kW	520
Payload Services Power	kW	5600
Railgun Recharge Power	kW	2500 for 4s
Railgun Firing Frequency	Hz	0.2

The ship performance for this test case is shown in Figure 4-1. The ship course shows that a turning circle manoeuvre is performed with firing operations occurring for a period of 100 s during the manoeuvre. It can also be seen that the vessel maintains an average speed of approximately 18.3 knots in the manoeuvre thus meeting the requirement of the average speed being greater than 18 knots. As the ship accelerates to this speed (i.e., between 0 and approximately 250 s), it starts in the electric mode where the electric machine provides the propulsion power. It then transitions to the shaft generation mode where the DF-methanol ICEs provide propulsion power and the electric machines feed the additional available power to the DC distribution system. It is seen that during the firing operations between 700 and 800 s, the electric machine exhibits power fluctuations due to the highly dynamic load of the rail gun. The main DF-methanol propulsion ICE is slower to respond, therefore, dynamics are introduced in the power delivered to the propeller resulting in speed and torque variations of the propeller. Therefore, while it is clear that while in the electric mode dynamics on the propulsion system would affect the power system, these simulations show that in the shaft-generation mode dynamics on the power system do have an effect on the propulsion system as well.

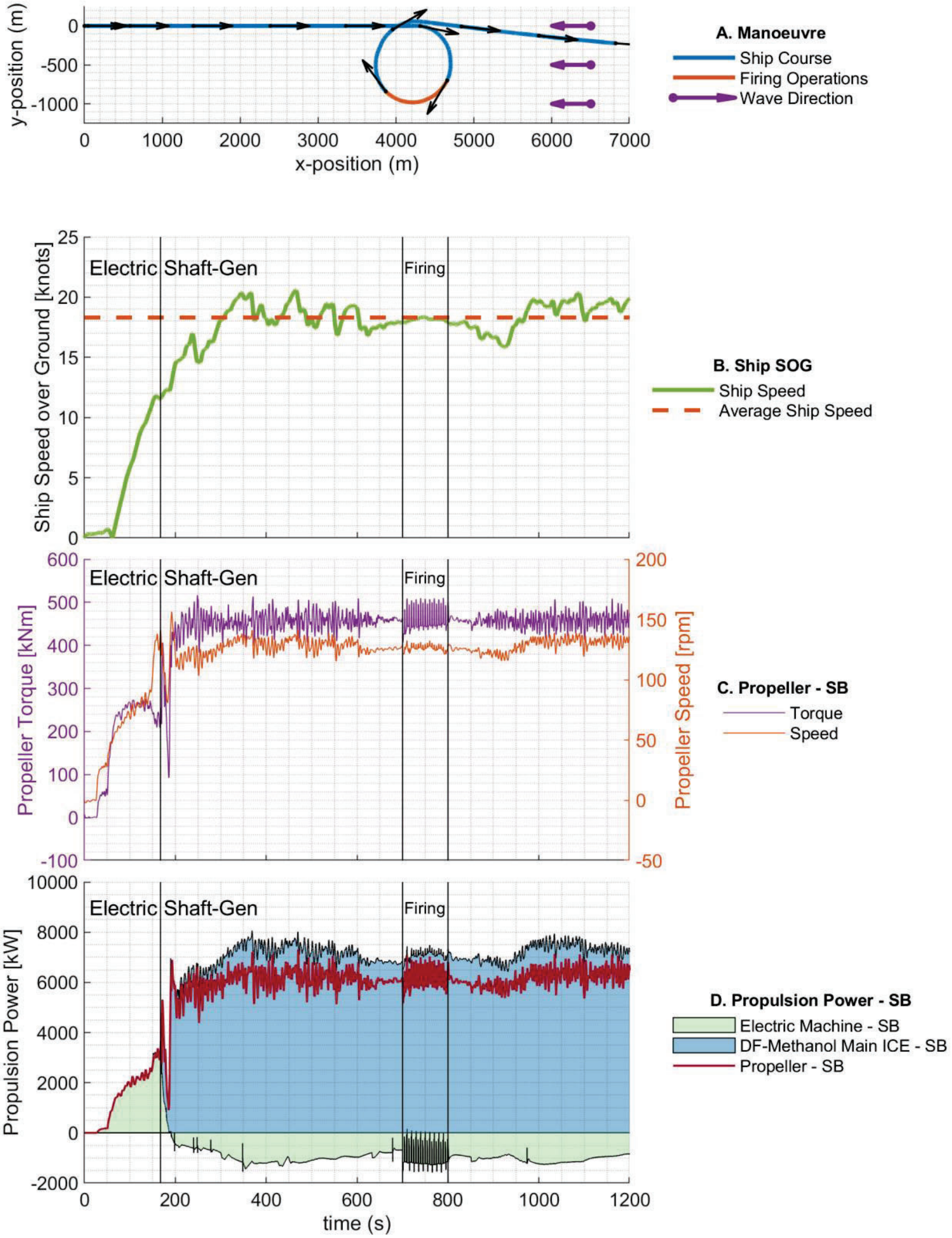

Figure 4-1 Ship performance for the simulated test case. The vessel operates in shaft generation mode where the Electric Machine operates as PTO and feeds excess power from the propulsion to the DC-distribution system. The vessel meets the test case speed requirement of maintaining an average speed of 18 knots when performing a turning circle manoeuvre in sea state 6 while recharging a railgun.

Figure 4-2 shows the performance of the PPE system focussed on the period of firing. To meet the dynamics introduced by the railgun there are two sources with high dynamic capabilities – the electric machines acting as generators and the battery systems. These sources have high ramp rate capabilities and increase power output to meet the demand. The power delivered by the batteries is limited by their nominal power capabilities while that for the electric machines is limited by the excess power available on the propulsion system. The DF-methanol gensets also contribute to the power dynamics, however, because they are slow acting sources their contribution is limited. These dynamics are reflected in the DC-bus voltage and while the system remains in operation, it is on the edge of the operating region and the large voltage variations could result in power quality issues though the power system. While these simulation results show that the designed system meets the set requirement, there are opportunities for design refinement:

- Batteries with higher discharge capabilities could be used to take up the dynamics loads leading to reduced dc-bus voltage disturbances. With more power available on the grid, the railguns could be charged with a lower ramp in power.
- Additional supercapacitors could be added to the system and designed according to a required firing pattern. The supercapacitors can be sized to meet the energy requirement for a number of salvos followed by a longer charging period where the batteries charge the supercapacitors with lower ramp-up and ramp-down rates.
- More power could be made available to the DC-bus from the propulsion system via the electric machines. This could be implemented by additional settings in the combinator curve where the pitch is reduced for firing the railgun in heavy seas. This would make additional power available for the DC-grid at the cost of a possible reduction in the achievable ship speed.

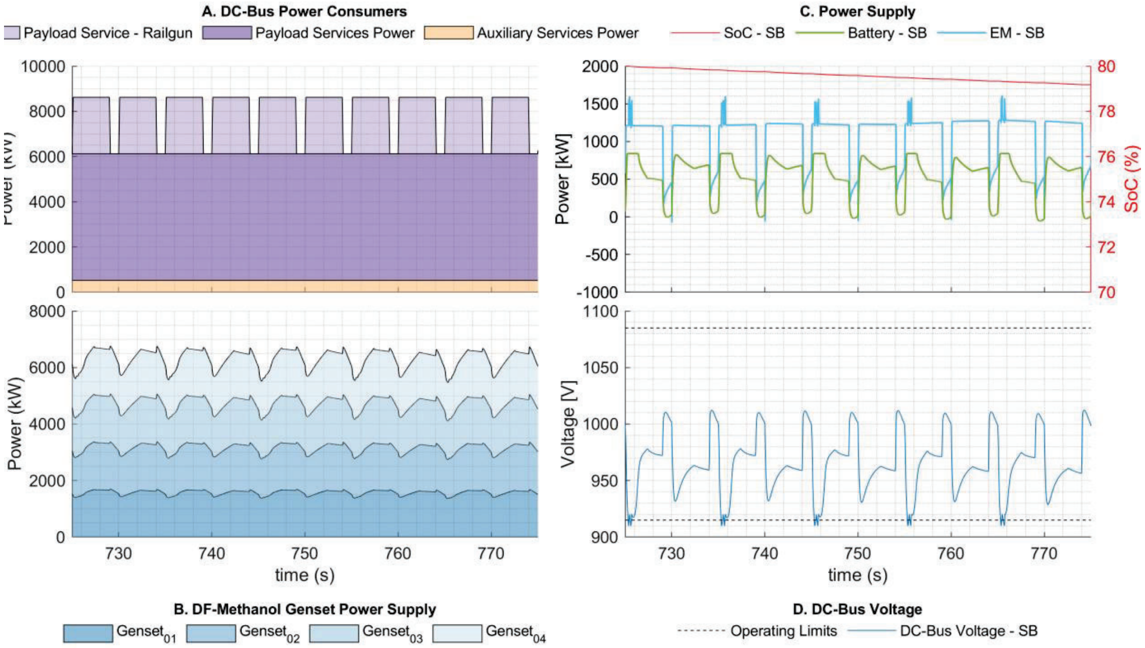

Figure 4-2 PPE System performance for the simulated test case focussed on the recharge operations of the railgun. The fast load dynamics are met by the batteries and electric machines acting as generators. While the system remains in operation, large voltage variations on the DC-bus are observed.

From the simulations it is clear that the electric machines contribute to meeting the dynamic demands of charging the railgun. It can therefore also be concluded that when sailing in the electric mode, without the possibility of feeding power to the DC-grid using the electric machines, the availability of dynamic power sources is limited to the batteries and the firing frequency of 0.2 Hz cannot be met. Therefore, a firing frequency of 0.1 Hz with a charging power of 1.25 MW for 8 s is simulated and the results presented in Figure 4-3. In this case too there are sharp dynamics seen on the DC-bus due to the charging profile which may be reduced with the addition of supercapacitors or batteries as discussed above or by implementing a combinator curve that allows sailing in the shaft generation mode at low vessel speeds for these firing operations.

It is clear with the simulation of this test case that the developed design should be refined to provide better performance during such challenging operations as sailing in heavy sea with re-charging of electro-magnetic and optical sensors and weapon systems. The results show the value of performing dynamic simulations to verify requirements involving dynamic situations that static calculations do not consider leading to valuable insight for further design iterations.

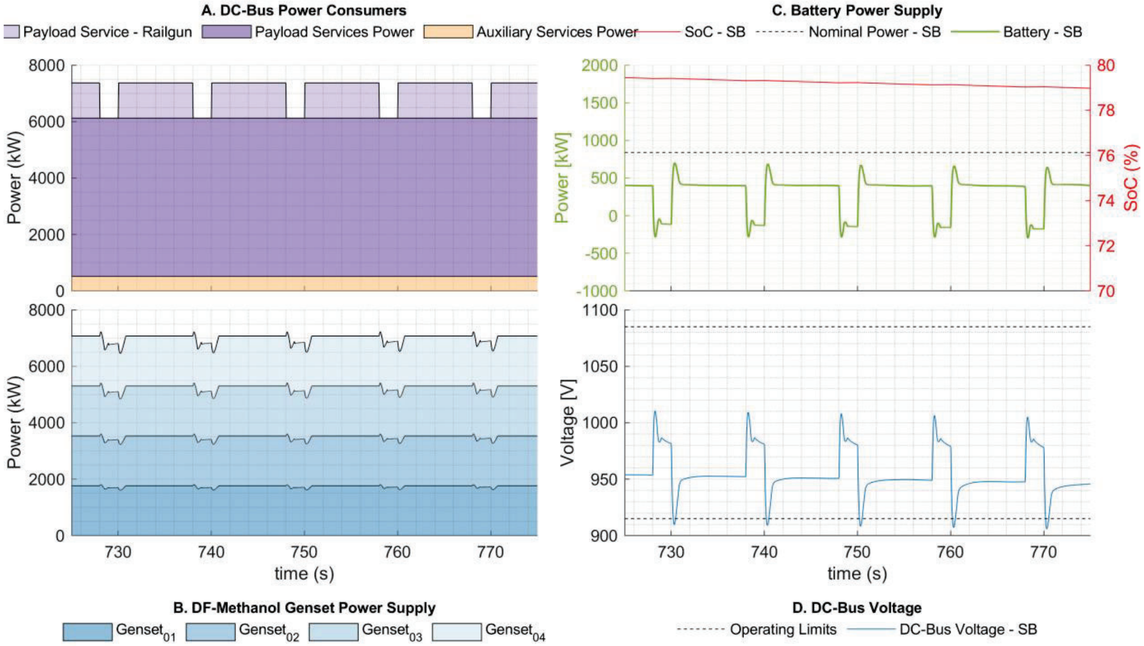

Figure 4-3 PPE performance focussed on railgun recharge operations while sailing in electric mode. Due to limited fast acting sources being available in the electric mode, the designed system in not capable of recharging the railgun for firing at 0.2 Hz. The results for a firing pattern with the railgun firing at 0.1 Hz is simulated.

5. Evaluation of Exhaust Emissions, Radiated Noise and detectability

After designing and testing the primary functionalities of the vessel, in this section two secondary characteristics of the ship's PPE system will be assessed; its exhaust gasses, radiated noise, and detectability. These aspects can be analysed from two different perspectives. For defence capabilities, they play a tactical role in detectability and susceptibility, while both also have an environmental impact. For military applications it is debatable whether exhaust gas emissions are of primary concern. Nevertheless a voluntary compliance [11] with Annex VI – Warships of the MARPOL Convention is frequently mentioned nowadays.

The proposed PPE design differs from conventional diesel powered systems in multiple ways. It has an intelligent topology, it makes use of methanol and hydrogen, and it can run in different operating modes. This has a significant impact, which will be analysed in this section. The analysis of CO_2 emissions is based on calculations performed during the conceptual design phase. All other aspects are considerations based on academic and industry knowledge and insights in the concepts and implemented components. Future research including further modelling and measurement of emissions and noise is on MARIN's research agenda.

5.1. Greenhouse gas emissions

The main concern with respect to global warming is the emission of CO_2 originating from fossil fuels, acting as a greenhouse gas in the atmosphere. The reduction can be achieved along two different pathways. A fuel with no or low carbon content can be used, in this way minimizing the tank to wake emissions. Another approach is to apply a fuel which is originating from renewable sources. Because no fossil fuel is extracted from earth as a source for such fuels, no new carbon (CO_2) is added to the atmosphere. Also for carbon-free fuel it is relevant that they are originating from renewable sources, otherwise their well to wake impact is limited.

In the proposed PPE design both pathways are followed. When operating on the fuel cells, or short-term on the batteries, no local emissions are produced. When either the propulsion engines or the gensets are used, exhaust gas is emitted by the dual fuel methanol engines.

To have a significant impact on greenhouse gas emissions, the dual fuel engines should run on renewable methanol. Today less than 1% of available methanol is green, the remainer is from fossil fuels[12]. With the ongoing adaption of methanol as shipping fuel to increase sustainability of the sector, this percentage is expected to grow. Besides an increase in bio-methanol production, the bulk of the growth is expected to originate from e-methanol; the hydrogen and captured carbon production route for synthetic methanol. To be sustainable, the used hydrogen has to be produced from renewable electricity.

5.1.1. Results for the concept

In the proposed concept the bulk of the greenhouse gas reduction comes from the application of renewable methanol and hydrogen. The exact number of the reduction is strongly dependent on the used sources to produce the fuel, and on the boundaries taken into account when calculating Well to Wake (WtW) CO_2 equivalent emissions. Considering a fossil reference of 99g CO_2 equivalent per MJ for HFO, for methanol a typical range between 5 and 46 gCO_2eq/MJ is reported [13]. In line with this, the ZERO project considers a 90% reduction of greenhouse gas emissions when applying methanol. Since in the designed concept dual fuel engines running on a 95% Methanol Energy Fraction (MEF) during medium and high load, still 5 percent of the energy is supplied by diesel, MFO or HFO. This limits the reduction of greenhouse gas emission by the choice of renewable methanol as a fuel to 86%. On low load the MEF value for most engines is even lower, but the versatile design of the PPE system can be controlled such, that engines are not used at very low load conditions. This is achieved by the introduction of electric, cross-shaft, and shaft-generation modes for the PPE system.

A further reduction could be achieved by replacing the fossil marine fuel oil by renewable Hydrotreated Vegetable Oil (HVO). This can be a direct substitution, so would not require further technical changes to the PPE system.

The fuel cells are used as the only power source in the zero emission operating mode, and can act as a support power in the other operating modes. They operate on hydrogen, so no direct CO_2 emission is taking place. For the well to tank emissions of hydrogen, the source for hydrogen production is relevant. In the worst case scenario, grey hydrogen is produced from fossil fuel, at an estimated 81 g CO_2 per MJ. This is only a small advantage compared to HFO. In the best case scenario green hydrogen is produced from offshore wind electricity, at 4.9 g CO_2 per MJ [14].

Since the ship's performance, weight, size and are changed, and only limited information of the diesel powered reference ship can be shared, it is not possible to make a direct comparison on absolute numbers regarding greenhouse gas emissions of the PPE system. As an alternative, a relative comparison was made, in which the efficiency improvement was estimated from the initial concept design for the four mission types. Combined with the well to tank emission of the used fuel (Fuel-based reduction), the total results were calculated. The resulting Well to Wake CO_2 reductions are shown in Table 5-1

Table 5-1 Emission reduction from fuel and PPE system efficiency increase with respect to the reference vessel operating on diesel, for all mission types

	Fuel-based GHG reduction[%]	Efficiency increase	Relative CO_2 emissions	Relative CO_2 reduction
Mission Type 1	86 %	10 %	12 %	87 %
Mission Type 2	86 %	20 %	11 %	89 %
Mission Type 3	86 %	20 %	11 %	89 %
Mission Type 4	95 %	60 %	2 %	98 %

It is good to notice that the bulk of the improvements come from the implementation of the renewable fuels. Although significant efficiency improvements can be achieved with new PPE system designs, they only have a limited effect on the total CO_2 reduction, because of the very low the WTW CO_2 impact of the chosen fuels. Nevertheless it is still preferable to increase system efficiency as much as possible. High efficiency results in lower fuel consumption and thus lower fuel costs. It has a direct impact on autonomy and/or the required bunker volume and mass, which ease the ship design. Finally, other emissions also scale with fuel consumption, and thus in general benefit from higher efficiency.

For mission type 1, 2 and 3, the Greenhouse Gas requirement was to be 70% climate neutral. Since the combination of fuel and engine performs better than the requirement, there is some space to sail a part of the missions with the engines in diesel-only operation. This reduces the required bunkering volume, and/or increases the autonomy of the ship. The ability to use diesel-only operation also increases fuel flexibility and thus availability of the total PPE system.

5.1.2. Non-CO_2 greenhouse gas emissions

Besides CO_2, also the emission of N_2O and methane are getting more and more attention, because of their high Global Warming Potential (GWP) [15]. For methanol dual fuel engines they are not considered as critical exhaust gas components, and occasionally reduced levels [16], [17] of N_2O are reported. Because of limited available information on the implemented engines, these exhaust gas components were not further included in this study.

5.2. Harmful emissions

The concept can run in Zero emission mode, powered by the fuel cells. When in other modes power is delivered by the dual fuel methanol gensets or main engines, in which exhaust gas emissions have to be considered. This is done on a theoretical level, since no emission modelling or measurement was performed within this project.

5.2.1. NOx

Regarding other emissions, in the maritime world most attention goes to the emission of NO_x. This is for example recognized in IMO Tier 3 with a minimum level of level 2g/kWh. For most diesel fuelled engines this requires the use of exhaust gas aftertreatment, specifically Selective Catalytic Reduction (SCR). Although this is a very effective measure, it has a significant impact on required building space, and complicates logistics because of the involved urea (Adblue, DEF) consumption. Several research campaigns show that moving from diesel to methanol dual fuel significantly reduces NO_x emissions, but without further measures Tier III levels are still challenging [17], [18], [19]. The lowering of NO_x emissions has two different causes. The injected methanol has an almost four times higher heat of vaporization. Combined with the more than two times higher required injection mass, in total eight times more heat is extracted from the air charge of the engine. This results in a lower process temperature, and thus lower NO_x production. The other cause can be found in the details of how a fuel combusts in an engine. Diesel burns in a very concentrated fuel-rich flame, which creates a very high peak temperature, hotter than the NO_x formation threshold. The methanol burns as a lean premixed flame through the cylinder, resulting in lower combustion temperature and thus lower NO_x formation.

5.2.2. SO_x

Sulphur oxide emissions can be fully contributed to the sulphur content of the used fuel. To reduce the emission of SO_x, IMO forces a maximum global limit of 0.5% for shipping fuels or the usage of scrubber exhaust gas aftertreatment. Methanol does not contain any sulphur, so its combustion does not emit SO_x [13]. Only the used pilot fuel can create sulphur emissions. As a result a reduction equal to the Methanol Energy Fraction can be expected from the combustion engines. The fuel cells do not emitting any SO_x,

5.2.3. PM

Particle emissions (black smoke), originate from incomplete breakdown of carbon chains in hydrocarbon fuels during combustion. Since methanol does not contain any carbon to carbon bonds, it does not generate PM emissions. Only the used pilot fuel could contribute to PM emissions. Since this is only a very small amount, the dual fuel methanol engines are able to comply with todays PM emission standards without the need for a Diesel Particle Filter (DPF).

5.2.4. HC & CO

Although not significant for diesel engines, the emission of uncombusted hydrocarbons and carbon-monoxide of a dual fuel engine can be considerable [20]. This is inherit for lean burn premixed combustion. Since no specific engine, including its emission data was used for the concept design, it cannot be decided whether an oxidation catalyst (DOC) [21] is required for the conceptual PPE system to comply with emission regulations.

5.3. Detectability

5.3.1. Radiated noise

The last two decades have seen an increasing interest in the reduction of underwater radiation noise (URN). The main driver here is protection of marine life. IMO addresses the topic both in their Marine Environment Protection Committee (MEPC) and in their Ship Design Committee (SDC). The EU Marine Strategic Framework Directive 2008/56/EC defines noise specifically as a pollution, which has to be restricted. For naval applications the URN relevance is on detectability and susceptibility, specifically by sonar.

For underwater radiated noise two main sources can be recognized; propeller induced cavitation and noise from onboard machinery, which either directly or through airborne transmission to the hull, excites the water. The reduction of cavitation is a delicate interplay between hull design, propeller design, and power control. On top of MARIN’s hull and propeller experience, the wide control options for the proposed PPE system extend the possibilities for cavitation reduction.

Since noise measurements or predictions were not part of this study, we focus on available studies and conceptual impact. Regarding the machinery noise, three scenarios can be recognized.

- Direct propulsion by the combustion engine. With a large combustion engine running, significant machine noise is being produced. The medium speed 4 stroke engine is known to allow a more flexible and thus less noise-conducting mounting because of a lower weight than a 2 stroke engines. The dual fuel engine has a more gradual combustion profile, also slightly reducing noise vibration and harshness. (NVH).
- Electric propellor drive, powered by the gensets. Since no direct coupling with the mechanical drive is required, here a more sound isolated mounting can be applied. In a study by TNO[22] this configuration was recognized as being more silent than diesel direct. During operation the hybrid mode could specifically be selected (and optimized) for that purpose.
- Electric propellor drive, powered by fuel-cells. Although the balance of plant of the fuel cells includes air blowers which can be relatively loud, not much sound is generated in strongly transmitting low frequency spectrum <125Hz [23]. The fuel cell mode is often referred as zero emission mode, but it can also be used as low noise mode.

Smith and Rigby [24] mentioned that low frequency noise (<125 Hz [23]) is mainly related to the propulsion engine firing rate and the propeller blade-rate harmonics. Higher frequencies originate from machinery, propeller and flow noise, and cavitation.

In a recent study the relation between electrification and airborne and underwater noise radiation was investigated [25]. This was done for three different hybrid ferries, consisting of an electric drive which could be powered by a diesel generator or batteries. Although the measurements were done at relative low speed in calm water, it nevertheless gives an impression of the impact of different power systems on radiated noise. In air the difference can be seen on around the engine’s base frequency. In the water the gensets only have a limited impact on the URN. Here it was concluded that the step from direct drive to genset operation has a larger impact on URN then the elimination of gensets in favor of another electricity power source.

5.3.2. Infrared

In a follow up NATO standard ShipIR/NTCS could be followed to come to a quantitative conclusion on infrared detectability. Regarding the exhaust gasses, the main contribution comes from the presence of carbon dioxide and water vapour at higher temperature. Although the methanol engine in general has a lower CO_2 concentration, a higher H_2O concentration and a slightly lower temperature, there is no change in the order of magnitude of these influences. Taking into account that it is common to passively cool the exhaust gas to close to ambient temperature, the impact of changing from diesel to methanol on the detectability by temperature will not be further discussed here.

Relevant is the possibility of the proposed PPE system to operate without running the combustion engines. Care has to be taken that this transition takes some time before it eliminates the impact of detectability, because of the heated exhausts, ducts and related components. They require time to cool down.

5.3.3. Exhaust gas components

Besides the measurement of temperature by IR, the Short Wave Infrared (SWIR) and Near Infrared (NIR) can also be used to detect specific component concentrations in the atmosphere. This is for example globally done for the detection of super-emitters of methane [26]. From a satellite only a limited resolution can be achieved, but more local detection could be done by for example an observation airplane or drone. In such a scenario, the increase of hydrocarbons from a dual fuel engine is a disadvantage. On the other hand, the close to zero soot emission prevents direct optical observability caused by black smoke.

6. Conclusions

This paper presents the conceptual design of a future surface combatant operating on methanol and hydrogen designed to meet the requirement of a 70% carbon neutral operation and the ability to sail short zero-emission missions. It further demonstrated the use of virtual models to test the ability of the design to meet requirements at an early design stage by simulating a test case of the vessel sailing in heavy seas while repeatedly firing a pulsed electro-magnetic weapon system. The concept design and requirement verification was followed by a qualitative analysis of the emission performance of the developed design. This study draws conclusions on a number of aspects related to the design of a complex future surface combatant.

From the standpoint of the design method, the study shows that a complex concept requires a systematic development method. The W-model employed in the study uses a thorough investigation of user needs to develop logical and physical design architectures. These architectures are tested in simulation to ensure that they meet the requirements developed in the design process. It also highlighted the use of such simulations in design refinement.

From the standpoint of simulation for requirement verification, the paper shows that by coupling dynamic PPE system models to hydrodynamic models in MARINs XMF framework an integrated verification could be performed. It showed how these two disciplines interact and have an effect on each other thereby making such integrated testing an important capability for testing new PPE and ship systems.

From the standpoint of the suitability of the developed design, the paper shows that while highly dynamic electro-magnetic weapon systems like railguns pose real challenges to the power system, future PPE systems could meet these challenges by using smart design and control approaches that leverage the use of fast power sources like batteries. It also shows the ability of the developed design to achieve a reduction of close 90% in greenhouse gas emissions while maintaining fuel-flexibility and autonomy extension with the conservation of a diesel-only sailing mode. It also shows the multi-mode concept that includes fuel cells and gensets allows multiple ways of reducing underwater radiated noise. In summary, the paper shows that demanding military operations can be performed, in a reliable way, by low-greenhouse gas Power, Propulsion and Energy systems.

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References

[1] "ZERO | MARIN." [Online]. Available: https://www.marin.nl/jips/zero
[2] C. Veldhuis, A. Grasman, J. Willemsen, and U. Shipurkar, "Systematic design of future marine power & energy systems," presented at the PRADS 2022, Dubrovnik, Croatia, Oct. 2022.

[3] D. S. Warnock, “Design and Optimisation of a 600-KJ Railgun Power Supply,” MSc, Naval Postgraduate School, Monterey, California, 2003.

[4] I. R. McNab *et al.*, “Development of a naval railgun,” *IEEE Trans. Magn.*, vol. 41, no. 1, pp. 206–210, Jan. 2005, doi: 10.1109/TMAG.2004.839285.

[5] F. Beach and I. McNab, “Present and Future Naval Applications for Pulsed Power,” in *2005 IEEE Pulsed Power Conference*, Monterey, CA, USA: IEEE, Jun. 2005, pp. 1–7. doi: 10.1109/PPC.2005.300462.

[6] S. Wilkins, U. Shipurkar, A. Dadikozyan, and C. Veldhuis, “Co-Design and Energy Management for Future Vessels,” *Modelling and Optimisation of Ship Energy Systems 2023*, 2023, doi: 10.59490/moses.2023.666.

[7] F. Mylonopoulos, H. Polinder, and A. Coraddu, “A Comprehensive Review of Modeling and Optimization Methods for Ship Energy Systems,” *IEEE Access*, vol. 11, pp. 32697–32707, 2023, doi: 10.1109/ACCESS.2023.3263719.

[8] J. Moulijn, R. Tonelli, and U. Shipurkar, “Propeller load variations for maneuvering ships in waves,” Apr. 2024, doi: 10.15480/882.9342.

[9] H. Yasukawa and Y. Nakayama, “6-DOF motion simulations of a turning ship in regular waves,” in *Proceedings of the international conference on marine simulation and ship manoeuvrability*, 2009, pp. 508–517.

[10] G. Kuiper, “The Wageningen propeller series,” *MARIN Publication 91-001’Published on the occasion of its 60th anniversary, MARIN Wageningen, The Netherlands*, 1992.

[11] J. M. Pernas Urrutia, R. Villa Caro, R. José De Espona, C. Heritier, and R. Perez-Fernandez, “Infrared Signatures in The Modern Warship,” *IJME*, vol. 163, no. A2, Jul. 2021, doi: 10.5750/ijme.v163iA2.762.

[12] IRENA and Methanol Institute, “Innovation Outlook: Renewable Methanol,” International Renewable Energy Agency, 2021.

[13] P. T. Aakko-Saksa *et al.*, “Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options,” *Progress in Energy and Combustion Science*, vol. 94, p. 101055, Jan. 2023, doi: 10.1016/j.pecs.2022.101055.

[14] M. Hermesmann and T. E. Müller, “Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems,” *Progress in Energy and Combustion Science*, vol. 90, p. 100996, 2022, doi: https://doi.org/10.1016/j.pecs.2022.100996.

[15] P. Forster *et al.*, “Changes in Atmospheric Constituents and in Radiative Forcing”,

[16] K. Cung *et al.*, “Engine-out Gaseous Emissions in a Diesel Engine using Methanol as a Low-carbon Fuel under Dual-fuel Operation,” SAE Technical Paper, 2024.

[17] T. P. van Lieshout, V. de Jonge, R. Verbeek, A. Vredeveldt, and S. Finner, “Green Maritime Methanol: WP3 factsheet and comparison with diesel and LNG,” TNO, TNO 2020 R11822, 2020.

[18] E. Fridell, H. Salberg, and K. Salo, “Measurements of Emissions to Air from a Marine Engine Fueled by Methanol,” *Journal of Marine Science and Application*, vol. 20, no. 1, pp. 138–143, Mar. 2021, doi: 10.1007/s11804-020-00150-6.

[19] J. Dierickx, Q. Dejaegere, J. Peeters, L. Sileghem, and S. Verhelst, “Performance and emissions of a high-speed marine dual-fuel engine operating with methanol-water blends as a fuel,” *Fuel*, vol. 333, p. 126349, 2023, doi: https://doi.org/10.1016/j.fuel.2022.126349.

[20] Dierickx, Jeroen and Beyen, Jorne and Block, Rudi and Hamrouni, Michel and Huyskens, Pieter and Meichelböck, Christoph and Verhelst, Sebastian, “Strategies for introducing methanol as an alternative fuel for shipping,” in *7th Transport Research Arena TRA 2018 (TRA 2018)*, Vienna: Ghent University, 2018, pp. 1–10.

[21] H. Wei, C. Yao, Z. Dou, B. Wang, C. Chen, and M. Liu, “Comparison of the conversion efficiency of DOC and DPOC to unregulated emissions from a DMDF engine,” *Fuel*, vol. 204, pp. 71–84, 2017, doi: https://doi.org/10.1016/j.fuel.2017.05.021.

[22] D. TNO Safety &. Security, “Reduction of emissions and underwater radiated noise for the Belgian shipping sector,” 2020,

[23] D.-Q. Li, J. Hallander, and T. Johansson, “Predicting underwater radiated noise of a full scale ship with model testing and numerical methods,” *Ocean Engineering*, vol. 161, pp. 121–135, 2018, doi: https://doi.org/10.1016/j.oceaneng.2018.03.027.

[24] T. A. Smith and J. Rigby, “Underwater radiated noise from marine vessels: A review of noise reduction methods and technology,” *Ocean Engineering*, vol. 266, p. 112863, Dec. 2022, doi: 10.1016/j.oceaneng.2022.112863.

[25] C. Andersson, A. T. Johansson, A. Genell, and J. Winroth, “Fully electric ship propulsion reduces airborne noise but not underwater noise,” *Ocean Engineering*, vol. 302, p. 117616, Jun. 2024, doi: 10.1016/j.oceaneng.2024.117616.

[26] B. J. Schuit *et al.*, “Automated detection and monitoring of methane super-emitters using satellite data,” *Atmospheric Chemistry and Physics*, vol. 23, no. 16, pp. 9071–9098, 2023, doi: 10.5194/acp-23-9071-2023.

Mobile Marine Fuel Generation Based on a Micro Nuclear Reactor

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Synopsis

Geopolitical and macroeconomic uncertainty, supply chain risks and the growing pressure for carbon-intensive industries to reduce emissions has resulted in great interest in synthetic fuels in recent years. Electrofuels are a type of synthetic fuel which are produced by combining hydrogen and carbon dioxide. This paper explores the use of a 5MWe micro nuclear reactor in order to provide energy to produce electrofuels onboard a vessel. This paper uses empirical data to determine the relationships between characteristics of various components in order to determine of electrical and thermal power and produce the maximum possible amount of fuel, as well as to determine the volume and mass of equipment. The paper concludes with discussion of ship impact and an outline of a possible synthetic fuel generating replenishment vessel.

Keywords: Electrofuels, Shipping, Transportation, Nuclear Energy, Sustainability

1. Introduction

Traditional fuels and refuelling infrastructure present certain limitations for both naval and commercial ships, including in areas such as sustainability, logistics and storage. Electrofuels offer an alternative which shows promise in addressing some of these concerns. An electrofuel is a type of synthetic fuel which is created by combining captured carbon dioxide and hydrogen extracted from water with the use of electricity (Royal Society, 2023). Electrofuels offer a number of advantages when compared to traditional petroleum products. One such advantage is the flexibility which comes with generating fuel on demand. Only the amount of fuel which will be consumed needs to be generated, potentially leading to weight and volume savings. Further, different fuels can be created depending on the type of fuel required e.g. either aviation fuels or marine fuels. They may also allow for a simpler and more robust supply chain, as there will be a lesser reliance on imported oil.

Another crucial aspect which must be considered is environmental impact. Electrofuels allow for a significant reduction in carbon dioxide emissions of 20-47% (considering an electricity supply with a low carbon intensity of 25 gCO2 e/MJ) when compared to traditional fuels (Malins, 2017). This is noteworthy given the maritime industry's historical difficulty in decarbonising, where existing alternatives like batteries prove impractical. The strategic importance of Navies combating climate change can be seen with the US Navy targeting a 65% reduction in greenhouse gas emissions by 2030 as compared to 2008 levels (USN, 2022). More broadly, the UK is at present committed to achieving Net-Zero by 2050 (Gov.uk, 2008), a process which does require a significant reduction in emissions from organisations including the Royal Navy.

The primary aim of this paper is to examine whether a micro-nuclear reactor, based on a device under development by Rolls Royce, is suitable for electrofuels generation aboard a naval support ship or a commercial vessel or platform. This paper examines whether the output of the reactor is sufficient to allow for the generation of the required electrofuels on board the ship. It will also consider the volume and mass of equipment required for such a process to occur, and thus whether it is viable. The paper also discusses different methods of obtaining and delivering the raw materials to the ship for electrofuels generation. One method involves storing a highly dense form of carbon on board, most likely derived from biological material, which can be hydrogenated and subsequently used in the creation of electrofuels. The other involves directly extracting carbon in situ, in the form of carbon dioxide in the air or water.

2. Literature review

2.1 Nuclear Energy in a marine context

Nuclear energy has a long history of being implemented in a maritime setting, typically as a source of propulsive power. The use of nuclear reactors in providing sea-faring vessels with power dates back to the 1950s, when a PWR (Pressure Water Reactor) prototype for use in a submarine was first developed by Westinghouse

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Author's Biography

Neil Kapoor is a Mechanical Engineering Undergraduate Student at UCL, currently in his third year of an integrated masters degree. Neil has attended work experiences at companies such as Leonardo and Deutsche Bank. He is currently enrolled in the DSUS (Defence STEM Undergraduate Sponsorship) Scheme under the Ministry of Defence and as part of this, will be attending a summer internship.

Rachel Pawling is Programme Director for the MSc Marine Engineering and Naval Architecture courses and a Lecturer in Ship Design at UCL, teaching the subject of ship design to undergraduate and postgraduate students. She obtained her PhD in computer aided ship design in 2007 and has subsequently continued her research in projects funded by the EC, UK and US governments.

https://doi.org/10.24868/11200

(Barré et al, 2016) and Ragheb (2016) notes that the 'largest experience in operating nuclear power plants has been in nuclear naval propulsion, particularly aircraft carriers and submarines'.

2.2 The Heat-Pipe Micro Reactor

This paper considers the use of an onboard micro-nuclear reactor to provide the electricity required to generate electrofuel. The specific reactor being considered is a 5MWe Nuclear Gas Turbine, sized by the second author based on information from Rolls Royce (2023). Whilst reactors of a similar power level have been employed in marine contexts, such as the propulsion system of the NR-1 submarine (Barré et al, 2016), none have been used to generate electrofuels on board a ship for the purpose of refuelling. Micro-reactors typically output between 1 and 10 Megawatts of power, with dimensions that allow for portability (Rolls-Royce, 2023). This contrasts with the small modular reactor (SMR), which provide around 0.5 Gigawatts of power.

The UCL concept micro-reactor was described by the second author for a submarine application in Pawling (2023) and is an engineering estimate based on published Rolls-Royce information (2023) and the specifications of other proposals, such as the eVinci (Arafat, 2019). It has not been subject to detailed nucleonic or thermodynamic analysis and so the overall parameters are estimates. The micro-reactor is a high-temperature reactor using TRISO fuel, with reactivity control via control drums and heat transfer through multiple heat pipes. These transfer heat from the core to Brayton cycle generators (essentially gas turbine generators). These can be used in a simple open cycle mode or potentially incorporate recuperation, waste heat steam generation, or be closed-cycle. A closed-cycle option for submarines is illustrated in Figure 1 (Pawling, 2023).

The reactor module achieves a small size (8.1m x 2.3m x 2.3m) and weight (80 tonnes) via a "shrink-wrapped" shielding geometry, repair and refuel by replacement, and compact power conversion systems, compared to the saturated steam plants of Pressurised Water Reactors. With a core life of 5 years it provides 5MWe of electricity and approximately 12MWth of waste heat. With core temperatures of 600-1000ºC, the exhaust is expected to be 200-300ºC. Incorporation of recuperation is estimated to allow for an increase in electrical output by 37%, from 5MWe to 6.85 MWe, whilst based on combined cycle gas turbine generating plants (Karaağaç et al, 2019) it is assumed that approximately half of the waste heat could be recovered by an exhaust gas boiler – 6MWth, which could be used for process heating or additional power generation.

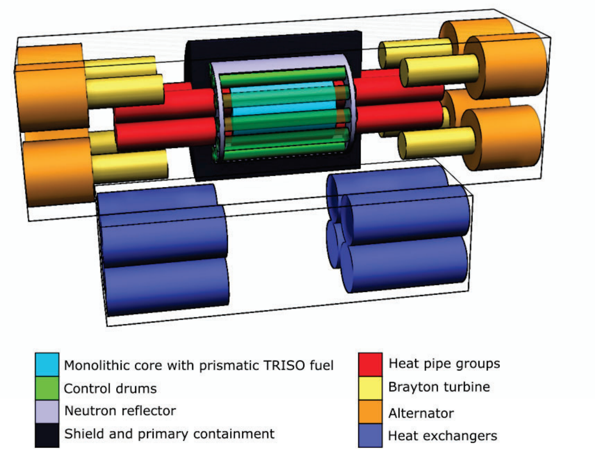


Figure 1: The notional UCL 5MWe Heat Pipe Gas Turbine Reactor (Pawling, 2023)

2.3 Electrofuels

With respect to commercial shipping, there has been widespread interest in various sustainable fuels, which allow for both a sustainable source of propulsion as well as a reduction in pollution attributed to the commercial shipping industry. Greenhouse gas emissions from the global shipping industry reached 1,076 million tonnes of CO_2 equivalent in 2018, a 9.6% increase with respect to emissions in 2012 (IMO, 2021).

One fuel widely considered to be a promising alternative is Methanol. Replacing traditional marine fuels with Methanol eliminates the emissions of sulphur oxides and reduces the emission of nitrogen oxides by 60% (Argus Media, 2020). This, in combination with the preexisting standards and regulations surrounding the fuel, makes it an attractive alternative for shipping companies. There is already significant interest in Methanol from major commercial players - as of 2023, Maersk has 24 container vessels on order, all of which are capable of operating on green Methanol (Maersk, 2023). This also suggests Methanol is an appropriate contender.

Ammonia is another fuel which has captured attention amongst those looking to decarbonise the commercial shipping industry. Like methane, ammonia is less energy dense than diesel but greater than hydrogen, a competing green fuel. Ammonia also has the advantage of already being a reasonably common cargo and so the maritime industry has experience in handling the fuel in bulk. It emits no carbon when burned and has a low range of flammability, enhancing safety. In spite of the fuel's otherwise green credentials, NOx emissions and particularly water use in production remain environmental concerns, (Ghavam et al, 2021).

While both fuels are of interest to the shipping industry, for the purposes of this paper, methanol was chosen as the fuel of interest for commercial purposes. One reason for this is that methanol already has regulatory acceptance under the International Marine Organisation's IGF Code, which ammonia does not. Another is that methanol can be stored as a liquid in much the same way as traditional marine fuels, whilst ammonia must be stored in a compressed state. Finally, the interest expressed in methanol by key players such as Maersk and Stena Bulk (Argus Media, 2020) suggests that methanol will gain traction among firms operating in the commercial shipping industry at a faster rate.

Regarding naval ships and other military use cases, the favoured choice is synthetic diesel. At present, Diesel Fuel Marine, which is commonly known via the NATO specification F-76, is the primary fuel used for propulsion by the US Navy (Sermarini, 2000). It is important to recognise that the desired characteristics of the optimal fuel differs between military and commercial uses. For example, F-76 contains stability additives which are not typically present in commercial fuels. It also has a minimum flash point specification of 140° F (60° C), as well as limits on particulates and water and corrosiveness to promote safety and limit engine damage over long periods of time (Sermarini, 2000).

There have been attempts to produce and implement various synthetic diesels in military contexts. Once such example is RediDiesel, a renewable biofuel developed by Applied Research Associates (ARA, 2016). One of the key advantages of this type of fuel is that is serves as a drop-in replacement for F-76, and so requires no additional equipment or operational modifications when used. The lack of requirement to retrofit is attractive in a military context, with this being a costly and time-consuming process which can impact fleet availability.

3. Theory and Calculation

3.1 Method

The overall methodology employed to carry out this project is outlined below. This process allows for the amount of a specific fuel which can be produced in a day aboard a refuelling ship to be found.

1. Determine which fuels are to be considered for electrofuel production.
2. Research key components, identifying key characteristics: volume, power input and output
3. Non-dimensionalise output of component.
4. Rebalance power to ensure optimal allocation of power input to components, allowing for optimal fuel production.
5. Determine the overall amount of fuel produced in a certain timeframe e.g. a day.
6. Repeat for all considered fuels

From the literature review, it was determined that Methanol was most appropriate for commercial purposes, whilst synthetic diesel is of interest for military vessels. Thus these are the fuels which will be considered in this paper. The process of electrofuel generation is illustrated in Figure 2, with the key components listed in Table 1.

In order to non-dimensionalise the key components, data can be collected and trendlines developed to describe the relationship between the output of a component and its power input. This allows for the optimal power distribution among components, and thereby the maximum amount of fuel produced for a given energy. Similarly the volume or weight of the component can be plotted against its output.

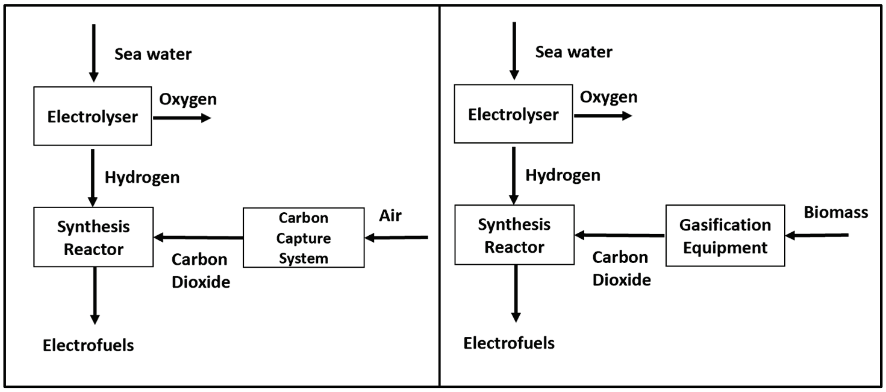


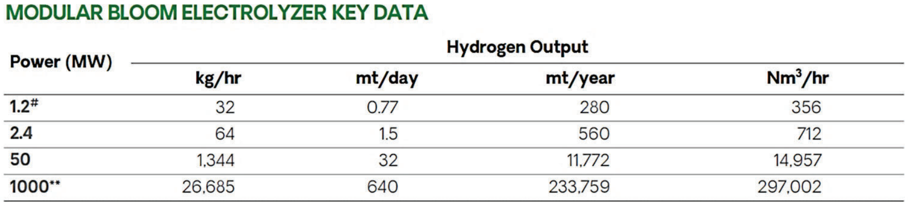
Figure 2: Diagram showing simplified overall process of electrofuel generation with carbon sourced from the air (L) and from Biomass (R)

Table 1: Key components required for electrofuel generation

Key Component	Function/Description
Electrolyser (including Gas separation unit)	Convert water into hydrogen and oxygen. Ensure hydrogen and oxygen are fully separated and pure
Synthesis Reactor	Combine hydrogen and carbon dioxide into electrofuels
Carbon Capture System	Capture carbon in situ (Not required for biomass carbon concept)
Gasification equipment	Convert biomass stock into carbon dioxide (not required for carbon capture concept)

3.2 *Electrolyser*

Whilst electrolysis has alternative processes which could theoretically achieve the same outcome (converting water into hydrogen and oxygen) such as thermal decomposition, electrolysis was preferred as thermal decomposition of water requires temperatures of between 500° to 2,000 ° C (energy.gov, 2020), whilst the micro-nuclear reactor being considered is only capable of providing exhaust gas at a temperature of 200-300° C and core temperatures of 600-1000° C. Electrolysers for hydrogen production are becoming more widely available and data on modular and unitised systems is readily available, for example the data sheet from Bloom (2023) summarised in Figure 3.



MODULAR BLOOM ELECTROLYZER KEY DATA

Power (MW)	Hydrogen Output			
	kg/hr	mt/day	mt/year	Nm^3/hr
1.2#	32	0.77	280	356
2.4	64	1.5	560	712
50	1,344	32	11,772	14,957
1000**	26,685	640	233,759	297,002

Figure 3: Key data table sourced from the Bloom Electrolyser Data Sheet (Bloom, 2023)

Some manufacturers provide performance metrics more useful for scaling. For example the ME450 from H-Tec (2023) has an efficiency of 53 kWh/kg and an output of 450 kg/day. Data from several sources can be compiled to derive a generic relationship between power and output, as illustrated in Figure 4. The trendline shows a linear relationship between hydrogen production and electrical power input, with an equation $y = 0.5603x$. We would expect a broadly linear relationship as, for a given technology, electrolysers use the same electrochemisty regardless of size and do not have the complexities of, say, a diesel engine. The Bloom datasheet was used to derive a thermal load of 0.345MWth per tonne H_2 per day for steam generation, if a high temperature cell is used.

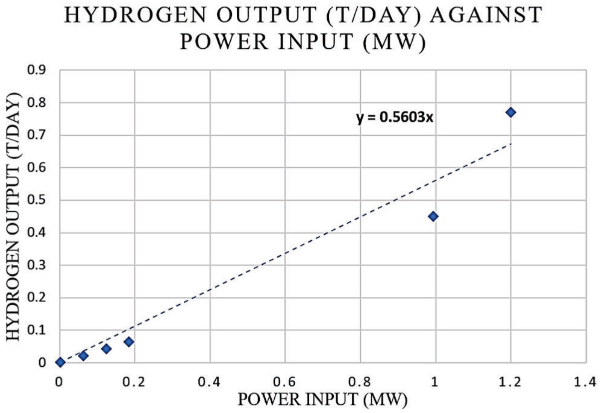


Figure 4: Graph showing relationship between hydrogen output and power input, with the trendline and equation shown

The volume of the equipment is also of interest. The Bloom data sheet quotes a size of 12.04 x 1.86 m for a 1.2MW module. As the height is not given, we can make a rough estimate by analysing the render depicted on the datasheet, as below:

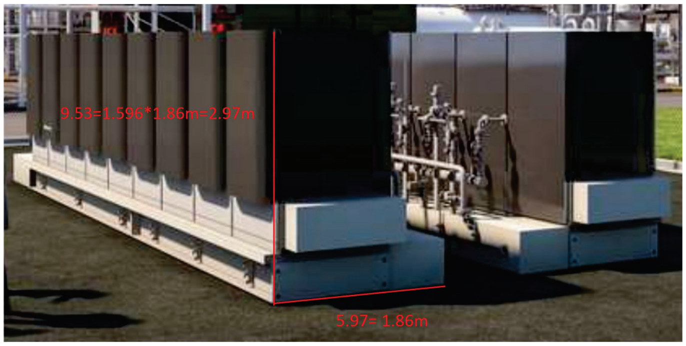


Figure 5: Depiction of how the height of the Bloom electrolyser was estimated by comparing lines (Bloom, 2023)

In Figure 5, the width of the electrolyser is known to be 1.86 m as per the data sheet. We can draw a line on a software such as PowerPoint along the width. As PowerPoint gives the length of the drawn line to be 5.97 cm, we can compare this with the length of the line drawn along the height of the electrolyser in order to determine its true height. The vertical line in PowerPoint comes to 9.53 cm. Thus the true height of the electrolyser is:

$$1.86\ m \times \frac{9.53\ cm}{5.97\ cm} = 2.97\ m$$

Thus we have dimensions of 12.04m * 1.86m * 2.97m giving a volume of 66.5 m^3. The relationship between volume and hydrogen output can thus be plotted as shown in Figure 6. Here we would expect a power relationship, with the exponent below 1, as a result of the greater efficiency achieved at greater equipment volumes, due to aspects such as the surface area to volume ratio.

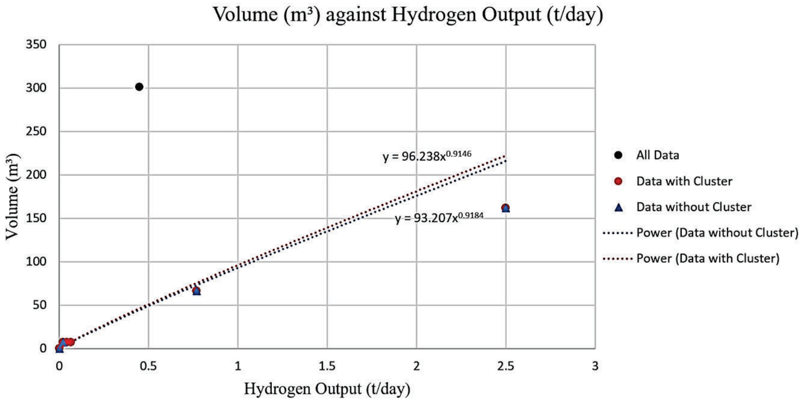


Figure 6: graph showing relationship between volume and hydrogen output. Note the outlier (black) and data with the cluster (red)

Note that there is a clear anomaly which was not included when creating the trendline. This anomaly is due to the electrolyser being used in a land-based industrial context where there is less incentive for the manufacturer to minimise volume. Also note that there are a cluster of red data points near the origin. The presence of several data points very close to each other disproportionately influences the power trendline (red), and so the 'data without cluster' dataset was created (blue triangles) and a trendline (blue) was subsequently found with the equation $y = 93.207x^{0.9184}$. This gives a more representative relationship.

As most electrolysers for the production of hydrogen use fresh water as their input to the electrolysis cell, Reverse Osmosis (RO) or Multistage Flash distillation (MSF) will be required. Some commercial units may already have this equipment fitted, but to be conservative it was assumed to be an additional item. From an energy and power perspective, the electrical loads of modern RO plants are small compared to the electrolysis loads above, with academic literature (Wade, 2001) and product specification sheets e.g. (Evac, 2016), indicating values between 4 and 8 kWhr/m^3 fresh water produced via RO, with a similarly small additional size and weight for the equipment.

3.3 Carbon Capture System: Air

Direct Air Capture (DAC) extracts carbon dioxide from the atmosphere, primarily through chemical processes. The energy requirements for these systems are generally a mix of thermal and electrical, although a unitised system such as Airthena uses internal heaters to provide the former, with only electrical input to the device. Sadiq et al (2020) provide an energy type breakdown for an Airthena type device, with 70% of the internal energy use being thermal, with temperatures around 80 degrees C.

Typically, direct air capture involves using an air contacting medium which exposes a sorbent to airflow, which results in the CO_2 being absorbed. One example is aqueous hydroxide sorbents, which result in following chemical reaction (Eloy et al, 2016).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Following the capture, the sorbent is then regenerated by heating. Here, the carbon dioxide is removed and the sorbent is able to absorb further carbon dioxide. Direct air capture is a technology which is expected to receive much investment in the coming years as more attention is paid to extracting carbon dioxide out of the atmosphere. In this regard, this component of the electrofuel generation system is certain to significantly improve in efficiency and performance in time. Table 2 compares the key characteristics of several carbon capture systems. The average density of a DAC unit was assumed to be similar to the air filtration units of a naval HVAC system (Bronswerk, 2017), at approximately 0.4 te/m^3.

Table 2: Characteristics of some selected DAC systems

Source	**Power in MWe**	**CO_2 out t/day**	**Volume m^3**	**Input kWeh/t**	**Output t/day/MWe**	**Notes**
Keith, 2006	1.4	208.219	1140398	161	148.7	Uses air handling tower
Casaban, 2023	0.2283125	10.959	450	500	48.0	
Kulkarni, 2012	0.009968	1.1	69.12	217	110.4	
Lackner, 2009	0.012732	1	90	306	78.5	
Sadiq, 2020	0.04	0.00042	3.9312	2285714	0.011	Modularised

Using a graphical method as described in section 3.2, the relationship between CO_2 output (t/day) and Power input (MW) was found to be $y = 146.11x$. However, as Table 2 shows, the single industrial-scale entry dominated this analysis of power demand. Removing the largest value led to relationship of $y = 46.78x$, and it is speculated that the lower performance of the smaller plants is due to their inclusion of mechanical air handling systems. Whilst the relationship between the volume of carbon capture system and the CO_2 output was $y=76.406x^{0.9184}$. These relationships are very similar to the equivalent relationships of the electrolyser, with direct air capture seeing similar volumetric efficiency gains as output increases.

While the total energy requirements for DAC are reasonable, due to the low concentration of carbon dioxide in the atmosphere a large amount of air must be handled. With a mass fraction of 0.0626% (Engineering Toolbox, 2024) a 100% efficient capture system would need to process 1597 tonnes of air per tonne of CO_2 captured, or approximately 1.3 million m^3. For land based, or static floating installations, this amount of air can easily be handled using large tower structures, with the example in Keith et al (2006) being over 100m in diameter and height. Spread over a 24-hour period, this equates to volume flow of approximately $54000m^3/hour$, which is equivalent to the total ventilation capacity (excluding machinery spaces) of the RNLN Holland class OPVs (Heinen & Hopman, n.d.). Data for naval air handling units was used to derive a value of 8×10^{-4} $kW/m^3/hr$ for air handling. Efficiency values for DAC vary significantly, with systems for scrubbing flue gas being 80-90% efficient but those for atmospheric extraction being much lower (Sodiq et al, 2023). For this study, an extraction efficiency of 50% was assumed.

3.3 Carbon Capture System: Water

Carbon dioxide is present in much higher proportions in seawater, although mostly in various compounds (Zeebe & Wolf-Gladrow, 2008), however our notional 100% efficient system would still need to process around 11,100 tonnes ($10,800m^3$) of seawater to extract one tonne of CO_2. Whilst this is still a very large volume, it is approximately equivalent to the flow through a 0.86m diameter tube, moving at 10 knots, for a day, small compared to the amount of water that would be moved through a waterjet propulsion system for example.

Most of the CO_2 in seawater is bound in other compounds, e.g. and an electrolysis process is used to drive a series of reactions leading to yields of around 87% extraction at an energy requirement of 122kJ/mol CO_2 (Kim et al, 2022). Whilst various experimental systems have been tested, seawater CO_2 extraction is not at the same level of development as DAC. As it uses a system of electrolysis, for the purposes of this study it was assumed that a notional CO_2 extraction system could be scaled from the hydrogen extraction system, scaling with the input water mass flow rate.

3.4 Gasification Equipment

A potential alternative source of carbon dioxide is through the gasification of biomass. For example, the 2.5 MW(e) biomass gasification module described by McLellan (2000). Here, the gas produced from woodchip with a 37% weight moisture content is only 4.4% carbon dioxide by volume, an inefficient means of producing carbon.

This method of sourcing carbon does have certain disadvantages when compared to direct air capture. Direct air capture extracts carbon in situ, whilst gasification requires biomass to be processed externally and loaded onto the vessel, making the supply chain inherently less robust and thus secure. The biomass may also present a fire risk, as it consists of flammable material. One method to mitigate this risk is to store it as bricks, where the surface area to volume ratio of the matter is lower than that of chips or pellets, for example. However, this then requires the bricks to be broken down before gasification, adding to capital costs, maintenance requirements and taking up space on board. For these reasons, as well as that there is more robust and applicable data available on direct air capture, this study proceeded in its calculations considering in-situ capture as the source of carbon.

3.5 Synthesis Reactor

The synthesis reactor is a vessel in which the electrofuel is synthesised. Alongside the well-known Fischer–Tropsch process for producing hydrocarbons from a mix of carbon monoxide and hydrogen, there are two primary methods of generating hydrocarbons from hydrogen and carbon dioxide. The first method, known as the two-step synthesis method, involves first converting carbon dioxide into carbon monoxide through the reverse water gas shift process:

$$CO_2 + H_2 \leftrightarrows H_2O + CO$$

This process usually occurs with the use of a catalyst, typically ZnO or Al_2O_3. The second step is the methanol synthesis, which takes place in a second reactor, and involves three reactions which occur simultaneously (Anicic et al. 2014):

$$\begin{gathered} CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \\ CO + 2H_2 \rightleftharpoons CH_3OH \\ CO_2 + H_2 \rightleftharpoons CO + H_2O \end{gathered}$$

The mixture obtained from this product is cooled and a flash separator is used to separate the components. The non-reactive components which are not of use can be discarded. The second method, hydrogenation of carbon dioxide, allows for direct methanol synthesis. Carbon dioxide and hydrogen are fed into a reactor and, in the presence of a catalyst such as zinc oxide react to form methanol and water as products. Other products include DME and methane (Anicic et al. 2014):

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

Estimating the energy required for this process from the literature is difficult as power is needed for pumps, pressurisation, heating and cooling (as some of the reactions are exothermic), and in many industrial contexts the thermal energy is provided as steam, which may be “taken for granted” in applications where waste heat is plentiful and the main concern is the additional mechanical work. A further complication is the use of heat exchangers to recover heat lost in cooling, which can significantly improve the thermal efficiency in a large synthesis plant. Table 3 summarises a sample of energy requirements for hydrocarbon synthesis.

Table 3: Thermal and electrical energy requirements for some synthesis studies

Input	**Produces**	**Electrical MWhr/t**	**Thermal MWhr/t**	**Total MW**	**Th:El ratio**	**Notes**	**Reference**
CO_2, H_2	meOH	0.748	-	0.748	-	Synthesis only	Sollai et al, 2023
	meOH single step	11.07	-	11.07	-	Complete system	Anicic et al, 2014
	meOH two step	10.63	-	10.63	-	Complete system	
	meOH	0.169	0.439	0.608	2.60	Synthesis only	Mar Pérez-Fortes, 2016
NH_4, CO_2	meOH	0.529	0.481	1.01	0.91	Synthesis only	Er-rbib et al, 2012
	Diesel	0.529	0.111	0.64	0.21	Synthesis only	
	Diesel	0.529	8.347	8.876	15.78	Synthesis only	

Combining these with other references, the methanol yield in tonnes per day was found to scale with input electrical power with the relationship y = 36.67x, with the thermal requirements being assumed to be twice the electrical. For diesel fuel the relationship was y = 17.17x, with the thermal requirements again varying significantly so assumed to be twice the electrical. The trendline for the data corresponding to synthesiser volume against methanol output was not found to be based on a power relationship, but a linear one, with an equation of y=0.0598x. This suggests that the volumetric efficiency gains encountered when the size of the synthesis reactor is increased is less significant than that of the electrolyser or direct air capture. Another potential explanation is that this improvement simply did not manifest itself in the selection of data.

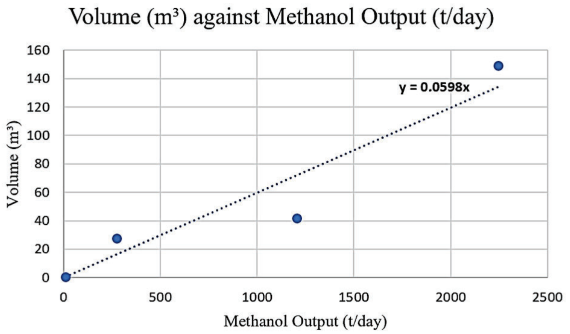


Figure 7: Graph showing linear relationship between methanol output and volume

3.6 Summary of relationships

The relationships between key characteristics of key equipment are shown in the table below, with references where these have not already been mentioned in the text.

Table 4: Relationships between key characteristics of components

Item	**y**	**x**	**Relationship**
RO plant	FW output (t/day)	Power input (MW)	y = 4307.6x
	Volume of RO plant (m^3)	FW output (t/day)	$y = 0.1499x^{0.93}$
	Mass of RO plant (te)	Volume of RO plant (m^3)	y = 0.2x
Electrolyser	Hydrogen output (t/day)	Power input (MW)	y = 0.5603x
	Heat input (MWth)	Hydrogen output (t/day)	y = 0.344x
	Volume of electrolyser (m^3)	Hydrogen output (t/day)	$y = 93.207x^{0.9184}$
	Mass of electrolyser (te)	Volume of electrolyser (m^3)	y = 0.46x
	Water required (t/day)	Hydrogen output (t/day)	y = 10x
DAC system	CO_2 output (t/day)	Power input (MWe)	y = 146.11x
	Heat input (MWth)	Power input (MWe)	y = 5.87x
	Volume of DAC (m^3)	CO_2 output (t/day)	$y = 76.406x^{0.9184}$
	Mass of DAC	Volume of DAC (m^3)	y = 0.4x
	Air required (t/day)	CO_2 output (t/day)	y = 3194x
Air handling	Power input (kW)	Air handled (t/day)	y = 0.027297x
Water CO_2 capture system (WCS)	CO_2 output (t/day)	Power input (MW)	y = 31.17x
	Water required (t/day)	CO_2 output (t/day)	y = 9643x
	Volume of WCS (m^3)	Water required (t/day)	y = 9.32x
	Mass of WCS (te)	Volume of WCS (m^3)	y = 0.46x
H_2O pumps	Power input (kW)	Water handled (t/day)	y = 0.02x
Synthesis reactor	Electrofuel Output (t/day)	Power Input (MWe)	y =36.67 x
	Heat Input (MWth)	Power Input (MWe)	y = 2x
	Volume of Synthesis Reactor (m^3)	Electrofuel Output (t/day)	y = 0.0598 x
	Mass of synthesis reactor (te)	Volume of Synthesis Reactor (m^3)	y = 1.25x

3.7 *Output and Volume Calculations for methanol, DAC method*

The synthesis reactor is not 100% efficient in terms of use of feed gasses, and the ratio of gas input to gas used in the product varies significantly depending on the catalyst and reactor design. Anicic et al (2014) and Pérez-Fortes (2015) were used to derive ratios of 1.98 (50.5% efficiency) for CO_2 and 1.6 (62.5%) for H_2 in methanol synthesis. According to literature, H_2 and CO_2 should enter the synthesis reactor at a molar ratio of 3:1 Anicic et al (2014). Hence, the mass flow ratio can be determined as follows:

$$mass\ flow\ ratio(H_2{:}\,CO_2)\ = (3)2.016\ g/mol : (1)44.01 g/mol$$

Therefore, the mass flow rate of CO_2 entering the synthesis reactor exceeds that of H_2 by a factor of 44.01/6.048=7.2767. This agrees with Anicic et al (2014), where the expected ratio of reactants per unit of methanol are 1.3758/0.1892=7.2717. From this, the rate at which each reactant must be generated:

$$\frac{1.98 \text{ x } 7.2767}{8.2767} \text{ tonnes/day of } CO_2 \text{ and } \frac{1.6 \text{ x } 1}{8.2767} \text{ tonnes/day of } H_2.$$

Applying the relevant relationships from Table 4, it therefore takes a constant 0.01191 MW to generate the required CO_2 to create 1 tonne of methanol per day, with a throughput of approximately 4.54 million m^3 of air per day or 189,000m^3 per hour with a parasitic load of 151kW. Similarly for hydrogen, 0.19331 tonnes per day are required, at a constant electrical load of 0.345MW, and a heat load of 66.5kWth for steam generation, requiring 1.933 tonnes of fresh water per day with a parasitic load of 0.45kW. Considering Methanol, for the synthesis reactor:

$$y_{MeOH} = 36.67 x_{MeOH}$$
$$x_{MeOH} = \frac{1}{36.67} = 0.02727\ MW\text{e}$$

Therefore, producing 1 tonne of Methanol a day requires:

$$11.91 + 151.77 + 345.02 + 0.45 + 0.039 + 27.27\ = 536.46\ kW\ = 0.536 MW$$

Given the micro nuclear reactor produces 5MWe, this allows for the production of 9.32 tonnes per day, and a thermal load of 1.78MWth, requiring an exhaust gas boiler. We can now apply the mass volume relationships to determine the volume of equipment required, resulting in plant equipment of 1385m^3 and 570te (minus the nuclear reactor, power conversion equipment etc).

3.7 *Output and Volume Calculations for synthetic diesel, DAC method*

Synthetic diesel with a chemical formula of $C_{12}H_{23}$ can be produced in reactors largely similar to methanol, such as tubular reactors (Awogbemi & Kallon, 2022). The molar ratio between hydrogen and carbon is reduced to 2:1. This is because a lower H_2:CO_2 ratio increases the probability of chain growth, as required for forming longer chain hydrocarbons such as diesel (Garcina et al, 2023). This is equivalent to a mass ratio of 10.92. Following the same method as for methanol, the ratio of CO_2 and H_2 required is:

$$\frac{10.92}{11.92}\frac{tonnes}{day}\ of\ CO_2\ \ \frac{1}{11.92}\frac{tonnes}{day}\ of\ H_2$$

However the efficiency of gas utilisation is much more variable, with values for Fischer-Tropsch synthesis ranging from 60% to 90% carbon utilisation (Luo, 2021). For this analysis a value of 80% is used (i.e. a ratio of 1.25), while hydrogen efficiency also varies, being as low as 6% in some studies (Medrano-García et al, 2022). For a baseline the same efficiency as the meOH process was assumed, a multiplication factor of 1.6. This resulted in a rate of production of 12.32 tonnes per day for a 5MWe reactor, with a total plant volume (excluding reactor) of and mass of 1258m^3 and 519te. A much larger waste heat boiler would be required, of 2.57MWth capacity.

3.8 *Output and Volume Calculations for synthetic diesel, water capture method*

This system is dominated by the size of the CO_2 extraction system (WCS). To produce one tonne of CO_2 per day we find that the input water flow is 9643 tonnes/day, with a WCS volume of 89880m^3 and WCS mass of

41345 tonnes. This is clearly non-viable for a mobile application, although the volume is broadly consistent with the size of the land-based 300kg/day plant developed by Equatic (2024).

4. Application to an RFA

4.1 Containerisation

The methanol production takes 1385m^3, approximately 36 twenty-foot shipping containers, whilst synthetic diesel would require 33 containers. With each reactor and associated power systems adding 4 containers, even a small coastal container ship (typically around 200 TEU) could in principle support multiple plants.

4.2 Example Design

An example design for a naval "tanker" using the synthetic diesel plant was worked up using the UCL MSc Ship Design Exercise database. A summary of the principal particulars is shown in Table 5 and the simplified layout is in Figure 8. With four reactors in an IFEP configuration and three synthesis plants, this concept can generate 25 tonnes of synthetic diesel per day whilst proceeding at 20 knots and 37 tonnes per day at 15 knots, allowing complete refilling of the storage tanks in 11 days.

Table 5: Principal particulars of the example design

Length, waterline	141m
Beam, waterline	17.76m
Draught	5.46m
Depth, amidships	12.2m
Displacement, deep	8430te
Accommodation	122
Synfuel storage	500m^3
Synthesis plants	3
5MWe reactors	4
Propulsion motors	2 x 4.6MW
Emergency DG	4 x 1MW
Max Ship hotel load	1000kWe
Maximum speed & power	20 knots, 9.2MW
Cruise speed & power (high)	15 knots, 3.3MW
Cruise speed & power (low)	10 knots, 0.93MW
Helicopter	1 x 5-tonne class
Armament	Sea Ceptor, 30mm, decoys

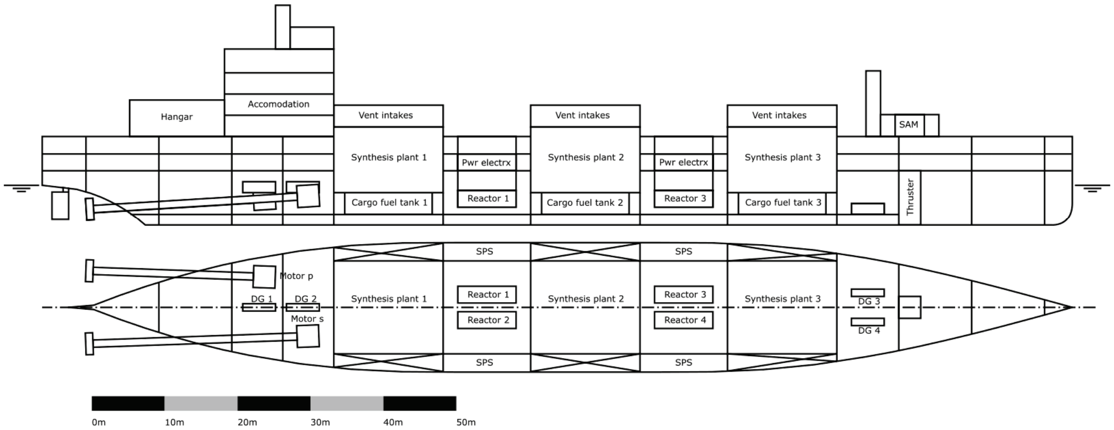


Figure 8: Outline general arrangement of the RFA

4.4 *Comparison with Combatant Fuel Loads*

The example tanker is somewhat smaller than existing RFA tankers, the 39,000 tonne Tide class, and the number of reactors and synthesis plants chosen was somewhat arbitrary, simply to provide an illustration. The output of 63 tonnes per day can be compared with some combatant fuel loads shown in Table 6 below. The RFA could refuel a large OPV once a week or, possibly more interestingly, support a large number of USVs up to patrol boat size.

Table 6: Fuel loads of various naval vessels

Vessel	Fuel (te)
C-Sweep USV	2
Armidale Class PB	58
Aker PV-85 OPV	306
Aker PV-50 FAC	75
Vosper Mk 10 FF	537

5. Discussion and conclusions

The scoping study described in this paper indicates that a micro-reactor has the potential to generate useful amounts of synthetic fuel at sea; approximately 12.32 tonnes of synthetic diesel can be produced daily, at an overall efficiency of 80% when comparing fuel energy out (using LHV) and plant energy in (electrical and thermal). Table 7 summarises the breakdown by main component. Note that the air handling was treated as part of the parent ship for this analysis.

Table 7: Main component breakdowns as percentages of the total

	Mass	Volume	Electrical	Thermal
DAC	82.06	84.78	1.93	22.06
Air handling			24.60	
Electrolysis	16.07	14.44	59.03	
RO	0.09	0.19	0.08	22.13
Synthesis reactor	1.77	0.59	14.35	55.81

A significant proportion of the volume of equipment was related to capturing carbon dioxide. The characteristics of DAC, both physical and energetic are one of the main areas of uncertainty in this study. As this technology is expected to improve significantly over the coming years, this means that the overall electrofuel generation system has the potential to become more compact over time. The electrical load is dominated by the electrolysis process to generate hydrogen and if this could be reduced further by better utilising waste heat, fuel yields would increase. A high temperature electrolysis machine using steam as an input has electrical power requirements 50-70% those of PEM devices.

The indicative design uses modularised synthesis plants distributed along the ship. An alternative approach to be investigated would be the use of a single integrated plant. This is likely to be more efficient, and make better use of hull volume, but design integration increases design interactions, significantly increasing complexity and risk. There are several practical considerations that would impact a ship installation, including;

- Provision of sufficient air intake ducting and physical arrangement of the ducts on the upperdeck.
- Air treatment required before air is fed to the DAC.
- Sensitivity of systems such as the synthesis reactor to ship motions and shock.
- Additional power requirements due to air and water ducting and piping.
- Additional space requirements for access and maintenance.

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- Buffer tanks for CO_2 and H_2 with associated safety concerns.
- Structural integration such as foundations and seatings

These suggest that the results obtained in the paper serve as a lower bound estimate for the size and weight of the plant.

6. Future work

There are certain limitations with the work outlined in this paper. Many of the components used in the data collection component of this paper have varying applications and scales, including experimental, modular and industrial. As a result, some relationships consider equipment which was designed with differing priorities and thus characteristics. If possible, equipment data should be grouped by industry or technology to obtain a more accurate sizing relationship. A key point that emerged from the literature review is that there are many possible chemical processes to be considered, specifically combinations of catalysts, use of waste heat to improve efficiency etc.

An area of conceptual uncertainty is the cost and cost-benefit of a synthetic fuel generating tanker. Given the complexity of the systems on board, it is likely that such a vessel will be similar to a combatant in UPC/tonne, rather than a fleet tanker. However this has to be weighed against infrastructure and operational savings and advantages.

7. Declarations

This paper is based on, and contains several sections from, the first author's final report and appendices submitted as part fulfilment of his final year individual project (Kapoor, 2024)

8. References

Anicic B, Trop P, Goricanec D, (2014), "Comparison between two methods of methanol production from carbon dioxide", Energy. 2014 Dec; 77:279–89. doi:https://doi.org/10.1016/j.energy.2014.09.069.

Applied Research Associates, (2016), "U.S. Navy Completes Sea Trial with ARA's 100% Drop-in Renewable Diesel Fuel". Available at: https://www.ara.com/news/no-petroleum-required/ (Accessed 15/01/24)

Arafat, Y & Van Wyk, J (2019), "eVinvi Micro Reactor", Nuclear Plant Journal, March-April 2019

Argus Media, (2003), (Methanol vs Green Ammonia: The future of marine fuels, 2020). Available at: https://view.argusmedia.com/rs/584-BUW-606/images/MethanolvsGreenAmmoniaEbook_ammonia%2003.09%20Final.pdf [Accessed 12/11/24]

Awogbemi O, Kallon DVV, (2022), "Application of Tubular Reactor Technologies for the Acceleration of Biodiesel Production", Bioengineering. 2022 Jul 27;9(8):347.

Barré, B, Anzieu, P & and Lenain, R, (2016), "Nuclear Reactor Systems: a technical, historical and dynamic approach", Les Ulis, France: EDP Sciences.

Bloom Energy, (2023), Bloom Electrolyzer, Datasheet, 1016755-1123, Available at: https://www.bloomenergy.com/wp-content/uploads/bloom-energy-electrolyzer-datasheet-december-2023.pdf

Bronswerk, (2017), "Bronswerk Military HVAC-R Product Catalog"

Casaban, D., Tsalaporta, E, (2023), "Life cycle assessment of a direct air capture and storage plant in Ireland", Sci Rep 13, 18309, https://doi.org/10.1038/s41598-023-44709-z

Department of the Navy, (2022), "Climate Action 2030", Available at: https://www.navy.mil/Portals/1/Documents/Department%20of%20the%20Navy%20Climate%20Action%202030.pdf (Accessed 17/10/23)

EngineeringToolbox, (2024), https://www.engineeringtoolbox.com/air-composition-d_212.html

Equatic, (2024), "Equatic Unveils Plans for the Worlds Largest Ocean-based Carbon Removal Plant", available from https://www.equatic.tech/articles/equatic-unveils-plans-for-the-worlds-largest-ocean-based-carbon-removal-plant

Evac, (2016), "Technical Specifications Fresh Water Maker, - Reverse Osmosis Unit 60t/d", REV 14.04.2016 Q-50-16-XXX. REVISION 0

Garcina A et al. "Study of Different H_2/CO_2 Ratios as Feed in Fischer-Tropsch Reactor with Iron-Based Nano-Hydrotalcite Catalysts"; online; 2023,105,223-228; DOI: 10.3303/CET23105038

Ghavam S, Vahdati M, Wilson IAG, Styring P, (2021), "Sustainable Ammonia Production Processes", Frontiers in Energy Research, Mar 29;9, doi: https://doi.org/10.3389/fenrg.2021.580808

H-TEC Systems, PEM Electrolyzer ME450, Datasheet, Available at: https://www.h-tec.com/en/products/detail/h-tec-pem-electrolyser-me450/me450/

Er-rbib, H, Bouallou, C, Werkoff, F, (2012), "Production of synthetic gasoline and diesel fuel from dry reforming of methane", Energy Procedia 29 156 – 165

Heinen & Hopman, "Case Report Navy Ocean Going Patrol Vessel - Holland Class"

Kapoor, N, (2024), "Mobile Fuel Generation based on a Micro Nuclear Reactor", MECH0020 Undergraduate Individual Project Report, UCL Department of Mechanical Engineering

Karaağaç, M O, Kabul, A & OĞUL, H (2019), "First- and second-law thermodynamic analyses of a combined natural gas cycle power plant: Sankey and Grossman diagrams", Turk J Phys 43: 93 – 108 doi:10.3906/fiz-1809-

Keith, D.W., Ha-Duong, M. & Stolaroff, J.K, (2006), "Climate Strategy with Co2 Capture from the Air",

Climatic Change 74, 17–45. https://doi.org/10.1007/s10584-005-9026-x

Kulkarni A, Sholl DS, (2012), "Analysis of Equilibrium-Based TSA Processes for Direct Capture of CO2 from Air", Industrial & Engineering Chemistry Research. 2012 Jun 18;51(25):8631–45, https://doi.org/10.1021/ie300691c

Kim, S, Nitzsche, M, Rufer, S, Lake, J, Varanasi, K & Hatton, T, (2023), "Asymmetric chloride-mediated electrochemical process for CO 2 removal from oceanwater". Energy Environ. Sci.,2023, 16, 2030 DOI: 10.1039/d2ee03804h

Lackner, K (2009), "Capture of carbon dioxide from ambient air", Eur. Phys. J. Spec. Top. 176, 93–106, https://doi.org/10.1140/epjst/e2009-01150-3

Lee P, (2022), "Carbon-Neutral Production Of Methanol Via Direct Air Carbon Capture And Blue Hydrogen", BSc, University of Virginia

Malins C. (2017), "What role is there for electrofuel technologies in European transport's low carbon future?", Cerulogy. Available at: https://te-cdn.ams3.digitaloceanspaces.com/files/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf (Accessed 16/10/23)

Maersk (2023), "Maersk to deploy first large Methanol-enabled vessel on Asia - Europe trade lane" [Press Release], available at: https://www.maersk.com/news/articles/2023/12/07/maersk-to-deploy-first-large-Methanol-enabled-vessel-on-asia-europe-trade-lane

McLellan R. (2000). "Design Of A 2.5MW(e) Biomass Gasification Power Generation Module", U.S. Department of Energy Office of Scientific and Technical Information; 2000. Available from: https://www.osti.gov/etdeweb/servlets/purl/20134131

Medrano-García, J, Charalambous, M, & Guillén-Gosálbez, G, (2022), "Economic and Environmental Barriers of CO 2 -Based Fischer−Tropsch Electro-Diesel", ACS Sustainable Chem. Eng. 2022, 10, 11751−11759 https://doi.org/10.1021/acssuschemeng.2c01983

International Maritime Organisation, (2020), Fourth IMO Greenhouse Gas Study 2020 Executive Summary. [online] 18th International Emissions Inventory Conference, 2021. 4 Albert Embankment, London SE1 7SR:

DNA Maritime LLC. Available at: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20Executive-Summary.pdf [Accessed 21 Apr. 2024].

Office of Energy Efficiency and Renewable Energy, (2020), "Hydrogen Production: Thermochemical Water Splitting", available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting

Pawling, R (2023), "Explorations of Novel Nuclear Propulsion for Submarines", RINA Warship 2023,

Pérez-Fortes, M, Schöneberger, J, Boulamanti, A, Tzimas, E, (2016), "Methanol synthesis using captured CO_2 as raw material: Techno-economic and environmental assessment", Applied Energy, Volume 161, 2016, Pages 718-732, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2015.07.067

Ragheb, M, (2016), "Nuclear Power– Deployment, Operation and Sustainability", Rijeka, Croatia: InTech.2016 ISNB: 9789533074740

Rolls Royce, (2023), "Rolls-Royce Micro-Reactor for Defence Applications", 2023. p3, available at :https://www.teamdefence.info/wp-content/uploads/2023/03/20230302-session-1-RR-MR-Op-energy-Conf-2023-V1.0.pdf

Royal Society, (2019), Sustainable synthetic fuels for transport, Royal Society [Internet]. royalsociety.org. 2019. Available from: https://royalsociety.org/news-resources/projects/low-carbon-energy-programme/sustainable-synthetic-carbon-based-fuels-for-transport/ [accessed 13/10/23]

Sadiq, M, Batten, M, Mulet, X, Freeman, C, Konstas, K, Mardel, J, Tanner, J, Ng, D, Wang, X, Howard, S, Hill, M, Thornton, A, (2020), "Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks". Adv. Sustainable Syst. 2020, 4, 2000101. https://doi.org/10.1002/adsu.202000101

Sanz-Pérez, E, Murdock, C, Didas, S, & Jones, C, (2016), "Direct Capture of CO_2 from Ambient Air", Chemical Reviews 2016 116 (19), 11840-11876 DOI: 10.1021/acs.chemrev.6b00173,

Sermarini, J. T. (2000), "The universal fuel at sea: Replacing F-76 With JP-5", Postgraduate Thesis. Naval Postgraduate School, Monterey, California. Available at: https://apps.dtic.mil/sti/citations/ADA378613

Sodiq, A, Abdullatif, Y, Aissa, B, Ostovar, A, Nassar, N, El-Naas, M, Amhamed, A, (2023), "A review on progress made in direct air capture of CO_2", Environmental Technology & Innovation, Volume 29, 2023,102991, ISSN 2352-1864, https://doi.org/10.1016/j.eti.2022.102991

Sollai, S, Porcu, A, Tola, V, Ferrara, F, Pettinau, A, (2023), "Renewable methanol production from green hydrogen and captured CO_2: A techno-economic assessment", Journal of CO_2 Utilization, Volume 68, 2023, 102345, ISSN 2212-9820, https://doi.org/10.1016/j.jcou.2022.102345

The Climate Change Act 2008 (2050 Target Amendment), Order 2019, London. Available at: https://www.legislation.gov.uk/uksi/2019/1056/contents/made (Accessed 20/10/23)

Wade, N M, (2001), "Distillation plant development and cost update", Desalination 136 (2001) 3–12

Zeebe, R. E., and D. A. Wolf-Gladrow, (2008), "Carbon dioxide, dissolved (ocean). Encyclopedia of Paleoclimatology and Ancient Environments", Ed. V. Gornitz, Kluwer Academic Publishers, Earth Science Series, 2008

Adapting Alternate Energy Sources and Future Loads in DC Power Systems

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Synopsis

Designing modern naval vessels to be fit to receive future extension modules is a way of futureproofing the vessel design, while at the same time reducing initial build cost. Energy storage technology is rapidly progressing, and navies should be capable of future proofing for the latest technology for operation gains.

Naval vessels have a relatively long lifetime compared to many commercial vessels and decreasing the complexity of integration or upgrade of power system modules such as batteries and fuel cells, while also allowing for higher share of pulsed high-power loads such as high energy weapons and radars during its lifetime could be beneficial.

DC power systems are marking their entry into the navy segment, where they offer advantages in flexibility and modularity of the power system, where all sources and loads are connected to one or multiple DC switchboards through converter modules.

In this paper, ways of futureproofing a DC power system design are examined, with a focus on gaining the capability to receive future power system modules throughout the lifetime of a vessel. The paper will introduce the DC power system and present possible future extensions of the power system and explore how such extensions may be integrated into it.

It will present different strategies such as design for a specific future component or be able to integrate a variety of different components. It will also explore the use cases for containerised Mission modules. Standards for DC power system will be discussed,

Keywords: DC Power Systems; Energy Storage Systems; Modularity; Design; Fit-to-Receive, Adapting Alternate Energy Sources.

1. Introduction

Vessel power systems have moved towards hybridization and integrated full electric propulsion systems, and now DC power systems for surface vessels are marking its entry. The US Navy points at frigates and destroyers as possible classes of vessels that will benefit from hybridization[1]. For smaller classes such as patrol and coast guard vessels there are several examples of hybridization, both with and without energy storage systems [2][3][4]. Recently, the German navy have selected a DC main distribution system for their newest frigates [5].

DC power systems offer benefits for flexibility and operation and enables:

- Fuel saving by employing variable speed engines with possible fewer genset online.
- Space-saving and optimal localization of equipment.
- Better power system stability and reliability.
- Easier integration of energy storage systems.

In addition, with the ability to handle more load dynamics and having more power available, the integration of new high-power sensors, Electronic Warfare (EW) equipment and laser systems is possible.

These kinds of loads are interesting because they differ significantly from the typical loads in a vessel power plant. What sets them apart from the other loads are that they typically are pulsed and stochastic in nature and with higher ramp rates, which can pose a significant challenge depending upon their power consumption and peak demand [6]. An AC system integrating such equipment will face challenges in keeping the system stable both statically and dynamically, as these kinds of

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loads needs significantly more power and ramp rate that generators are able to offer. This is one key reason why DC based system will ensure future proofing of naval vessels, as they are more capable of handling large dynamic loads.

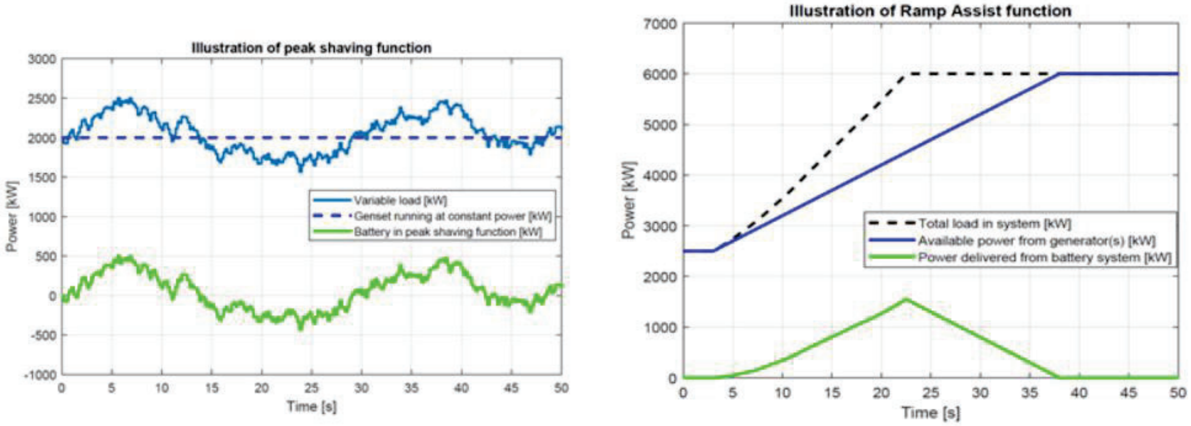

Figure 1: Illustration of BESS support function of a hybrid vessel power plant during dynamic loading.

Hybrid DC systems are interesting, because they can be easily integrated on existing platform designs, with minimal changes in the vessel design without impacting bulkhead position. ABBs Onboard DC Grid™ (ODCG) delivers DC power for hybrid vessel power systems, were the gensets are operated at variable speed to maximize efficiency and the BESS are integrated to provide support for dynamic loading of the power plant. Current limits and ramp rates are controlled by converters, depending on available power. Protection and selectivity are handled by solid-state circuit breakers and fast-acting fuses.

The functions illustrated in Figure 1, which today already are improving the operation of many commercial vessels, will also be beneficial for naval vessels. Figure 2 illustrates how the typical naval loads such as sensors, Directed Energy Weapons (DEW) and Electronic Warfare (EW) will act towards the vessel power plant.

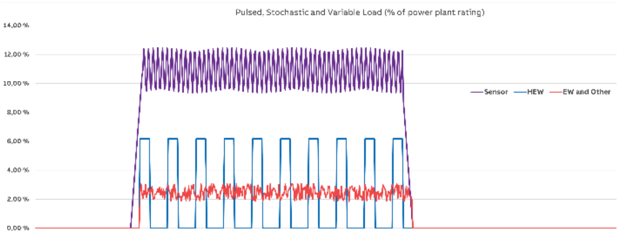

Figure 2: Illustration of how different naval loads looks like towards the power system, with power on the y-axis. Figure in-spired by presentation in [12].

From examining Figure 1 and Figure 2 it is clear that a well dimensioned Battery Energy Storage System (BESS) with functions like peak shaving and ramp assist can assist in stable operation of a vessel power plant even with high dynamic loading. Pulsed loads are interesting because for the BESS, these would look like smaller series of spinning reserve events (load rejection and/or loss of generator events).

2. Naval design of LVDC

The typical way of designing an LVDC power system for a naval surface vessel is shown in Figure 3, here the system is split into two or four similar arrangements, to have electrical redundancy. BESS is integrated into each switchboard section for increased redundancy if generator or bus transfer is lost. The LVAC supply is handled by Off-Grid Converters (OGC), that ensures smooth 440VAC to downstream consumers. The propulsion system is fed by inverter units creating variable speed to the shaftline. Variable frequency drive supplied loads can also be supplied from the DC switchboards to reduce THD in the LVAC system.

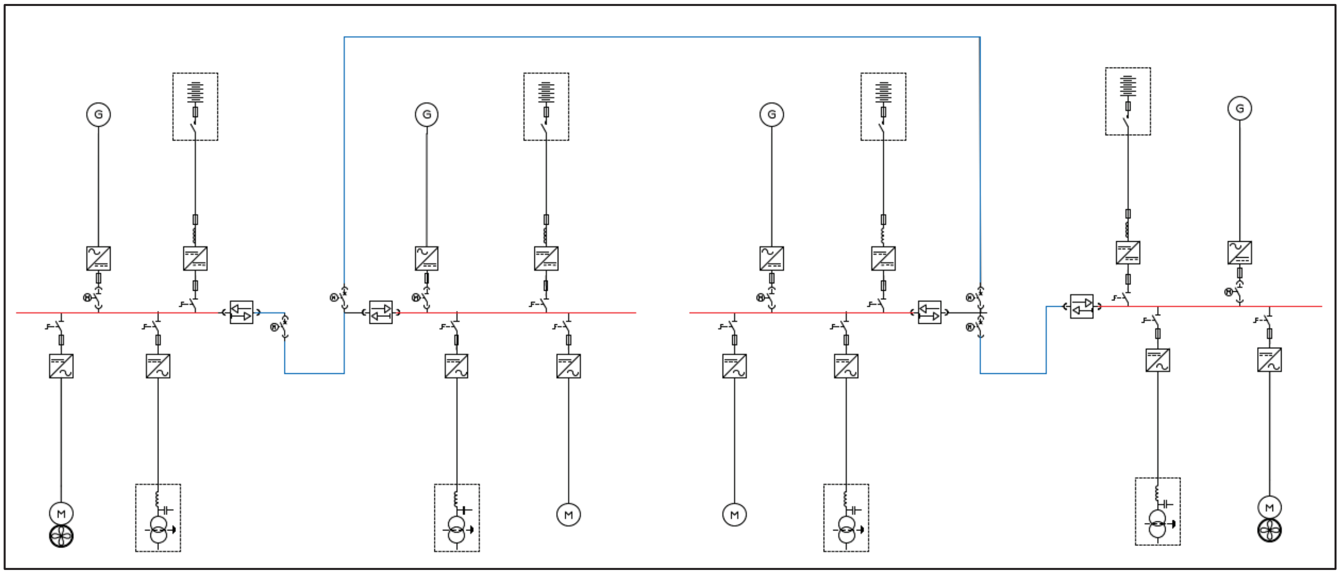

Figure 3: Illustration of a DC power system with redundancy splits showing power generation, energy storage, auxiliary power propulsion load and the solid-state breaker.

BESS can be connected to the DC system with either DC/DC converters or directly through a fused feeder. However, the use of DC/DC converters is generally preferred as the batteries can be operated regardless of their State-of-Charge (SoC). Directly connected batteries are typically used where BESS is the main source of power, such as a zero-emission ferry or now on smaller unmanned platforms.

As discussed in [7], all DC switchboards should be connected in normal operation, i.e. the solid-state DC breaker closed, as the number of generators online can be optimized for better fuel efficiency.

For combat mode, or as requested, the system can be split into redundancy zones. Load sharing is done by voltage droop control, and a power and energy management system (PEMS), a very capable redundant, distributed control system coordinates all control functions for all operating modes as required.

The protection of a DC power system is handled differently than a conventional AC power system. Each converter unit in Figure 3 is protected by its own fuse. In case of internal fault in the converter, the short-circuit current provided by the energy stored in the capacitors of other converter units will quickly, within microseconds, make the fuse operate and segregate the faulty converter from the rest of the system. In case of faults on main bus bars in either the link (red) or grid (blue) section, protection signals from solid-state breakers and current measurement Current Transformers (CTs) will identify the fault location and open correct breakers. If switch-disconnectors or disconnectors are used, solid-state breakers and converters can block short-circuit current to allow bus-ties and feeders to open.

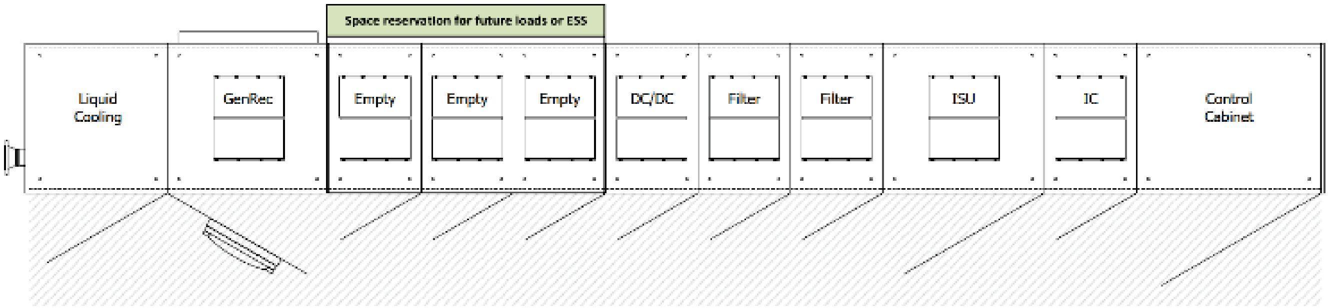

Figure 4: Illustration of cabinet drawing for the system in Figure 5 with space reservation for future modules. Can be installed with modules or just busbars passing through

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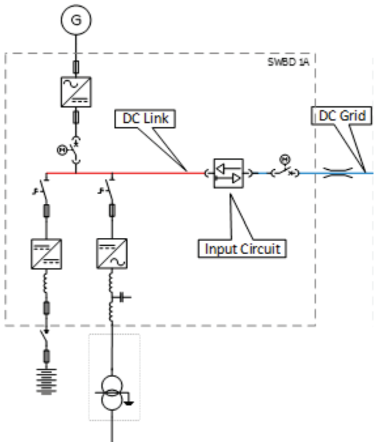

Figure 5: Notional SLD detail for a combatant damage zone BESS integration

3. Fit-to-Receive LVDC Designs

Fit-to-Receive LVDC designs means being able to integrate future loads and sources, increase energy/power consumption or generation with the same power system design or to give opportunities to connect mission modules as required. Some examples of fit-to-receive BESS have been discussed where basically the DC/DC cabinets would be there but not the actual Line Replaceable Unit (LRU)/Converter as shown in Figure 4. This is an example of a cost saving measure to await future BESS technology. In addition, the future-proofing of large BESS could also incorporate a Solid-State Circuit Breaker to make sure that the system can cope with the peak short-circuits from a BESS. Another example would be that cabinets are in the design; however, the subsystem function is not designed yet. Then, the same cabinets and inverters could be used for: Inverter Unit (INU) for variable speed motors, Inverter Supply Unit (ISU) for static conversion to LVAC or shore connection and DC/DC for future DC based loads.

4. Containerized Mission modules

Another simple way to future-proof a platform today is to install future feeders to Mission Bays / Hangars as can be seen in Figure 6 and Figure 7.

In this example, each Grid connected DC breaker has a capacity of up to 6 MW, directly connected to the Onboard DC Grid™ patented Grid zone protection that enables selective design with DC ACBs instead of fuses. ABB always recommend installing those and a fibre optic cable for the PEMS system to be futureproof. This creates flexible and changeable capabilities on the other end of the cable in either the Hangar or Mission Bay.

These capabilities can include:

- Containerised ESS
    - High power for pulsed loads
    - Energy for silent and zero emission operations
- Containerised Gensets
    - Double damped high-speed gensets for silent operations
    - Retrofit for under-dimensioned powerplants
- Load bank for genset testing
- Fuel cells for
    - Zero emission operations
    - Silent operations powered by F76
- High power demanding DEW
- High power demanding sensors, radars, sensors
- Desalination and tropicalization

Overall, the tactical benefits of using DC power and electrical propulsion with a variety of available or future Energy Storage Systems (ESS) can result in improved dynamic performance and optimal uptime on sensors and mission systems. One common denominator is that ESS are typically DC based.

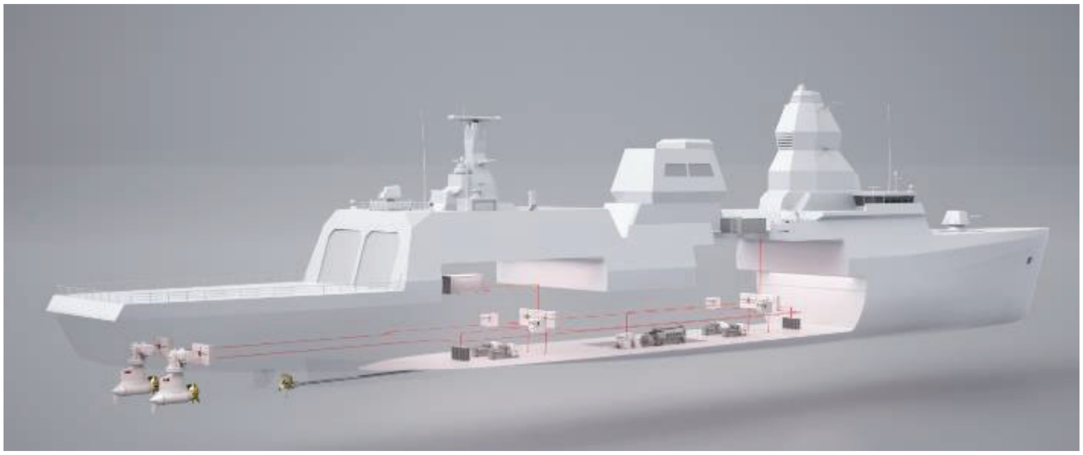

Figure 6: ABB Rendering of Wingpod concept as presented by BAE systems during Euronaval 2022.

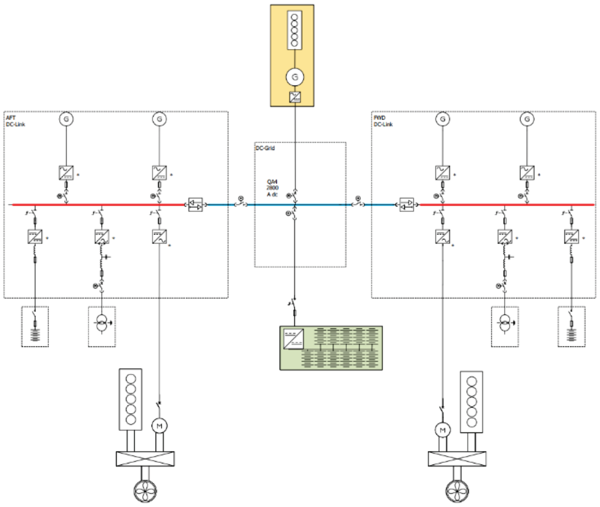

Figure 7: Illustration of integration of containerized mission modules into a DC power system.

4.1. Mission Module – BESS

Complete and self-contained BESS solutions for marine vessels have been announced by ABB [8] as shown in Figure 9. In this system, the batteries, converter, control, interface, and auxiliary equipment is placed in a container for easy installation onboard a vessel. This is a solution for both retrofit and newbuild projects. Note that for example China based CATL recently release a 6,25 MWh LFP BESS in a 20'' container [9]. The containerized BESS will have the same functionality as conventional BESS in a DC power system: spinning reserve, ramp assist and peak shaving. The use case could be for zero-emission operation or assisting the power plant in dynamic load conditions. If considering a midsize Anti-Submarine Warfare (ASW) Frigate with combined hotel load and propulsion of 1 MW, then around 5 hours of ASW in low knots can be achieved with merely one container. The containerized BESS would be easily interchangeable if not needed or for upgrade of battery technology.

4.2. Mission Module – Genset

This use case could be discussed for retrofit, adding special capabilities to a Multirole Frigate such as double damped high speed gensets for silent operations. This genset would be placed far up, preferably in the boat deck and far away from the water for longer Structure Bourne Noise (SBN) travel path from hull to water.

For vessels with under-dimensioned power plants, not suitable for taking in future loads or with one genset out due to service, a containerized genset module could be beneficial. Naturally simple on paper and normal caveats for fuel, exhaust, selectivity, installation, Selective Catalytic Reduction (SCR) etc. applies, however certainly plausible. In commercial vessels, DNV has published the class guideline DNV-CG-0588 for containerized gensets.

Figure 8: Illustrative model of a containerized ESS module from SH Group.

Figure 9: ABB visualization of containerized ESS for an offshore support vessel.

4.3. Mission Module – Fuel cell

One example of a 3 MW fuel cell concept system can be seen in Figure 10 below. Naturally hydrogen and the size of the 2022 version can be discussed with Naval eyes.

As we move into the future it is expected that the industry will develop into more power dense solutions in the future if the safety, supply, density, and stability of the fuel can be overcome and comply with Naval standards.

Figure 10: Conceptual model of a containerized fuel cell module [10].

5. Interoperability – DC standards

The draft version of US MIL 1399-300-4 outlines a standard for LVDC with the simple goal of ensuring standardised interfaces. Considerations of pulsed power can be seen below.

- The maximum rate that a load can increase or decrease its power consumption.
- The maximum current drawn by pulsed loads in the power system.
- The maximum and minimum pulse width of the load.
- The recovery or recharge time between each pulse.
- The length of the pulse series.

Integration of significant pulsed loads or high ramp rate loads needs to consider operational limitations implemented in the vessel power and management system with regards to the points above.

However, it should be noted that commercial Marine already have integrated various 1,000 VDC system from various OEMs by just means of Electrical Engineers speaking and agreeing. In addition, the Danish company SH Defence have worked out several of these interconnection standards in their Cube™ System[11] as depicted in the earlier Figure 8.

While a new standard may have appeal to navies, however it also comes with the risk of slowing innovation and benefitting from the benefits of established proven systems.

6. Conclusions, Future work

This paper indicates some solutions to futureproof Naval platforms that can be considered in the initial platform designs for footprint and weight allocation on surface ships. The successful integration of future loads such as laser weapons, advanced sensors, fast charging systems for unmanned systems etc. will see benefits of having hybrid DC power systems, preferably with energy storage systems. This is because DC power system with integrated energy storage allows faster load dynamics than AC systems. Mission modules in the form of containerized BESS or Gensets can easily be integrated into a DC power system. There maintain perceived challenges in the industry relating to the safety of BESS on a combatant, such as the implications for firefighting. Many of these issues have been overcome, however their remains a lack of awareness and understanding within the naval community and time and resources should be invested on this topic.

References

[1] PMS320 Naval Power Systems Technology Development Roadmap https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2018/02/NavalPowerSystemsTechnology-Roadmap.pdf

[2] https://new.abb.com/news/detail/101639/abb-to-power-two-new-multi-purpose-patrol-vessels-for-finnish-border-guard

[3] https://www.danfoss.com/en/about-danfoss/news/cf/danfoss-helps-estonia-combat-pollution-with-new-hybrid-patrol-ship/

[4] https://www.canadianmanufacturing.com/manufacturing/canadian-coast-guard-to-build-hybrid-vessel-in-gaspe-295505/

[5] Damen agrees with ABB Marine to support power systems of F126 frigates - Naval News

[6] Stephen P. Markle. Naval Power & Energy Systems: Way Forward Surface Navy Association: 32nd Annual National Symposium, 15 January 2020

[7] Krattiger et all, LVDC Systems for Naval Applications, 2019 ASNE TSS

[8] Containerized energy storage brochure.pdf (abb.com)

[9] CATL unveils 6.25-MWh energy storage system TENER (solarpowerworldonline.com)

[10] ABB and Ballard reach milestone toward fuel cell-powered marine transport

[11] The Cube – SH Defence

Selecting and validating Li-Ion Battery Energy Storage Systems for Surface Combatants with DC Power Distribution

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Synopsis

Increasingly, Surface Combatants built use Electrical Direct Current, DC, Power Distribution technology, and feature distributed power generation and energy storage. DC Power Distribution supplies power for mission, propulsion, and hotel loads, while meeting the survivability requirements of naval applications.

Retaining a certain amount of energy storage in those systems is critical to support the highly dynamic loads and system reconfiguration requirements, and the Direct Current DC Power Distribution does this all while performing at significantly higher fuel efficiencies than conventionally powered vessels. Furthermore, energy storage technology selection is a holistic process, and safety characteristics of Li-ion batteries are a major concern for Navies.

This paper first establishes the various needs for DC power distribution systems based on the power requirements of current surface combatants and future margin. Then, it derives the energy storage characteristics, such as power, energy, cycle life, size and weight for these vessels. The paper then guides through the process that establishes criteria and evaluates the different aspects of the available technologies to be suited. Safety aspects will be described from battery chemistry to cooling methods to FIFI and battery room demands. The selection process presents energy storage technology suitable for NATO combatants. This technology is now being used for several Combatants within NATO Europe.

Keywords: Energy storage; Li-Ion; Navy; Battery Safety; LTO; F126 Frigates.

1. Introduction

Shipboard power systems evolved from the conventional diesel mechanical (DM) propulsion system that is complemented with a diesel electrical (DE) auxiliary power system, to the Integrated AC Power System (AC-IPS) that shares the diesel electrical power plant with propulsion and auxiliary loads, to the Integrated DC Power and Energy (DC-IPES) system that integrates energy storage [1].

The need for energy storage onboard marine vessels with electrical power distribution is well established and has been implemented on a growing numbers of different vessel types across the past decade. The driving factors for energy storage depends on the vessel type, but in general these are 1) increasing fuel efficiency for environmental reason and mission duration; 2) Improving the power system performance dealing with dynamic loads; and 3) enhancing the power system reliability.

Li-Ion batteries have been in use by the commercial shipping industry for more than a decade. More recently, Naval Submarines have started to embrace the benefits; however, some of the surface fleets have been hesitant to install such systems specifically due to concerns on their safety and survivability impact on the overall platform.

This paper aims to show the differences in the various Li-Ion chemistries and that these designs have significantly diverse safety characteristics and performance; and that specific types of Li-Ion batteries are safe to work in a Naval surface environment.

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2. Why BESS on a Combatant

The first and most important question is what purpose the Energy storage will have onboard the combatant. While there are ambitions for full Zero Emission Operations such as green port entry and for silent modes such as for anti-submarine warfare (ASW) operations, these functions require a large energy type of BESS. However, reasonably sized energy type BESS systems would currently still have limited endurance, considering the powers needed onboard a large or even medium sized combatant. While battery energy densities will improve and increase endurance in the future, for currently built combatants in Europe, the intent has been to dimension the powerplants to support following functions:

- Increasing efficiency and dynamic response on the powerplant
- Increasing QPS (Quality Power Systems) with blackout prevention to load centers in the unlikely event of a diesel genset being out of service
- Futureproofing powerplant for pulsed loads and mission systems
- Acting as redundant power supply when vessel is on Shore connection

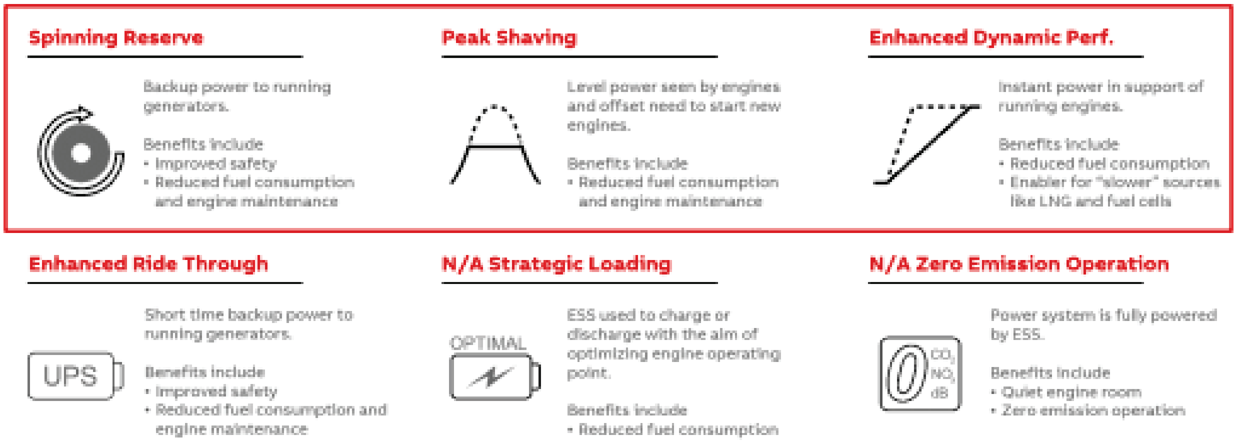

Figure 1 - shows an overview of the BESS functions in a DC power system, with the focused functions discussed above highlighted

Overall, the tactical benefits of using DC power and electrical propulsion with energy storage systems ESS result in improved dynamic performance and optimal uptime on sensors and mission systems. The focus BESS functions mentioned indicate that a High-Power and High-Cycle Life battery is preferable.

3. Integration of BESS to The Power System

Naval combatant powerplant systems are built with forward (FWD) and rear (AFT) electrical redundancy, typically in a two or four split arrangement. In this design the BESS is incorporated in each of these splits as can be seen in Figure 2 which is a notional two split power system. Each of these autonomous subsystems include two generators, one battery, one Off-Grid Converter (OGC) to produce the 440 VAC STANAG1008 voltage, and a propulsion converter.

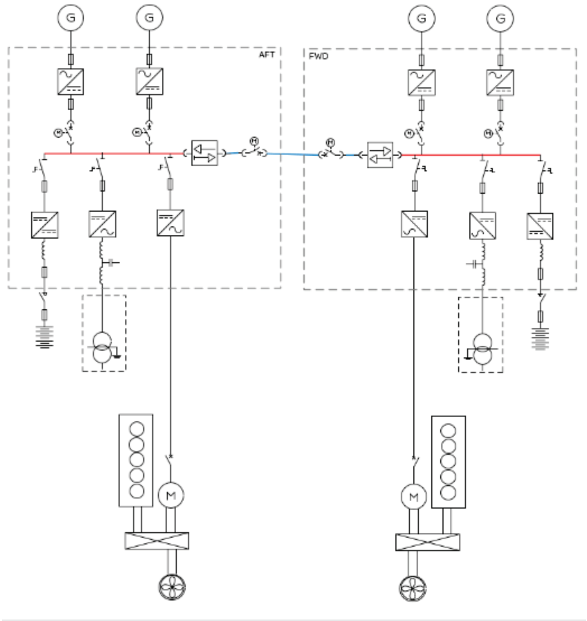

Figure 2 - Notional CODELAD two split DC-IPES showing power generation, energy storage, auxiliary power, propulsion load and the solid state breaker

As discussed in [3], all subsystems should be connected in normal operation, i.e. the solid-state DC breaker closed, and just disconnected for maintenance or as required by fault and ship damage situations. This provides for the optimal vessel fuel efficiency, as just the minimal amount of gensets need to be online to cover the overall vessel power needs. On discretion of the vessel commander the system can run in the disconnect mode, or in any other configuration, during e.g. combat. The shown propulsion arrangement is CODELAD, the propulsion motor could be full power take in/out (PTI/PTO) as desired. Load sharing is done by droop control, and a power and energy management system (PEMS), a very capable redundant, distributed control system coordinates all control functions for all operating modes as required.

The batteries are connected to the DC system with DC-DC converters. While these DC-DC converters take space, and have losses, this arrangement is preferred, as the batteries can be connected to the system and operate regardless of the individual battery State of Charge (SOC). This becomes obvious when e.g. connecting/energizing a subsystem, and the system DC voltage of each subsystem needs to match before closing the solid-state breaker.

It should be noted, that in some application that depend on very large energy stored onboard the vessel, e.g. an all battery-operated ferry or submarine, the batteries are connected directly to the DC link, and thus all batteries need to be on the same voltage, i.e. SOC. This eliminates the losses, and thus increases the round trip energy efficiency, but the system DC link voltage will fluctuate, and inefficiencies come by increased margins of the DC link connected power converters.

Figure 3 shows a detail of one “damage zone” for further discussion. Note, no propulsion load is present, since propulsion is part of another subsystem. Assigning the different loads and other assets to several connected subsystems is an optimization process that considers survivability, space at the specific damage zone, and many other factors, all proprietary and cannot be discussed here. However, the DC distribution technology allows for all such variations in the most flexible way.

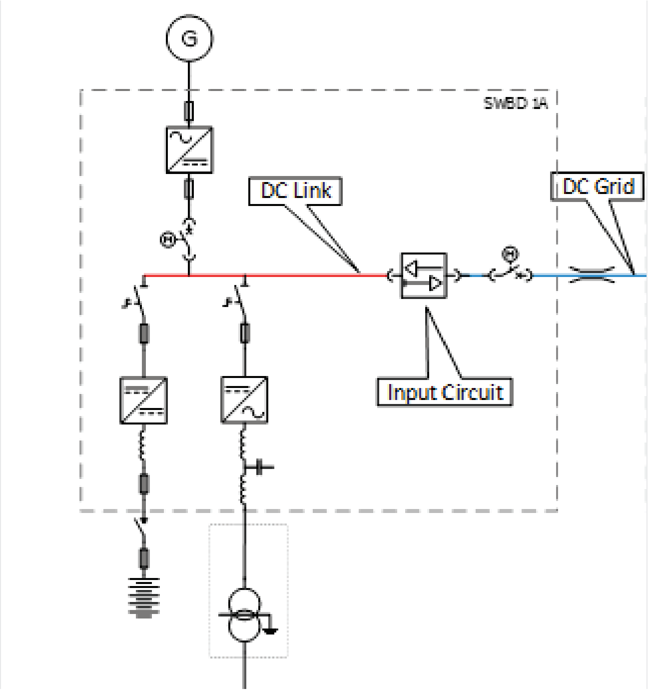

Figure 3 – Notional SLD detail for a combatant damage zone BESS integration. Note complete e.g. four split configurations and SLD can be commercially sensitive and thus is not presented

4. BESS SIZING

As an example, a typical generator size for a CODLAD/CODLAG Frigate is 2-3 MW. The battery could then be set to the full power of one generator to provide the full spinning reserve battery function. However, due to the hybrid design the BESS does not need to be dimensioned for the full power loss of the generator. In fact, in case of a generator loss the electrical propulsion power would be instantly shed by the drives control and PEMS in a fault ride through scenario. This assures the hotel load and vital mission system maintain power and prevent a blackout. So, for such scenario the battery power required notionally could be 1,25 MW per FWD/AFT split. This is shown in the visual representation of the system wide battery usage in Figure 4. Therefore, the dimensioning criteria for this exercise is 1,25 MW FWD or AFT for the time needed to startup one genset (with one failed attempt) until a new genset is online or changeover from FWD/AFT load center has occurred., i.e. notionally energy required for spinning reserve is 1.25 MW for 2 x ~30 s

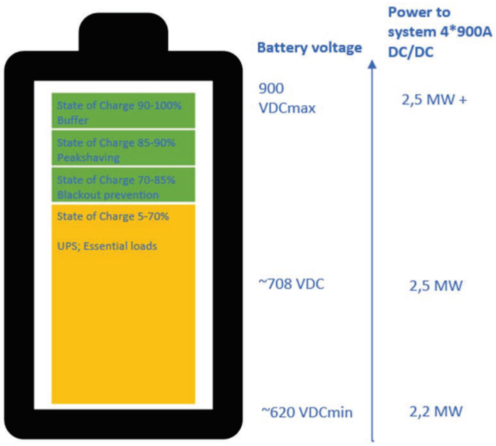

Figure 4 – Example for visual representation of Battery usage, Battery voltage and available power to the system (total for vessel).

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The total energy of the BESS system on the vessel could be as low as 250 kWh. The final selected installed energy could consider future growth and other margins. Figure 4 also indicates some other interesting facts, such as minimal and maximal SOC are limited for battery life and operational margins, and the UPS function supporting essential loads for several hours in certain blackout situation allocates the most energy installed (yellow section).

5. BESS design selection criteria

Since 2017, ABB Coast Guard & Navy have conducted extensive research, testing and simulations covering numerous leading OEMs and cell types to find a suitable technology. This analysis was led by our embedded marine Battery Experts within our Corporate Research function. In order to conduct this evaluation, a high level selection criteria was made as depicted in Figure 5:

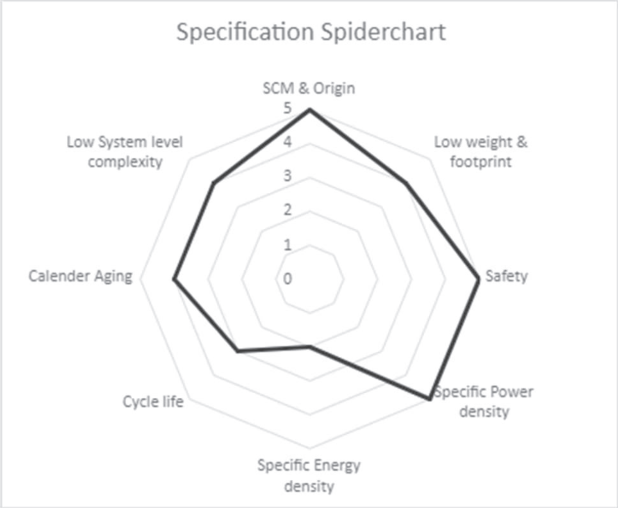

Figure 5 – Main criteria and importance (1-5) for BESS design

Since Supply Chain Management SCM & Origin is sensitive for a NATO Combatant, a large portion of the Marine BESS market was ruled out in the study at an early stage. In addition, some OEMs are hesitant to work with the defense industry and MIL standards.

Future promising technologies were also part of the study however ruled out due to low technical readiness level TRL numbers.

For the stated specification and other requirements for the BESS Application on combatants above, below in Figure 6 are estimated results for the shortlist of three major Li-Ion chemistries with mature TRL levels:

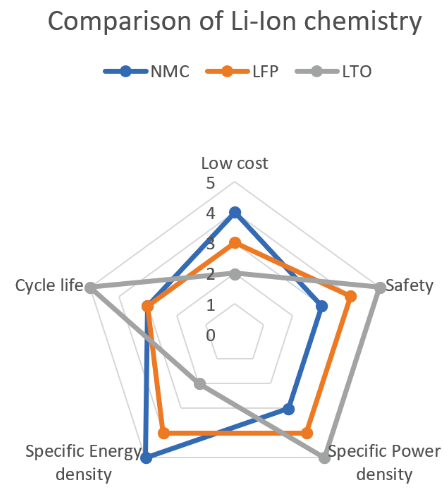

Figure 6 – Shortlist of three different Li-Ion chemistries and assessment of main characteristics.

Table 1 lists additional information on the three Li-Ion chemistries considered.

Chemistry	Anode	Cathode	Typical C-rate (System)	Cycle life typically
NMC	Graphite	NMC	3	6000+
LFP	Graphite	LFP	10-15	6000+
LTO	LTO	NMC	10-15	30 000+

Table 1 – Characteristics of the three Li-Ion chemistries

As a reference, Lead-Acid batteries typically have a cycle life of ~500 – 2,000cycles.

The extensive battery evaluation study led to recommending LTO in this application being the frontrunner over NMC and LFP due to the combined benefits of high cycle life, high C-rates and high Safety characteristics. The downside of LTO is higher cost and lower specific Energy density as shown in Figure 6.

To explain the superior cycle life of LTO: LTO is a “zero-strain” material, meaning it undergoes minimal volume change (<1%) during lithium ion insertion/extraction. This stability contributes to excellent cycling stability, allowing for over 30,000 cycles.

Not shown in Table 1 is the operating temperature. According to [4] LTO has an increased operating temperature range of -30C to 75C whereas LFP and NMC have a -20C to 60C range. This is due to the absence of a carbon anode in LTO, which does not form an SEI layer, and thus TR onset temperature of the LTO cell is higher, see further below.

In total the BESS weight due to the lifecycle and C-rates for LTO can be below 5 tons total for a BESS systems capable of delivering 2,5 MW+ consisting of approx. 4+4 strings and250 kWh vessel total.

Moving forward in this paper LTO BESS will be described in more detail.

6. Thermal runaway (TR)

Li-Ion batteries can develop a thermal runaway that exponentially generates heat over time. This can be initiated by external forces or internal failures such as internal/external short circuit, overcharge/over-discharge, and overcurrent.

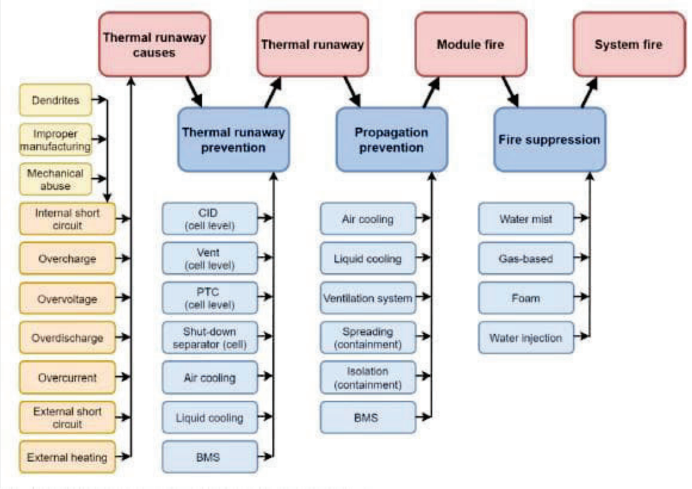

Figure 7– Causes and prevention methods of TR [4]

If a battery is operated and stored within the limits recommended by the manufacturer, the failure rate is estimated to only be 1 in 40 million [4]. An overview is presented, and the main causes and methods of TR prevention is shown in Figure 7.

As the Cycle Life and weight of LTO in this application is superior the below depicts the safety aspects of LTO chemistry.

6.1 *Causes of Thermal Runaway*

LTO cells can go into thermal runaway but requires much more abuse to do so. In case of severe abuse, a cell may vent flammable electrolyte fumes and explosive gases. Adequate ventilation is therefore required by class. The higher degree of robustness originates from:

- No SEI (Solid Electrolyte Interphase) layer
  →no exothermic SEI decomposition
  → pushes TR onset temperature higher
  → therefore more robust to thermal abuse

6.2 *Internal short circuit*

Limited by design as shown in Figure 8, dendrites formation in LTO anode will not occur as a risk for internal short-circuit because an SEI layer is not formed.

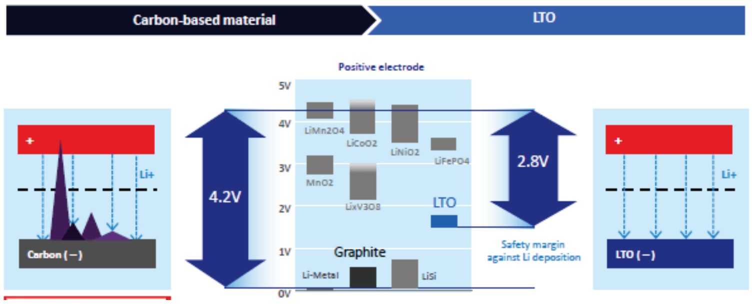

Figure 8 – How LTO compares with Graphite/Carbon Anode

There is a huge electrochemical margin to Li-metal plating, potentially more resistant to overcharging, and no risk for dendrite formation and internal short circuit.

LTO phase transformation at high current densities prevent fast discharge and thermal runaway TR in case of internal short (due to i.e. nail penetration). For the mechanical abuse tests with 0.50 Caliber (12,7 mm) penetration and crushing tests shows no explosion or fire.

Figure 9 - Overcharge/Overdischarge/Overcurrent/Overvoltage/external short circuit

Due to DC/DC converters maximum current limitation, the overcharge and overvoltage fault is limited by design. In addition, the battery management system (BMS) monitors voltage and current as well as temperatures initiating a trip of the affected battery string. In addition, System OEM designs selectivity with fuses and selectivity to protect cabling and DC switchboard and ensure personnel safety.

6.3 *External heating*

Due to the 180C onset temperature of LTO and tests for external fires, this risk is reduced compared to other chemistries, however, it cannot be dismissed. Exothermic reaction can still be triggered in cathode if cell temperature goes above 180C. If cells are heated above ~180C, cathode and electrolyte will decompose exothermally (but without contribution from the LTO anode) or if extensively overcharged to >200% SOC (4.8V/cell). On the other hand, the qualitive hotspot testing using gas burner indicates 700-800℃ for fifty minutes until one cell goes into TR without propagation to other cells or modules.

Figure 10 – Picture of external heat test

If the external temperatures can reach those levels with the A60 barrier, then there are other severe issues onboard the platform not originating from the BESS.

6.4 Thermal runaway prevention & propagation

Class tests for nail penetration show that the LTO in addition to the physical abuse requires overvoltage to get the affected cell into TR. This one cell is proven not to propagate to other cells eliminating the needs for current interrupting device (CID), Vent, positive temperature coefficient (PTC), Cell to Cell isolation (Shut-down separator (cell)), or active Cooling.

The battery system manufacturer needs to prove that the system is by its own accord, or has sufficient safety measurements built in, to be deemed safe to use onboard a ship. One of these tests is the Propagation test. DNVGL is using IEC62619 modified to one of two design options.

1.The battery system is designed for no propagation between cells within a module.

2.The battery system is designed for no propagation between modules - with or without an extinguishing agent.

The performed tests aim to fulfil design option 1, thus no propagation between cells within a module. the designed.

The battery system manufacturer has also proved that the LTO module has sufficient safety measurements built in, to be able to pass three propagation tests according to the DNVGL standard based on IEC 62619. No propagation took place in the battery module when the battery trigger cell was overcharged to less than or equal to 4.1 V, which corresponds to 152% of overcharge of the battery cell voltage.

6.5 Battery management system BMS

Needless to state the BMS plays a vital role in the safety of the BESS, and needs to be immune to electromagnetic disturbance and proven in use. It is recommended that the BMS always stays on active to make early detection of any abnormalities. Fault safe monitoring and redundant measurements (Cell/Module voltage and temperatures) are required.

6.6 Fire Suppression

Due to the CBRN (Chemical, Biological, Radiological and Nuclear) design with overpressure onboard combatants, this makes the design of some of the commercial firefighting FIFI systems such as NOVEC or CO2, that is also toxic to the crew, not favorable onboard vessels [7]. Typically, the shipyard designs with a water mist system that is further discussed below.

Water Injection or immersive cooling is a promising technology for BESS with higher energy content and lower onset temperature for TR

6.7 Gas generation during TR

A thermal runaway event will lead to the release of gases that are measured during testing. These contain a mixture of H2, CO2 and CO, CH4, C2H4 and C2H6, and including the highly toxic hydrogen fluoride HF. As the LTO modules are tested not to propagate, the gas released for one cell is very limited, for the LTO example < 100 l per cell .

6.8 Water or Air cooling

Water cooling is a fairly common design in Marine BESS that gives thermal benefits for an energy dense profile that have high RMS C-rates. However, water-cooling can lead to safety aspects, see [6] for a summary of a battery event on a Norwegian vessel in 2019.

The use profile depicted in the combatant simulation for system wide heat rejection, resulted in the average cell temperatures listed in Table 2 for the two BESS functions, spinning reserve and peak-shaving.

This means that in this application there is no need for active water-cooling. Air cooling eliminates the need for managing condensation that could occur with water cooled battery systems and it is safe even in case of failure of the cooling system. Air-cooling in this application lowers the system complexity, improves the system reliability and is easier to comply with Shock and Vibration according to MIL mechanical standards.

Function	C-rate & Power	Systemwide heat rejection	Average Cell temperature
Continuous Peakshaving	1C RMS ~30 kW per string	~2,5 kW	~20->26°C
Spinning reserve/Blackout prevention	12C Pulse one minute, 310 kW	<1kW	~20->23°C

Table 2 – Heat dissipation simulation results

Nevertheless, it should be noted that a in a different application active water-cooling may be preferred.

6.9 Summary FIFI cell originated TR

For the LTO case several abusive tests show that if one cell is forced to go into TR this is undramatic with no fire or explosion. The affected string will be disconnected and in the same time the gas-sensor detects and opens the off-gas ducting and start to ventilate the <100 l gases overboard. Battery Room ventilation is activated. See Figure 11 for a notional diagram of an air cooled LTO battery ventilation system.

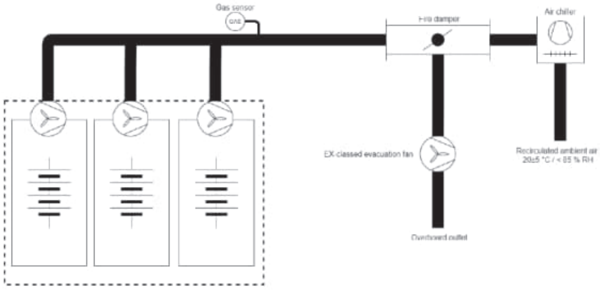

Figure 11 – Notional picture on aircooled LTO Strings with combined gasevacuation and cooling duct. Note that the separate Battery Room ventilation is not indicated in figure.

6.10 Summary FIFI external fire

In a confirmed fire onboard a combatant the ventilation will be turned OFF, as there could be the need to evacuate personnel. The purpose to turn ventilation off in the affected zone is to keep the smoke propagation confined. The Battery room should be a sub-citadel with kept ventilation to evacuate any potential gas during abnormal events.

Cooling of an adjacent fire will be performed either by using Hi-Fog systems or manually by the Battle Damage Repair Team (BDR) using hoses. Purpose of the external cooling is to make sure the LTO cells are not heated up.

If the external fire is spreading, then the Power drain of the BESS can be evaluated. Alternatively, if the BESS is the only power source onboard, then battle-override can void temperature alarms from BMS and a temporary seawater powered fan can be used to cool the batteries to increase survivability.

Flooding of the battery room should be the very last resort as flooding with Seawater will create electrolysis and thus H2 and O2 generation. Room ventilation must be kept running. Qualitive drench tests in saltwater tests have been performed that generated corrosion however otherwise undramatic, no fire nor explosion.

Figure 12 – Output of qualitive drench test in saltwater

6.11 Summary FIFI events

As summary Table 3 provides basic input to the Killcards for the Damage Control System:

Stage	**Thermal Runaway**	**Cooling of adjacent room fire**	**FIFI in battery Room**
Description	One cell vents gases ~<100 liters	To limit or make sure cells are not heated up >180 C	Adjacent fire have spread to battery room
Battery Room air handling	BESS Gas evacuation ON Battery Room Ventilation ON	Watermist ON BESS cooling ON Room Ventilation ON	Hi-Fog, Sprinkler, Seawater Room Ventilation ON
Impact	Only the affected string is disconnected by BMS	None unless BMS detects abnormal temps; Evaluate battle override to keep vital systems running. Evaluate increasing power drain if situation get worse to reduce stored energy	BESS inoperable
Comment	Undramatic in the case of LTO cells, no fire	Depending on the specification of the BESS and the fire state onboard	This should be the very last resort as flooding with Seawater will create electrolysis and thus H2 and O2 generation

Table 3 – Simplified layout of FIFI events onboard a combatant with an LTO BESS

7. Further Validation & Testing

Needless to say that after the extensive internal testing our end users have commenced on significant performance tests of their own. [8]

8. Conclusions, future work

This paper indicates the operational benefits of hybrid Combatants with ESS integrated through a DC power distribution architecture:

- Distributed DC power generation and energy storage technology allows for robust designs with superior survivability
- Increase efficiency and Dynamic response on Powerplant

- Increase QPS with blackout prevention to load centers in the unlikely event of diesel generator is out of service
- Futureproof powerplant for Pulsed loads and mission systems
- Act as redundant power supply when vessel is on Shore Connection

The ESS can be realized with a remarkable small footprint and weight using High Power LTO technology. The most important for safety in the design is the cell chemistry used and the BMS. The superior safety aspects of LTO is well suited for use on Naval Combatants. For the cooling on this Combatant ESS LTO application, the introduction of water-cooling would merely generate an additional risk and no additional benefits. Due to the safety aspects of LTO the greatest concern for TR is adjacent fires that can heat up the module. European Navies have started to embrace and build Frigates with Li-Ion LTO ESS to embrace the operational benefits while still managing the safety aspects.

DC power distribution systems, with battery energy storage and power generation, all distributed across the vessel, have been applied in numerous ships in the commercial industry in the past decade. The flexibility in building architectures to meet the specific vessel application, and very significant fuel efficiency gains have been well established.

Further work is required for guidance on ESS design on warships for further applications such as Containerized Energy storage for Zero emission/silent operations with a high Energy cell. In addition, guidance for charging of drones onboard vessels is also required.

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References

[1] Mutarraf et all, Energy Storage Systems for Shipboard Microgrids—A Review, 2018 MDPI https://www.mdpi.com/1996-1073/11/12/3492

[2] PMS320 Naval Power Systems Technology Development Roadmap https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2018/02/NavalPowerSystemsTechnology-Roadmap.pdf

[3] Krattiger et all, LVDC Systems for Naval Applications, 2019 ASNE TSS

[4] N.H.D Gartner, Thermal behaviour of lithium-ion batteries and the implications on submarine system design , TU Delft Master Thesis, 2021. https://repository.tudelft.nl/islandora/object/uuid:f102aa75-fa6a-48d2-83c9-92c9e632ff6a/datastream/OBJ/download

[5] EMSA Guidance on the Safety of Battery Energy Storage Systems (BESS) on board ships, 2023 https://www.emsa.europa.eu/component/flexicontent/download/7643/5061/23.html

[6] Supporting preliminary findings after battery incident - Norwegian Maritime Authority (sdir.no) MF Ytterøyningen. 12/12 2019 https://www.sdir.no/en/news/news-from-the-nma/supporting-preliminary-report-after-battery-incident/

[7] S. Klüh et all, Fire Safety of Lithium-Ion Traction Batteries, 2020 https://www.ri.se/sites/default/files/2020-12/Klueh2020_Fire_Safety_of_Lithium-Ion_Traction_Batteries.pdf

[8] Class 126 frigate – self-sufficient power supply by means of batteries (bundeswehr.de)

Optimization of Propulsion Layout & Energy Management System for Future Marine Powertrains using Co-Design

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Abstract

Marine energy systems are rapidly evolving, following the demand for decarbonization and increased energy efficiency. Design options are ever expanding due to an increased degree of electrification, inclusion of energy storage systems, novel energy converters such as fuel cells and dual- fuel engines, and alternative fuels such as hydrogen, methanol, or ammonia. These increasingly complex layouts also necessitate the development of accompanying energy management systems to orchestrate the operation and power split between different sources in an optimal fashion.

Design of such systems is increasingly supported by simulation and optimization methods. Optimization criteria can vary depending on the intended vessel mission and often include metrics such as; energy efficiency/range optimization, Operating/ Capital Expenditure (OPEX/CAPEX) minimization, system State-of-Health (SoH), and uptime considerations. The need for these methods is further emphasized by the characteristics of new energy converters and storage systems, considering the in-use degradation of battery and fuel cell systems, increased footprint required to place these systems, (early adopter) cost, and the reduced energy content of alternative fuels.

In the current paper benefits and challenges of applying methodology for co-design of the energy system together with the energy management in an integrated and optimal fashion are explored. The testcase considered is that of a fast ferry operating on Hydrogen (H_2) powered by a Low Temperature Proton Exchange Membrane (LT-PEM) fuel cell. The benefits are compared with traditional design approaches, in which either the system layout or energy management logic is optimized, in order to quantify the added benefit of integrated design.

While the testcase for this methodology is a commercial vessel, the methodology is designed to be generally applicable and may also strongly benefit the design of complex naval vessels. While it is unlikely that naval vessels will adopt hydrogen as a primary fuel, it can become a part of the energy sources onboard to supply smaller (unmanned) assets (UXVs) or to run fuel cells in support of low-signature operation. Using co-design to optimize towards metrics such as footprint or system health is vital to integrate these novel energy systems and guarantee their effectiveness in future marine powertrains.

Keywords: Energy Management, Marine Power Systems, Simulation, Optimization

1. Introduction:

Decarbonization and sustainability, together with digitalization and autonomy are themes that are often brought up in discussions about the future of maritime transport- operations, for commercial, private and even military applications.

Especially on the decarbonization topic, the landscape is far from clear. Multiple alternative future energy carriers, power conversion sources, technologies and propulsion layouts are being considered (Boonen 2023). These have different implications on ship design, while greatly increasing the design degrees of freedom.

The traditional powertrain design process, while straightforward for diesel-direct propulsion layouts, becomes suboptimal. Usually, the process is split in two distinct steps; the design of the physical system (i.e. the plant and its components) and the design of the control system. As the complexity of the propulsion and power generation

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Author's Biography

Nikolaos Sakellaridis completed his Mechanical Engineering studies up to PhD level in the National Technical University of Athens, Greece, on the topic of Marine Diesel Engine Simulation & Diagnosis. After working in the automotive field on 1-D/ 3-D simulations, joined Damen Research as Research Engineer. His interest include: Simulation of power/ propulsion systems, emissions reduction & energy saving technology & alternative fuels.

Erik-Jan Boonen is principal research engineer in the field of mechanics & systems at the R&D department of Damen Shipyards. He graduated in 2009 at Delft university of technology with a master's degree in mechanical engineering. After his graduation he worked as a researcher at the university and thereafter at Van Oord. Erik-Jan works for Damen since 2012 and has worked previously as a mechanical and R&D engineer. System integration, simulation and sustainability are the main themes through his career.

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system increases, the amount of design decisions and degrees of freedom to control also grows significantly. In the current approach the initial focus is on the plant design, finding the optimal sizing of the components, after which a controller is designed that keeps the plant as close as possible to its desired state. This is illustrated in Figure 1; the optimal plant is identified first without any modifications to the controller, moving from baseline 'B' to sequential step 1 'S1'. This is followed by identifying the optimal controller for the now fixed 'optimal' plant, moving from 'S1' to sequential step 2 'S2'. By sequentially executing these steps, the design space is constrained early, which helps in reducing the complexity by considering only one dimension at a time, but also ignores any design interactions between plant and controller. In co-design an integral approach is followed, keeping the development of plant and controller in parallel, aiming of solutions that are optimal on a system (i.e. ship) level (Wilkins et al., 2023). This is shown in figure 1 by moving from baseline 'B' to the co-design solution 'CD'.

Various options for co-design exist, ranging from iterative methods that alternate back and forth between plant and controller, to nested or even fully integrated optimization methods that simultaneously consider plant and controller in each step (Mylonopoulos, Polinder and Coraddu, 2023). By emphasizing optimal solutions on a system level, co-design may result in new capabilities that improve system performance that would have been disregarded if only looking at the performance of the plant decoupled from the controller. Note that the sequential solution 'S2' in Figure 1 is less optimal than the co-design solution 'CD'.

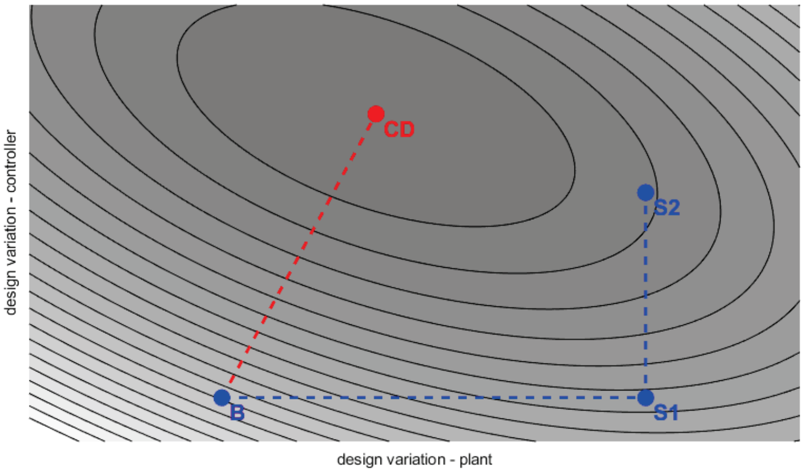

Figure 1: sequential optimization vs. co-design approach

Model Based Systems Engineering (MBSE) acts an excellent framework for experimenting with co-design, providing the methodology, the language, and an array of useful tools. By implementing both plant and controller using the MBSE process, both parts become part of a wholistic system description. Analysis, requirements, interfaces, and traceability become more consistent, which greatly simplifies the introduction of co-design. As an added benefit MBSE also encourages a data-centric approach, meaning that any iterative processes or methods can be easily accommodated.

In the paper a practical co- design application is presented using a PEM- FC powered, fast catamaran passenger ferry as a testcase to explore the requirements, applicability, and benefits of co- design in practice. The sizing of the fuel cell & battery of the hybrid system considering system health degradation, as well as rules of the Energy Management System (EMS) are optimized with respect to OPEX/ CAPEX.

The general methodology for co-design is equally valuable for naval vessels. One reason is the complexity of the power and propulsion systems found in the current and next-generation surface combatants, which include complex hybrid topologies, DC-grids, and energy storage. It very likely that traditional sequential development of plant and controller will not leverage the full capabilities of these power and propulsion systems. Co-design is needed to check the impact of early-stage cost-benefit decisions with respect to the overall system capabilities. Decisions that may be perceived as obvious and beneficial when driven by plant requirements, are in fact harmful when evaluating the integral performance of the system.

Secondly, it is expected that hydrogen will become part of the fuels carried on board of naval vessels, making parts of this work directly applicable to future product development in that market segment. Hydrogen will likely be used to (re)fuel small drones (De Wagter et al., 2021) and to feed fuel cells, needed for the reduction of emissions and/or reduction of signatures.

2. Testcase Description

The Damen Waterbus 2907 is a small, high speed catamaran ferry for inland navigation. Operating close to urban areas, it is a prime candidate for conversion to zero emission operation. This can be achieved through electrification, either as battery-electric or hybrid powertrain using H_2 fuel cells. Although an internal combustion engine (ICE) can achieve near-zero emission with appropriate aftertreatment running on alternative & renewably produced fuels, an ICE hybrid variant is not considered here.

From the two considered options, the full electric variant is the most technologically mature, using established battery technology. Complications include the need for shore-side high-power charging, while it might be necessary to alter the operation to account for battery/ charging limitations depending on the desired operation profile. Some operations are outright not possible/-practical due to current Li-Ion battery technology.

For these cases, the PEM FC hybrid configuration appears as an attractive ‘zero emission’ candidate technology. It allows operation in a more familiar way, i.e. daily bunkering and continuous operation as a direct replacement of the diesel hybrid. Of course, considerations also apply such as the relatively lower familiarity of the maritime industry with fuel cells and the limited availability of ‘green’ hydrogen. A concept of PEM-FC powered version of the Damen Waterbus 2907 is presented in Figure 2.

Fuel cell systems are often referred to as ‘high efficiency and ‘zero/low maintenance’. However, the characteristic of a fuel cell differs significantly from a combustion engine. Peak efficiency for a typical PEM fuel cell is achieved at low load factor of about 30%, with efficiency sloping downwards towards full load operation. Moreover, the auxiliary components of the fuel cell consume a significant amount of electrical energy, with main consumer being the air compressor.

In general, it can be said that a fuel cell has a very high efficiency in low part load, while net efficiency at full load is comparable to a large-scale diesel. As for the ‘zero maintenance’ part, the fuel cell stacks do degrade as a result of the operating conditions as will be described in 4.1, which needs to be accounted for in the design process.

Figure 2: Illustration of Damen Waterbus 2907 H_2 concept

3. Design Process: Baseline & Co- Design

In the current paper we explore the benefits and considerations for practical application of co-design compared with traditional design approach using a testcase of a fuel cell hybrid vessel. The design is in both cases supported by a developed simulation model of the vessel propulsion layout and energy management system, described in chapter 4.

In the baseline case definition, sizing of battery & fuel cell is defined using typical best-practice margins and considerations, while the settings of the energy management system are defined using a trial-and-error approach using the simulation model.

In the co-design case, the simulation model is coupled to an optimizer, which allows to optimize either the sizing of fuel cell and battery, EMS setpoints, or both at once. The optimization in the current work is performed with respect to OPEX and CAPEX (2 objectives), since for such a commercial application these are most important (client) considerations.

For other applications and ship types, such as naval combatants and naval auxiliary vessels, other objectives could be considered such as the endurance, power dynamics of the system (i.e. power ramp rates), or possibly even the acoustic and thermal signatures of components for any given operating point. In addition to the optimization objective, naval use cases may also introduce additional constraints. For example, with respect to required system redundancy, required degraded performance after damage, or stored energy required for vital non-propulsion and emergency loads.

More details about the baseline and co- design methodologies are given in 3.1 and 3.2 respectively.

3.1. Baseline design

The baseline design of the H_2 propulsion layout is defined using a linear process that uses the actual measured operating profile. Two full operating days are used: one referring to a high energy but average overall loading, and a second profile with less energy consumed but higher average propulsion power demands. Measured hotel load is also used as input.

The design process starts from the existing diesel hybrid version of the Waterbus 2907 and consists of the following steps:

- The diesel system including generator sets, tanks and fuel system is removed. This frees up a mass budget, that constrains the fuel cell and H_2 storage system sizing.
- 350 bar H_2 storage is chosen, considering the experience from heavy duty truck applications, and fuelling infrastructure availability, as well as a favourable footprint.
- Simple energy management system: fuel cell operates between 2 setpoints, which are determined by trial-and-error approach using the simulation model, while enforcing charge sustaining operation. The high setpoint is used as much as possible, while the low setpoint is defined to limit excessively high battery SoC condition while avoiding a start-stop of the fuel cell which is detrimental to stack lifetime.
- The battery is sized considering load-levelling operation of the fuel cell as above, incorporating margins on the maximum battery Depth-of-Discharge (DoD).
- Fuel cell size is defined such that at end-of-life (20% reduction in efficiency and power output) the output power is sufficient to cover the average load.
- The rest of the propulsion layout & vessel remain identical.

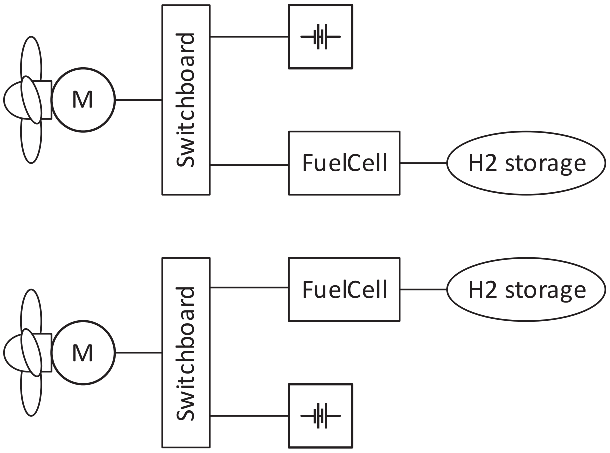

Figure 3: PEM FC propulsion layout considered.

3.2. Co-design

The simulation model is coupled to a multi- objective optimizer of using Matlab Optimization toolbox. The genetic algorithm based on NSGA-II is used for this work, given its adaptability to problems of varying complexity and global optimum estimation capability (Kalyanmoy et al., 2002).

The simulation model is coupled directly to the optimizer, with each evaluation of the objective involves a call to the model in Simulink in an inner loop. This is due to implicit coupling of the objective with the model results (e.g the H_2 storage sizing is defined by H_2 consumption result, but H_2 consumption is itself influenced by the mass of the storage).

The margins and requirements as defined in the baseline design process are introduced either as constraints of the optimization variables or as penalties to the objective functions when they are exceeded. To ensure sufficient search of the design space, a first calculation is performed with quite wide limits for the optimization variables, and based on the results, a second one is set up with narrower permissible upper and lower limits of the optimization variables.

The following calculations are performed:

- Design-of-Experiments exploration of the fuel cell-battery size design space. The results are evaluated and interpreted, showing the model’s capability of capturing the essential trade-offs and system effects.
- Propulsion Layout Sizing optimization: The battery and fuel cell size are optimized in a 2-objective optimization w.r.t OPEX/ CAPEX and compared with baseline case. EMS settings are kept at the values defined in the baseline case.
- EMS settings/ rules optimization, wherein the settings of the EMS are optimized in a 2-objective optimization (OPEX/ CAPEX) while the sizing of the battery and fuel cell are kept at the values defined in the baseline design.
- Full co-design calculation, wherein the EMS settings and the sizing of fuel cell and battery are optimized within a single optimization run.

This step-by-step approach helps to quantify the added benefit of optimization,co-design and interpretation of results.

4. Simulation Model

A simulation model is constructed in Matlab Simulink using an in-house, modular propulsion system model library methodology presented in (Sakellardis, Boonen and Vink, 2022). Purpose of the model is to estimate the propulsion layout sizing and effect of energy management at initial project phase, using limited input data that is usually available at this stage. It relies on power calculation to represent the propulsion layout, and uses as input the operating profile of the vessel, the hotel load, the sizing of the fuel cell and battery, as well as setpoints of the energy management system.

Outputs of the model that are used as objectives for the optimization in this work are:

- CAPEX contribution of the propulsion system only, limited to battery, fuel cell and compressed hydrogen storage. It is assumed that battery system cost is 800 €/kWh (DNV,2024), PEM fuel cell cost is 2000 €/kW (Clean Hydrogen Joint Undertaking, 2022), and compressed hydrogen storage is 600 €/kg per kg of stored H_2 (Shin and Ha, 2023)
- OPEX, that is calculated by the daily H_2 consumption calculated at 5 €/kg (Frieden and Leker, 2024) as well as the depreciation of battery and fuel cell components. It is assumed for this work that residual value of battery at 70% SoH is zero, while that at 80% SoH the fuel cell stacks need to be replaced, with the cost of the stacks estimated as half of the total FC module cost from (Wei et al., 2014).

The basic trade-off design loops are accounted for in the model: The added mass associated with the battery, fuel cell and compressed hydrogen storage is taken implicitly into account in the propulsion power calculation. This allows the model to capture effects like, for example, diminishing returns for electric operating range when battery size increases, due to increased vessel displacement.

Other important system-level interactions that such a model must be able to account for is the trade-off between battery size and life, i.e. a smaller battery, besides the mass advantage, is also favourable regarding CAPEX. However, the battery is stressed more heavily, leading to lower lifetime and faster depreciation, therefore it is unfavourable regarding OPEX. This is compounded by higher battery temperatures due to higher C-rates, so a snowball-effect is expected at very low battery capacities.

Finally, a larger battery allows for more steady-state loading of the fuel cell, while a larger fuel cell is also expected to lead to favourable efficiency and thus H_2 consumption, subject to the same mass considerations as the battery.

The final consideration is that, as the system complexity increases, the optimal system configuration becomes less obvious. In a model-based approach, the important trade-offs must be identified in advance, and the simulation model needs to be of sufficient complexity and predictive capability to resolve these system-level effects. This needs to be balanced against the usual lack of detailed input data at initial project phase, as well as calculation cost, especially when the model is directly coupled to an optimizer, such as in the current work. Overview of the modelling approach is provided in Figure 4.

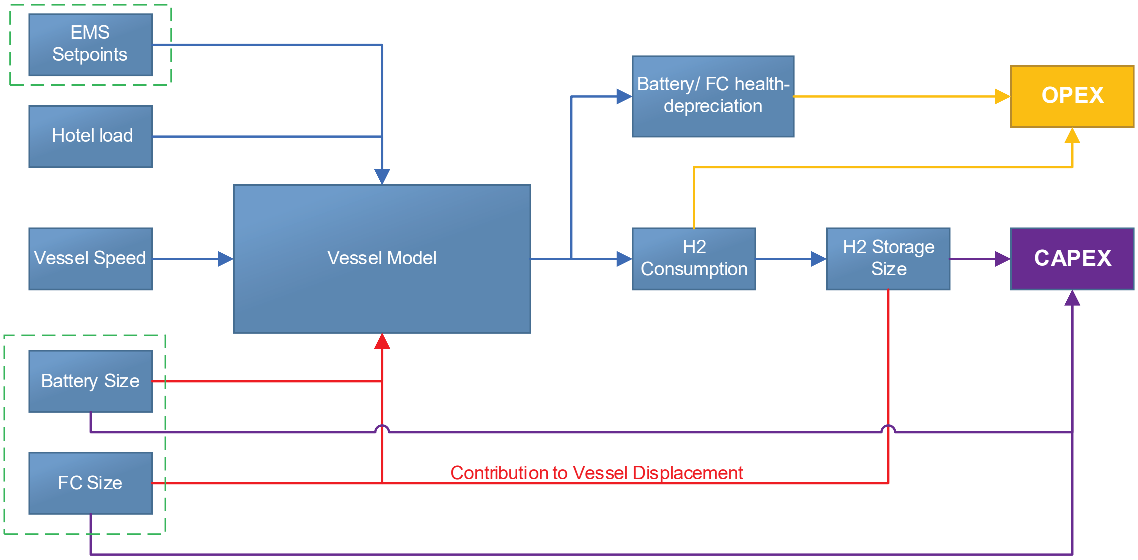

Figure 4: Overall Modelling Approach. Parameters subject to optimization within dashed green line.

4.1. *Fuel Cell*

The fuel cell model takes the calculated fuel cell power as input, and outputs the state of health (SoH, i.e voltage degradation) and the hydrogen consumption.

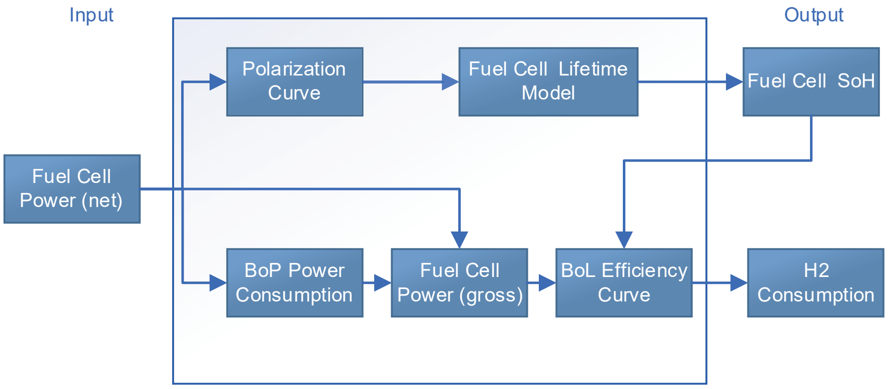

Figure 5: Fuel Cell modelling overview

The net power is model input, calculated by the vessel model, as requested by the EMS model. The consumption of the Balance-of-Plant (BoP) consumers (in practical applications this is mainly the air compressor) is calculated using in-house data of BoP load vs. load factor and assumes that this energy recirculation occurs loss-free within the module. This allows to define the total power of the fuel cell stacks and therefore the overall H_2 consumption by looking up the Beginning-of-Life (BoL) efficiency curve, corrected for current SoH

Lifetime is modelled according to (Desantes et al., 2022), in which the most important degradation mechanisms are modelled using semi empirical correlations using the voltage and current density:

- ☐ startstop
- ☐ transient operation
- ☐ operation under extreme loads (high/low- idle)
- ☐ natural degradation

The polarization curve and efficiency curve of the stack for this work is derived from (Ramírez-Cruzado, 2020). For commercial applications of the method, these values need to come from FC supplier.

4.2. *Battery*

The battery model also uses as input the energy. Starting from an initial State-of-Charge (SoC) the SoC time trace can be defined. Battery losses are calculated and used as input to a thermal model, used to define the average module temperature.

Temperature together with other stress factors such as throughput, C-rate, DoD etc. are input to a battery health/ lifetime model in order to estimate battery SoH (i.e capacity degradation). In the current work the simple model presented in (Wang et. al., 2011) for $LiFePO_4$ battery cells is used.

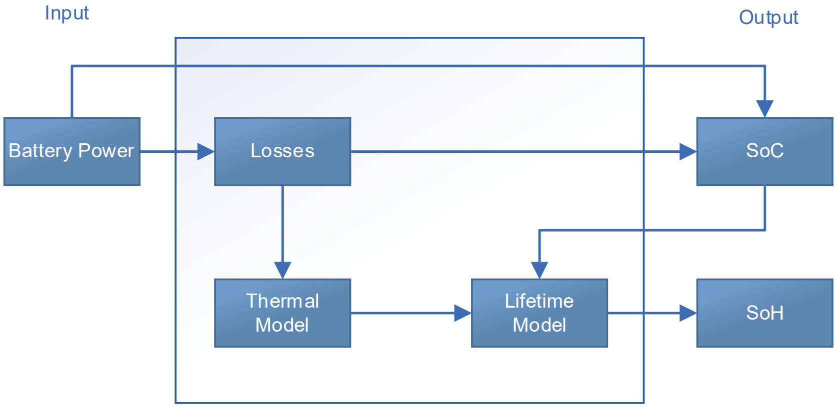

Figure 6: Battery modelling overview

The dependence of battery losses (and heat load) on the SoH has not been modelled in the current work.

5. Results & discussion

As described in section 3.2, a step-by-step approach to co-design is used in order to evaluate the added benefit vs. complexity, as well as make sure that the results are interpretable and explainable. The latter part is very important in model-based optimization, since in essence the optimizer is a black-box algorithm, and results can be affected significantly from model inaccuracies, inability to resolve trends and trade-offs that affect the real physical process, as well as model artifacts. These could be caused, for example, by model outputs under extreme input conditions, so model must be checked to behave consistently under any foreseeable input combinations during the co-design process.

Therefore, the work starts off with a Design-of-Experiments calculation and results interpretation, and proceeds with design optimization, EMS optimization and simultaneous EMS/propulsion layout co-design.

5.1. *Baseline*

Following the procedure outlined in 3.1 the baseline spec is defined, which is used as reference for comparison with the optimization results:

- ☐ Battery capacity is sized at 168 kWh and fuel cell at 438 kW. The load levelling point of the fuel cell is defined at 350kW, with power reduced as necessary to 15kW to avoid idling of the fuel cell and simultaneously keep the battery SoC within predefined limits.
- ☐ CAPEX for the fuel cell, battery and H_2 storage is estimated at 1.2 million €, with a yearly OPEX of 833,000 € assuming the vessel is utilized every single day. Almost half of the OPEX is attributed to depreciation due to fuel cell and battery aging, and the rest is defined by the fuel cost.

5.2. *Design Space Exploration: DoE*

The sizing of the battery and the fuel cell is varied between a minimum and maximum value in a full factorial calculation. Purpose is to explore the design space and assess model behaviour & robustness. Energy management philosophy is same as in the baseline case, described in 3.1. Therefore, by adjusting the fuel cell size the operational load factor changes, i.e. a small fuel cell operates closer to full load and a larger one in a lower part load condition.

Results are displayed in Figure 7. The left-hand side plot presents the H_2 consumption change vs baseline as function of the battery and fuel cell sizing. At low fuel cell capacity, the efficiency is low, together with highest parasitic consumption of BoP components. This leads to a rapid increase of fuel consumption in this region that overshadows the benefit of low fuel cell mass. This increase is compounded by the increased mass of the necessary

H_2 storage system. As expected, increase in battery size increases the fuel consumption due to increase in vessel displacement. There is an opposing trend of battery losses that tend to reduce as battery size increases, however, this effect is too minor to influence the overall result.

At higher fuel cell capacity the fuel consumption reduces, up to a point. The fuel cell average load factor is approx. 40%, even at the highest FC capacity considered, so the peak efficiency of the module has not been reached in this DoE, however the fuel efficiency of the vessel peaks around an average module load factor of 65%, due to the increased displacement that accompanies the oversized fuel cell.

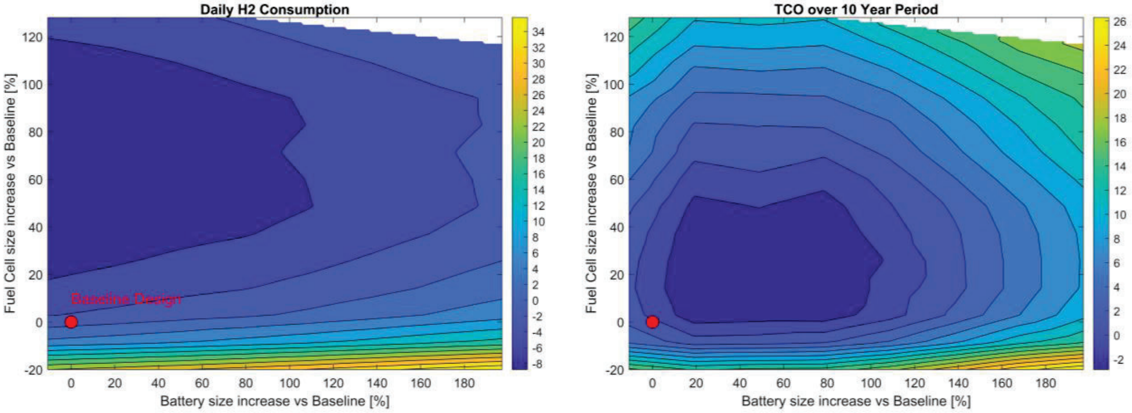

Figure 7: Daily Consumption of H_2 (left) and TCO over a 10 year period (right). Values in % change vs baseline (positive→increase, negative→decrease)

The right-hand side of Figure 7 displays the Total Cost of Ownership (TCO) associated with a 10 year period. A clear region of optimal TCO is identified, that partly overlaps with the minimum fuel consumption, but is also strongly affected with CAPEX (scaling linearly both with FC and battery unit cost). However, a smaller fuel cell operates at high load factor, which tends to reduce its lifetime, and similarly with a small battery size, that tends to have reduced lifetime due to being over-stressed and subject to higher temperatures, which from a TCO perspective tend to balance out the beneficial effect of reduced capex associated with low installed battery capacity and FC rated power.

To summarize, the baseline sizing has been achieved considering the smallest size of fuel cell and battery to fulfil the demand within the established margins and is not very far from the defined optimum of the DoE. However, there seems to be a case for some degree of battery and fuel cell over-sizing that leads to TCO reduction of about 2.5%.

5.3. Optimization: Fuel Cell & Battery Sizing

We use the optimizer as described in 3.2 to define the trade- off between OPEX and CAPEX that results when optimizing the sizing of the propulsion layout components, i.e. the fuel cell size and the battery size. In Figure 8 is presented the Pareto-front that results from the optimization calculation.

Each point represents a propulsion layout design candidate (variation of FC and battery size). Blue are the points considered by the optimization algorithm, while the pareto points (points that dominate the others, i.e. achieve the best trade off between the conflicting objectives) are shown in red. Finally, green point is the baseline design achieved with the baseline design process.

The first observation is that the baseline design is quite close to the pareto front define by the optimizer. This verifies that the traditional design approach, following best practice and expert knowledge is still effective. In this work, where the added benefits of advanced design processes are evaluated, it is important to have a best practice method that defines the baseline, or else the benefits that are observed can be attributed not to the new method, but to the fact that baseline design is largely sub-optimal and therefore there is a lot of improvement margin.

This type of analysis results in a collection of optimal solutions that one can choose from, depending on the particular requirements and/or intended function of the vessel. For example, a vessel that will be continuously operated can be designed with OPEX minimization in mind, therefore a red point to the right-hand side of the Pareto shall be chosen. Points to the right are characterized by increased battery and fuel cell size for reduction in fuel consumption and high lifetime, while points to the left represent designs with small FC- battery capacity that focus on CAPEX minimization.

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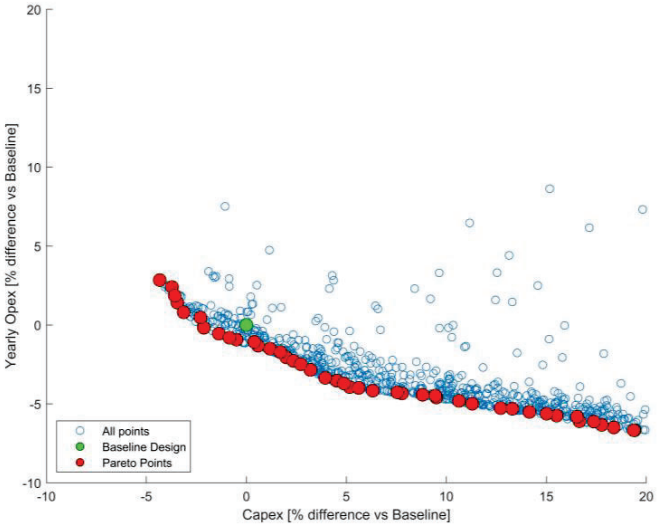

Figure 8: Optimal Solutions (pareto front) for a fuel cell-battery sizing optimization

As mentioned, the objectives and selection criteria for different application types are expected to be different. If this method would be applied to a naval combatant, a similar Pareto front could be formed, for example, one describing the trade-off between maximum endurance and maximum power dynamics. Similarly to what is shown in Figure 8, this can result in choosing an 'oversized' solution that focuses on improved power dynamics, but penalizes the efficiency and thus endurance of such a system.

5.4. Optimization: EMS setpoints

In Figure 9 the result of optimizing the EMS setpoints/ rules is shown. The simple load-levelling, rule-based EMS, as described in 3.1 is parameterized using 5 setpoints, being the high & low setpoint and corresponding SoC switching thresholds, a well as a maximum ramp-up of the fuel cell. It is interesting to note that the result consists of a very narrow pareto front, showing that the main benefit is found, as expected, in the OPEX objective, ranging from 9-10%. This improvement is attributed mainly to reduced fuel consumption in the order of 6.5 to 8.5 %, and secondly to improved FC and battery lifetime, which is improved 10-15% for both the battery and fuel cell. The CAPEX reduction is due to the slightly lower storage system needed because of H_2 consumption reduction. However EMS optimization, as expected, mostly affects OPEX.

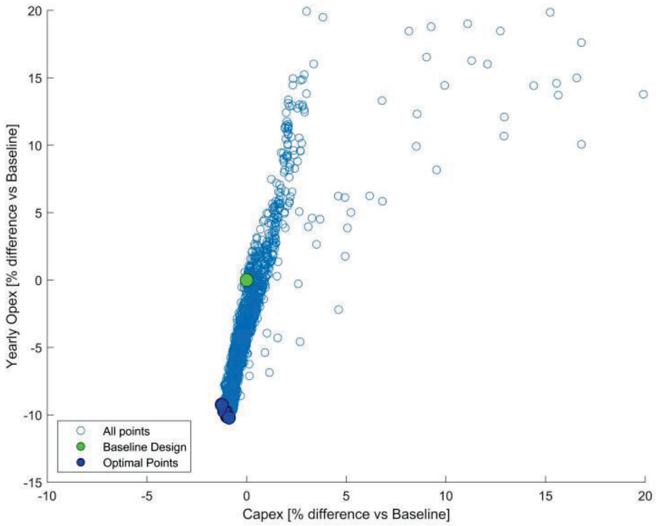

Figure 9: Optimization of EMS setpoints

5.5. Optimization: Co-Design

Finally, the design parameters (FC and battery sizing) as well as EMS setpoints are included in the optimization in a 1-step process (co-design of propulsion layout and tuning of the EMS) to evaluate the added benefit compared to sequential optimization (first optimizing design, then optimizing EMS for said design), with the results displayed in Figure 10.

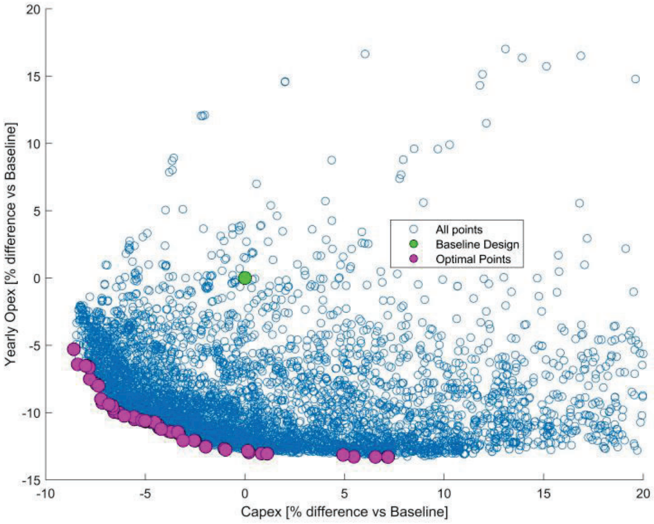

Figure 10: Co- design results

An added OPEX benefit is observed when compared to the sequential optimization of design and EMS, as well as diminishing returns in the OPEX savings by CAPEX increase (i.e. oversizing of FC and battery to achieve reduced fuel consumption and extend component lifetime).

In order to properly compare the added benefit and interpret the results, all optimal configurations are plotted on the same axes in Figure 11, resulting in a more detailed view of specific points on the Pareto-front.

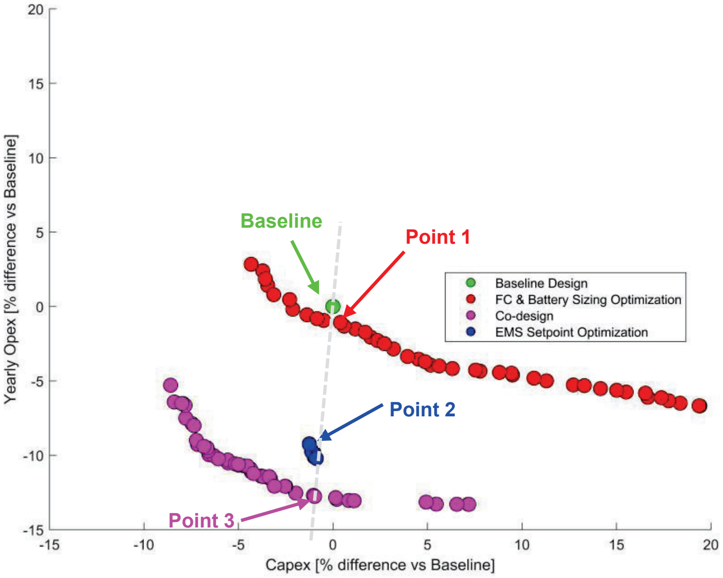

Figure 11: Comparative evaluation of results

A summary of the resulting specification of points 1 to 3, as well as the baseline, are provided in

Table 1: Summary of selected points on

	FC Size [kW]	Battery Size [kWh]	Fuel Cell Setpoint Low [kW]	Fuel Cell Setpoint High [kW]	H2 Consumption [kg/day]
Baseline	438	168	15	350	465
Point1: Design Optimization	430	189	15	350	471
Point 2: EMS Optimization	438	168	84	330	426
Point 3: Co-design	424	203	81	323	429

Point 1, which results from battery and fuel cell size optimization (i.e. system design), is very close to the baseline. Battery size is increased 11% compared to baseline with a very minor FC size reduction, that keeps CAPEX within 0.5% if the baseline. Most of the OPEX benefit is provided by 15% predicted battery lifetime increase, that overcompensates for a 1% fuel consumption increase. This shows that the marginal benefit of the size optimization is heavily influenced by the predictive capability of models used for FC and battery lifetime.

Point 2 results from optimization of the EMS parameters, with the small CAPEX improvement attributed to reduced size of H_2 storage needed on board. Leading to the conclusions that most of the 9.5% OPEX reduction is caused by fuel consumption reduction. Any remaining improvement are attributed to the slight increase in fuel cell and battery lifetime (around 10%), since the EMS setpoints tend to move towards the peak efficiency region, and both fuel cell and battery cycling reduces slightly. The ramp rate of the fuel cell also reduces compared to the baseline.

Finally, point 3 results from combined EMS and system sizing optimization, with a predicted 12.5% percent OPEX benefit and a more modest 1% CAPEX reduction. CAPEX reduction comes as a result of reduced H_2 storage requirements while a small reduction in FC size balances out a significant battery size increase (34%). The reduction in H_2 consumption is 7.8%. The fuel cost represents the larges part of OPEX improvements, at a predicted 70%, with the rest being battery and fuel cell depreciation. The remainder of the OPEX benefit is attributed to a 34% increased battery lifetime as a result of sizing increase of 20% and optimal EMS setpoints that result in reduced cycling, and secondarily to a 9% increase in fuel cell lifetime.

6. Conclusions & Next Steps

In this paper was presented a methodology for co-design and optimization of the energy system together with the energy management in an integrated fashion, and results compared with traditional design approaches or sequential system/ EMS optimization. A fuel cell- battery hybrid layout of a fast ferry was chosen as a test-case, representative of an electrified, zero emission future propulsion layout.

The conclusions of the work can be summarized as follows:

- ❑ Co-design has been successfully applied to study the propulsion layout, identifying and quantifying the benefits of co-design.
- ❑ The fidelity and complexity of the model used should be able to resolve the relevant trade offs to be usable in such a study. Therefore, the modelling approach should be considered in advance, taking into account the exact purpose, objectives, and desired outputs.
- ❑ When sized according to a traditional design process, the resulting configuration is close to optimal, when best practices and expert knowledge are employed.
- ❑ Some degree of battery capacity increase was found to be beneficial regrading lifetime extension, outweighing the negative effect of increased vessel displacement. This conclusion is specific to the testcase however, as vessels less sensitive to weight increase might further benefit from fuel cell/ battery over-sizing.

Based on the above results, it follows that practical application of the methodology is very interesting for the optimization of complex ship energy systems of the future. There is still considerable work towards generalized and robust implementation in practical applications:

- ❑ The proposed methodology should be accompanied in practice by critical evaluation of results that gives overview of the design space and model behaviour. DoE approach as described can act as a check and first step in the process.
- ❑ The robustness of the optimisation to uncertainties needs to be evaluated (e.g. OPEX & CAPEX being highly dependent on assumed costs for fuel and components, possible uncertainty in lifetime estimation of components or uncertainty in inputs such as operating profile). As a next step, robust optimization methodologies can be explored and applied, from simple repetition of the optimization under different scenarios of inputs to more complex methodologies of handling uncertainty, such as Monte Carlo analysis as per (Dall'Armi, Pivetta, and Taccani, 2022).

- ☐ Adoption is dependent on robust, well parameterized/ modularized and validated (sub)models, for both propulsion layout and EMS.
- ☐ As seen during the exercise, sometimes the calculated benefit was a result of component lifetime extension. Battery and fuel cell lifetime modelling are topics of ongoing research, with significant part of the knowledge residing with (component) suppliers. To overcome the problem of IP protection and facilitate collaboration, integration of the methodology within a co-simulation framework using Functional Mock-up Unit (FMU) 'black box' models is an interesting option.
- ☐ As degrees of freedom increase, so does calculation run time for reaching optimizer convergence. Proper selection of optimization algorithm & parameters (e.g. population and generation number for GA's) is important to ensure on the one hand convergence while not leading to excessive computation times.
- ☐ In the current work a limited operation time was simulated, since the model was implemented in the optimizer loop. However, from model calculations that span over several operational years it is seen that fuel cell and battery degradation are not fully linear effects, especially when approaching end-of-life. Therefore, lengthy and extensive DoE calculation until end-of-life and using a metamodel to fit the results could be an alternative approach, with the metamodel being implemented in the optimizer loop. This helps better quantify end of life effects and apply more consistently the associated constraints, allows rapid optimization process and possibility to change objectives without repeating calculations, but some loss of accuracy is incurred during model fit.

References

Boonen, E. J,(2023). Impact of alternative fuels on ship design - A shipbuilders perspective. In 30th CIMAC World Congress on Combustion Engine

Wilkins, Steven, et al. "Co-Design and Energy Management for Future Vessels." Modelling and Optimisation of Ship Energy Systems 2023 (2023).

Mylonopoulos, Foivos, Henk Polinder, and Andrea Coraddu. "A comprehensive review of modelling and optimization methods for ship energy systems." IEEE Access (2023).

De Wagter, Christophe, et al. "The NederDrone: A hybrid lift, hybrid energy hydrogen UAV." international journal of hydrogen energy 46.29 (2021): 16003-16018.

Deb, Kalyanmoy, et al. "A fast and elitist multiobjective genetic algorithm: NSGA-II." IEEE transactions on evolutionary computation 6.2 (2002): 182-197.

Sakellaridis, Nikolaos, Erik-Jan Boonen, and Bastiaan Vink. "Model-Based Propulsion Layout Definition, Comparison and Optimization." Conference Proceedings of INEC. 2022.

www.dnv.com. (n.d.). Batteries gain momentum in the maritime sector. [online] Available at: https://www.dnv.com/expert-story/maritime-impact/Batteries-gain-momentum-in-the-maritime-sector/ [Accessed 17 Jul. 2024].

Clean Hydrogen Joint Undertaking. "Strategic research and innovation agenda 2021–2027."(2022).

Shin, Hyun Kyu, and Sung Kyu Ha. "A review on the cost analysis of hydrogen gas storage tanks for fuel cell vehicles." Energies 16.13 (2023): 5233.

Frieden, Florian, and Jens Leker. "Future costs of hydrogen: a quantitative review." Sustainable Energy & Fuels (2024).

Wei, Max, et al. A total cost of ownership model for low temperature PEM fuel cells in combined heat and power and backup power applications. No. LBNL-6772E. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2014.

Desantes, J. M., et al. "A modelling framework for predicting the effect of the operating conditions and component sizing on fuel cell degradation and performance for automotive applications." Applied Energy 317 (2022): 119137.

Ramírez-Cruzado, Andrea, et al. "Experimental analysis of the performance and load cycling of a Polymer Electrolyte Membrane Fuel Cell." Processes 8.5 (2020): 608.

Wang, John, et al. "Cycle-life model for graphite-LiFePO4 cells." Journal of power sources 196.8 (2011): 3942-3948.

Dall'Armi, C., Pivetta, D., & Taccani, R. (2022). Uncertainty analysis of the optimal health-conscious operation of a hybrid PEMFC coastal ferry. *international journal of hydrogen energy*, *47*(21), 11428-11440.

Comparative Analysis of AI-Based Optimisation Techniques for a Conceptual Frigate Hullform Design

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Synopsis

This paper presents the results of an investigation conducted to assess the efficacy of Artificial Intelligence (AI) in optimising the hullform of a conceptual frigate. A frigate, with a length of 130 meters and a top speed of 24 knots, served as the subject for the experiment. A baseline hull was initially designed, and spatial constraints were defined for the study. Three different contractors were invited to optimise the bare hull resistance for various speeds and displacements. The optimisation process considered a weighted grading matrix based on the ship's operational profile.

One contractor employed traditional optimisation techniques, including empirical knowledge, regression series, and the modification of ship hydrostatic characteristics. A parametric hullform model was created to produce candidate designs. Final analysis was made using Computational Fluid Dynamics (CFD). Another contractor utilised machine learning with neural networks, with training data sourced from a parametric hullform model and CFD results. The final contractor employed a combination of a parametric hullform model, T-Search optimisation, potential flow, and CFD, with a specific focus on achieving maximum top speed with the lowest resistance.

Results indicated that traditional techniques improved bare hull resistance by an average of 8%. The use of neural networks significantly outperformed traditional methods, demonstrating a remarkable average improvement of 22% in bare hull resistance. However, a critical observation emerged regarding the optimisation focused on top speed only, where machine learning techniques demonstrated a 28% improvement on resistance. This improvement, however, came at the cost of a notable detriment to lower speeds resistance, resulting in an average overall increase in resistance of 14% across the speed range.

The findings of this study present a dilemma for naval architects and customers alike. While prioritising top-speed optimisation may lead to reduced capital expenditures (CAPEX) due to lower costs associated with machinery and auxiliary systems, it could also result in increased through-life costs due to high resistance at lower speeds, which constitute the majority of operational time at sea. This highlights the importance of a balanced approach and careful consideration when implementing AI-based optimisation techniques in naval vessel design. Ensuring a holistic view of performance and costs throughout the vessel's lifecycle is crucial for making informed decisions.

Keywords: Hull Design; Artificial Intelligence; Hullform Resistance; Optimisation

1. Introduction

Naval frigate design continues to evolve, driven by the imperative to enhance operational capabilities while managing costs and environmental impact. The development of the 130m Adaptable Strike Frigate (ASF) design that was launched at EuroNaval 2022 responded to these challenges. Designed as a light frigate with specialised mine hunting capabilities, the ASF 130 represents a promising platform for future naval operations (see Figure 1).

To further optimise the performance of the ASF 130, three contractors were tasked with refining its hullform resistance using distinct methodologies. These methodologies include the traditional design spiral approach, artificial intelligence (AI) and neural networks, and optimisation software. The objective of this optimisation study was to explore new methods of resistance optimisation within the context of a more integrated simulation-driven design approach.

The adoption of a simulation-driven design approach aims to holistically address all key aspects of ship design, from hullform resistance to subsystem integration. By integrating various design aspects early in the

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conceptualisation phase, this approach seeks to increase the maturity of concept designs while reducing costly design margins that ultimately impact the final price of the vessel.

In this essay, we delve into the comparative analysis of the three methods employed to optimise hullform resistance for the ASF 130 frigate. Through this exploration, we aim to highlight the strengths and limitations of each methodology, as well as their implications for future naval frigate design. Additionally, we examine how these optimisation efforts contribute to the overarching goal of achieving more efficient, cost-effective, and operationally capable naval platforms.

Figure 1: Adaptable Strike Frigate - Conceptual Design

2. Background

In the pursuit of advancing naval ships design, the optimisation of hullform resistance stands as a critical design task. This essay presents the exploration of three distinct methodologies employed to optimise hullform resistance: the traditional design spiral approach, artificial intelligence (AI) and neural networks, and the utilisation of optimisation software. This discussion is contextualised within the framework of the ASF 130 design, poised as a future light frigate with enhanced mine hunting contender for the UK Royal Navy and export. The overarching aim is to achieve a more efficient ship design, thereby reducing both capital expenditure (CapEx) and operational expenditure (OpEx).

The imperative for such optimisation stems from various factors. Foremost is the global drive towards achieving net zero emissions, where maritime operations play a pivotal role. An optimised hullform design can significantly contribute to enhancing vessel efficiency, thereby mitigating environmental impact. Furthermore, optimising hullform resistance is instrumental in improving design margins, ensuring operational capability, and achieving design maturity earlier in the conceptualisation phase.

The traditional design spiral methodology, a tried-and-tested approach, involves iterative cycles of design, analysis, and refinement. While reliable, this method may lack the agility and computational power necessary to explore the vast design space comprehensively. In contrast, the integration of AI and neural networks introduces a paradigm shift by enabling the exploration of a much wider design space. AI algorithms can discern complex patterns and correlations within data, facilitating the identification of optimal hullform configurations that might elude conventional methods.

Moreover, the utilisation of optimisation software offers a systematic approach to fine-tuning hullform resistance. These tools leverage mathematical algorithms to iteratively refine design parameters, maximising performance objectives while adhering to specified constraints. By harnessing the computational prowess of optimisation software allied to resistance numerical prediction tools such as CFD (Computational Fluid Dynamics), naval architects can expedite the design process and unearth innovative solutions.

The significance of hullform optimisation is emphasised by its centrality to the ship's concept design. As the key element upon which various naval architecture sub disciplines are dependent such as seakeeping, manoeuvring or the general arrangement, the hullform dictates vessel performance across a range of operational conditions. Thus, optimising hullform resistance is not merely a technical exercise but an imperative in defining the entire naval ship design in terms the operational capability and environmental sustainability.

In conclusion, the journey for optimising hullform resistance for future frontline naval ships embodies a multifaceted challenge, necessitating the integration of diverse methodologies. The transition from traditional design spiral legacy approaches to AI-driven exploration and optimisation software signifies a shift towards leveraging advanced computational techniques to achieve superior design outcomes. By embracing innovation in

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hullform optimisation, naval architects can define the way for more efficient, environmentally sustainable, and operationally capable naval vessels.

3. Methodology

To maximise the potential of the ASF 130 design, three contractors were employed and tasked with optimising the ASF 130 hullform for barehull resistance. Each contractor adopted a different optimisation approach, as identified in Section 1, allowing each method to be quantified in terms of the resistance performance gains. These methodologies include the traditional design spiral approach, AI and neural networks, and optimisation software.

Each contractor was provided with the same optimisation brief for fairness (including design condition, operational profile and spatial constraints) with the common objective of optimising the design for barehull resistance.

3.1 Optimisation Constraints

The ASF 130 design is a monohull displacement hullform of 130m in length and 18m in beam (see Figure 1). For the optimisation, a number of design constraints were imposed. This comprised of limits on length (overall and waterline), beam and depth at given locations to ensure there would be no conflicts in other areas of the design (shaftline, propeller clearance, tank capacity etc.).

Each contractor was provided with a common target displacement and longitudinal centre of buoyancy (LCB) for each assessed condition for the optimisation.

3.2 Operation Profile & Scoring Matrix

The optimisation was performed for a given operation profile, as shown in Figure 2. The operational profile was provided to each contractor to further inform the optimisation process.

Based on the operational profile, a scoring matrix (as shown in Table 3) was also provided to each contractor to allow a score to be assigned to each new optimised hullform design, quantifying the overall resistance improvement across the speed and displacement range and subsequently lead to the identification of the 'optimal' design.

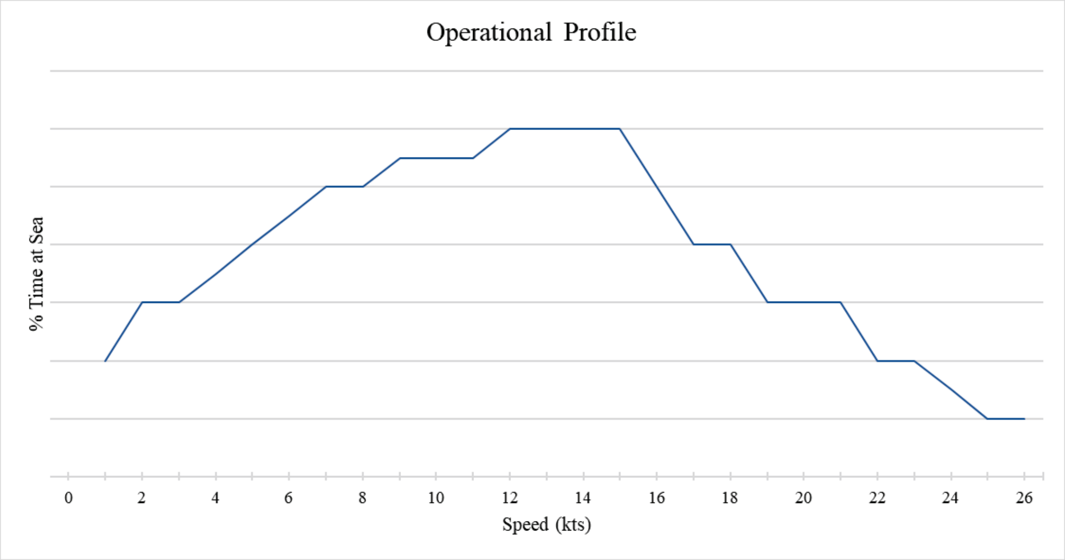

Figure 2: Operational Profile - Typical Frigate

Table 1: Optimisation Scoring Matrix for a Typical Frigate

Speed (kts)	**Displacement Condition** **Light**	 **Design**	 **Deep**	**Weighted Total**
12	1	5	3	16%
16	2	5	5	21%
20	3	7	7	30%
24	3	7	8	32%
Weighted Total	16%	43%	41%	100%

It should be noted that not all contractors performed the optimisation for the entire operational profile or considered all displacement conditions, therefore only the design condition will be compared for this study to ensure commonality between the results.

3.3 Contractor 1: Traditional Optimisation Method

Traditionally, an existing basis hull form is initially selected based on the target mission objectives, size and performance. The design is 'optimised' using a computer aided design (CAD) software for the specific design brief and ship requirements. Using Rhinoceros Grasshopper, a 3D CAD parametric modelling tool, a hull form is generated based on a series of parameters controlled as inputs within an embedded control panel. The control panel allows for modification of hydrostatic outputs along with the modification of section location and curve controls, resulting in a rapid hull form development and analysis. The Grasshopper script was initially used to re-create the baseline hullform, followed by two development design iterations.

Each design iteration is optimised based on experience, subject matter expert (SME) judgement and inevitably involves an element of good fortune to maintain the hullform design within the boundaries specified by the ship requirements.

3.4 Contractor 2: Artificial Intelligence Optimisation Method

This method adopts AI techniques with intelligently generated CFD analysis to learn trends in the resistance data for various hull shapes. An parametric hullform of the baseline is initially created, with numerous hullform shape parameters each with assigned adjustable ranges (set depending on design constraints and optimisation goals) to create an extensive quantity of unique hullforms.

In this case 500 hullforms were created within the design space and defined constraints, where the resistance of each these design are calculated using CFD. This resistance data is subsequently used to train the neural networks. The optimisation process cycles through the many combinations of hull shapes to achieve the best score against requirements/constraints. The best contenders are then passed back through the CFD and compared with the baseline hull at the defined speeds and displacements.

3.5 Contractor 3: Optimisation Software Method

The third method of optimisation using a 3D Shape Optimisation Software, where a parametric model was created of the baseline hullform design. The software also has integrated capabilities for process automation and shape optimisation. The optimisation software allows you to build robust parametric ship models with smarter shape control. Optimisation and automated design exploration augment the development process leading to better and optimised designs.

Using the optimisation software method, a potential flow solver was used to run an initial design of experiments, followed by a Tangent-Search (T-Search) optimisation. The main purpose of the T-Search method is to identify a descent search direction in the solution space, enabling a rapid improvement in the desired solution direction, whilst maintaining the solution within a feasible design domain.

In this case, a T-Search optimisation was conducted for a maximum of 50 design cases, where 38 feasible designs were created and CFD simulations were subsequently completed, and the optimal design was selected. The method detects a local minimum within the design solution space, where a number of predefined variables are subject to explicit bounds, i.e. a lower and an upper bound, along with any design constraints that apply. If a constraint bound is approached a tangent move in hyperspace is conducted tangential to the constraint either to keep the search in the feasible domain or to bring it back to the feasible domain.

In addition, as a result of the optimisation the software generates graphs showing the relationship of various design parameters and variables, allowing sensitivity analysis of design parameters to be understood.

4. Optimisation Results

The baseline hullform was 'optimised' using the previously described techniques; Traditional Methods (Contractor 1), AI and Neural Networks (Contractor 2), and Optimisation Software (Contractor 3). Refer to Table 2 and Figure 3 for the resulting optimised hullform designs.

Using the traditional optimisation method, the optimised hullform results in some minor changes from the baseline design including a reduction in volume made in the bow and reducing the half angle of entrance (HAE), the LCB was moved further aft by 1%, and a reduction in the bilge radius aft of midships.

Using AI and neural networks, there were modifications made to the beam (an increase in 10%) at midships, transom knuckle height was increased, reduced block coefficient at the transom section, finer bow entry, amongst other changes.

Contractor 3, using the shape optimisation software, only optimised the baseline design for top speed and not the entire speed range. Therefore the optimised hullform design is notably different to the baseline and other optimised designs, this is most prominent at the bow.

The optimised design by each contractor differ from the baseline most notably at the bow, this was due to their being a specific optimisation constraint in terms of a given minimum beam in order to accommodate a particular combat system compartment located in the forward part of the ship.

Table 2: Optimised Hullform Hydrostatic Parameters

Parameter	**Baseline**	**Traditional Method (Contractor 1)**	**AI & Neural Networks (Contractor 2)**	**Optimisation Software (Contractor 3)**
Block Coefficient	0.492	0.494	0.478	0.492
Midships Coefficient	0.784	0.809	0.790	0.837
Prismatic Coefficient	0.628	0.610	0.605	0.588
Waterplane Coefficient	0.820	0.808	0.720	0.784

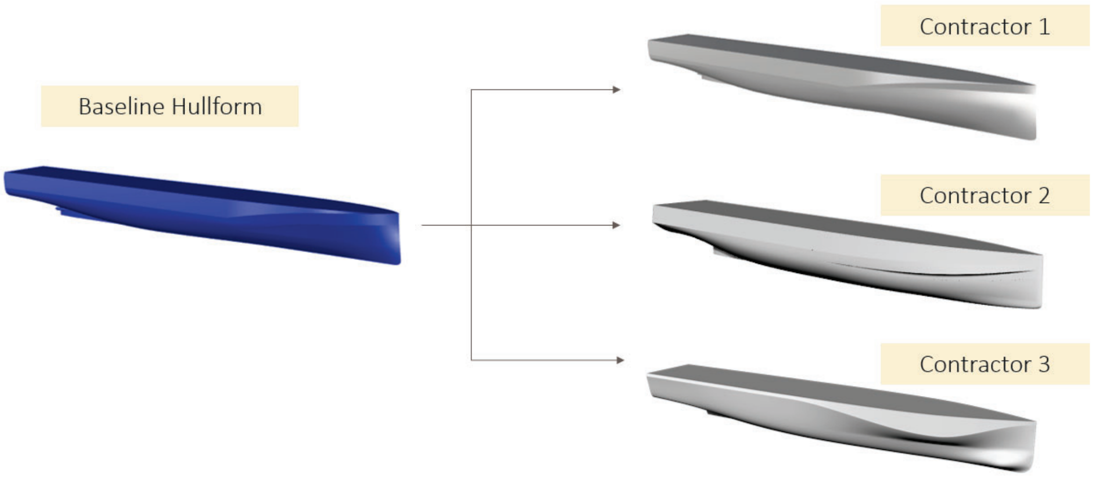

Figure 3: Optimised Hullforms

As previously discussed, for each optimisation method only one ship loading condition was assessed by all contractors, therefore the results are presented solely for the design condition.

AI and neural networks method (Contractor 2) proved to be the most effective in terms of the achieved average resistance reduction over the entire speed range. However, the method adopted by Contractor 3 showed the greatest resistance reduction at top speed, with a 28% reduction against the baseline design in the Design

Condition. Refer to Table 3 and Figure 4 for the comprehensive results for the design condition for each Contractor.

Table 3: Design Condition - Optimisation Results

	Contractor 1	**Contractor 2**	**Contractor 3***
Ship Speed (kts)	**% from Baseline**	**% from Baseline**	**% from Baseline**
12	-10.5%	-19.3%	+98.0%
16	-10.6%	-26.5%	+13.0%
20	-6.3%	-22.2%	-26.0%
24	-4.8%	-18.2%	-28.0%
Average:	***-8.0%***	***-21.6%***	***+14.3%***

*Hullform optimised for top speed only.

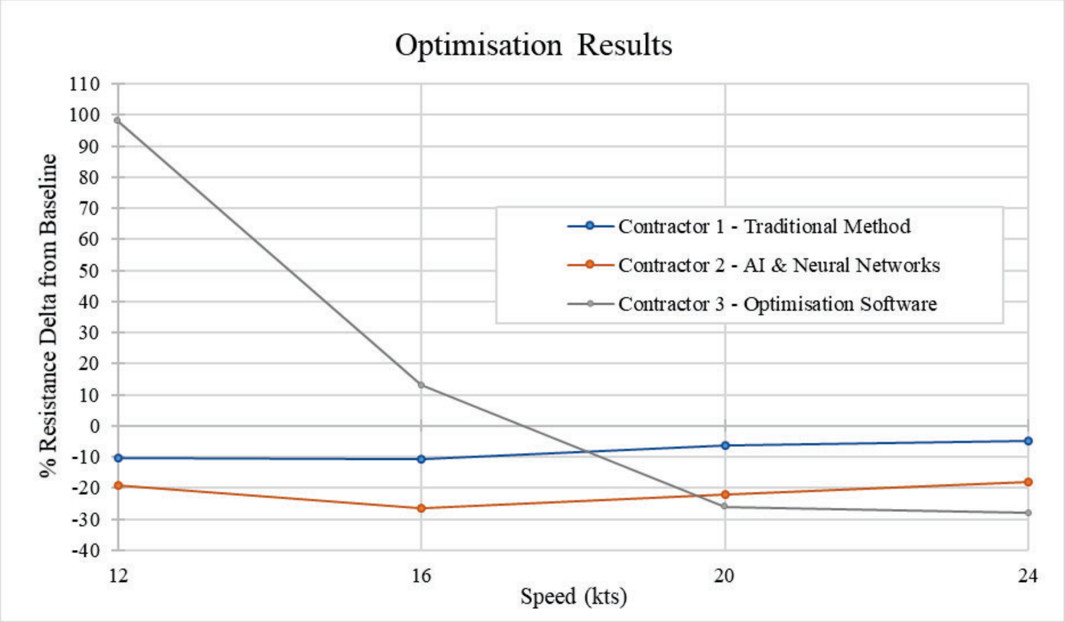

Figure 4: Design Condition - Optimisation Results

Using the scoring matrix presented in Table 1, each optimised hullform was subsequently 'scored', where the lowest scoring hullform represents the most efficient resistance hullform across the speed range. For the design condition only (the common condition), the score for each hullform is presented in Table 4.

Table 4: Scoring for Design Condition

	Method	**Score**
Contractor 1	Traditional	93.9
Contractor 2	Artificial Intelligence	78.0
Contractor 3	Optimisation Software	102.3

The resulting impact on wake, appendage design, appendage alignment, and propulsive coefficients on each of the optimised ASF 130 hullform designs were not assessed for this study. During the concept phase, the hullform design informs each of these design characteristics, therefore it would not be fair to compare these parameters to the baseline design, especially as the ASF 130 design is in early development.

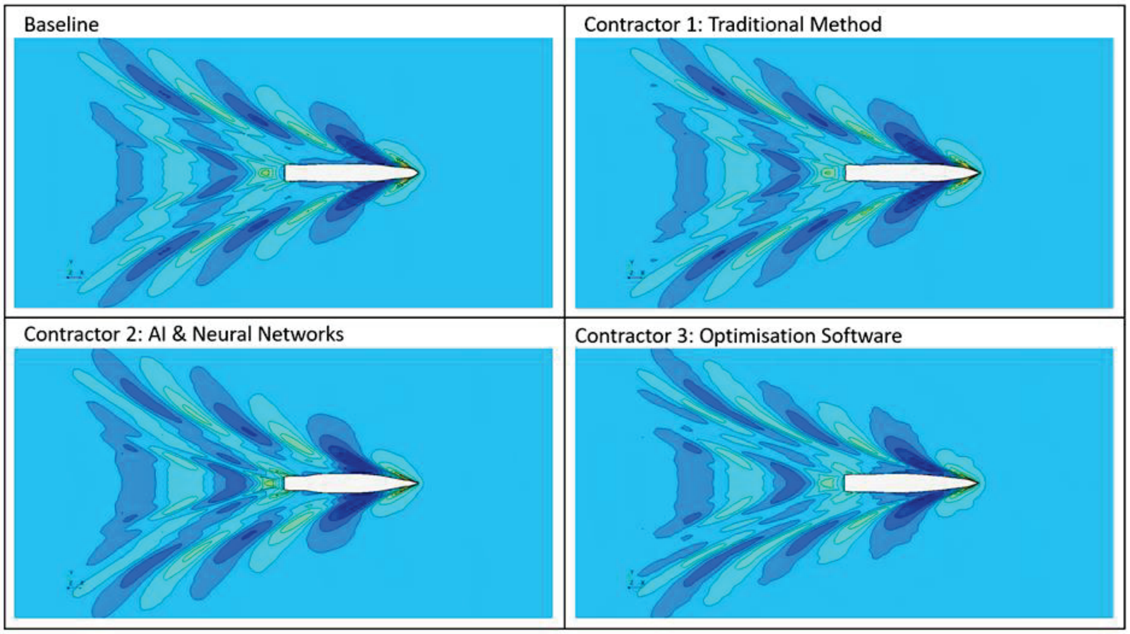

Figure 5: Design Condition at 24kts - Free Surface (Plan View)

5. Validation

The results presented in Table *3* were based on the optimisation performed by each contractor. The resulting optimised hullform designs were provided to BAE Systems where the barehull resistance results were subsequently validated by completing a CFD analysis (using STAR CCM+ version 2020.2 (15.04.008)). The validation was conducted using the same discretisation and physical models for each optimised design, with mesh refinements for areas with more complex flow characteristics such the stern and bow positions (refer to Figure 6). The free surface was modelled using the Volume of Fraction (VOF) and Moving Reference of Frame (MRF) to account for the running sinkage and trim of the vessel, wall functions were also used. The selected turbulence model used for the simulations was the K-Omega Shear Stress Transport (SST). Each CFD validation used approximately 1.6 million cells and each simulation used an average of 128 cores to complete the analysis.

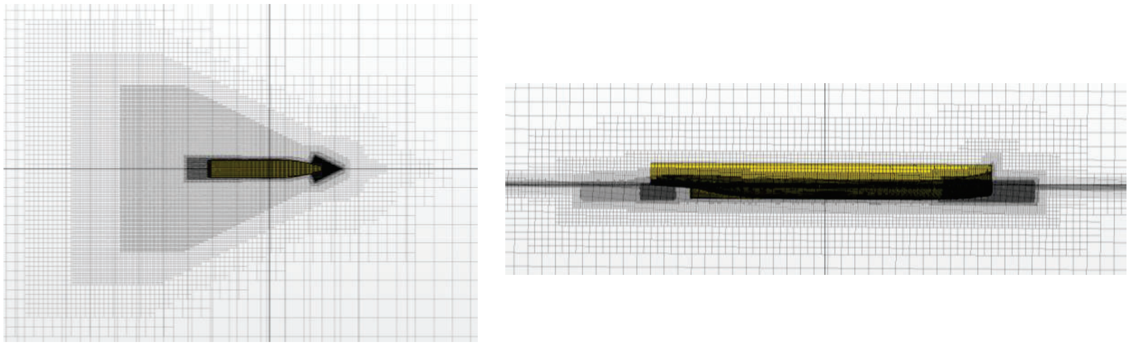

Figure 6: CFD Validation Mesh Fidelity – Plan View (Left) & Profile View (Right)

The results of the validation are presented in Figure 7. The optimisation results for Contractor 1 and Contractor 2 are within the 2% uncertainty margin, where this margin is represented by the ‘green band’ in the graph presented below.

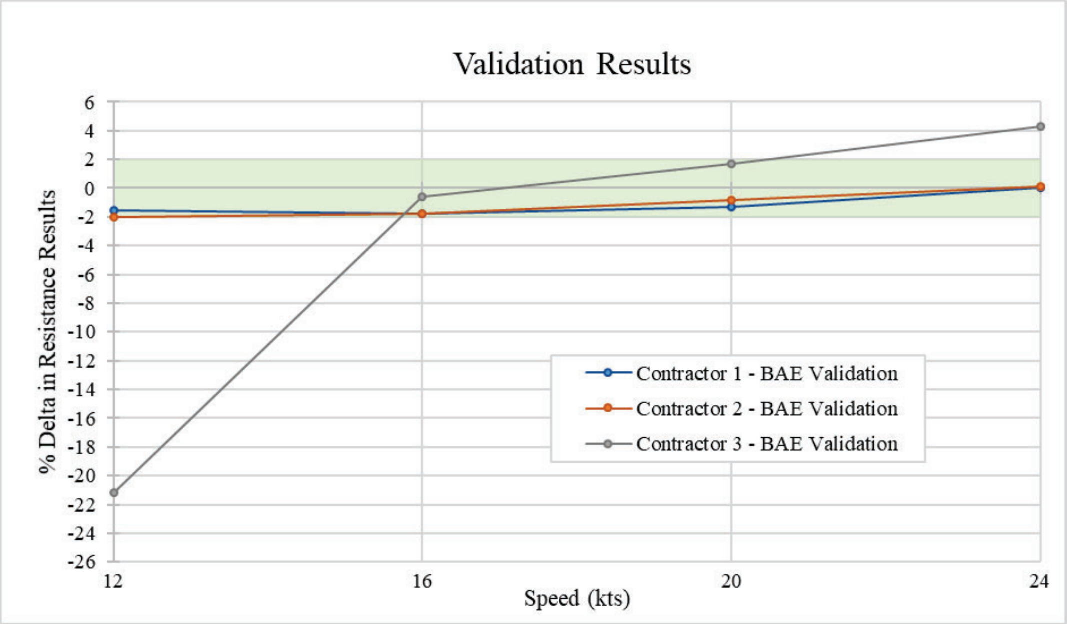

Figure 7: Validation Results for Design Condition

The average delta between the Contractor 2 results and validation is likely due to the difference in CFD software used to assess the optimised hullform. The difference between Contractor 1 and the validation is likely due to the delta in cells used in the analysis as Contractor 1 used a significantly refined mesh discretisation.

For Contractor 3, the results did not show a good correlation at lower speeds. This cannot be explained with a specific cause, however it is believed that the delta at lower speeds is likely due to a difference in the discretisation model used for the analysis. It should also be noted that Contractor 3 also used an alternative CFD software package for the analysis.

As the AI and neural networks method adopted by Contractor 2 showed the greatest average resistance reduction over the entire speed range and was the lowest scoring hullform (see Table 4), resistance model tests are being planned for mid-late 2024 to provide further validation of results.

6. Discussion

6.1 Cost

The optimisation performed by Contractors 1 and 2 was to a financial cost, whereas Contractor 3’s optimisation had no associated cost due to it being an opportunity to demonstrate their optimisation software capability. The optimisation cost using the traditional approach and the AI approach were of similar magnitude.

With the optimisation software approach, although on this occasion a cost was not incurred due to it being a demonstration only, in normal circumstances there would be a yearly license fee in order to acquire and use the software package. It should be noted that in this study, an approximate cost saving of 50% would be achieved if utilising licensed in-house optimisation software rather than outsourcing the same work to a consultancy. This cost saving amplified when considering that in reality there are often multiple design projects ongoing per year within a typical ship design company.

6.2 Design Space

Due to the significant reliance on SME expertise, the manual iteration of the parametric model, and manual analysis of designs/results, the exploration of the design space was limited for the traditional method adopted by Contractor 1. Each design iteration required individual assessment and review by the SME panel before progressing to the next iteration, resulting in a time-consuming optimisation process, where the final solution is often not ‘optimal’ due to their being too many design parameter variables to manually iterate and explore. In total, only two design iterations from the baseline were made, both of which did not vary significantly due to the limited timeframe and budget.

This method is a reflection on the design of previous naval ships, where the data of proven hullforms was used to help inform and define future designs, resulting in a lack of design variability. The traditional method of optimisation does not facilitate the efficient exploration of the wider design space within a feasible project timescale and budget.

On the other hand, the automated optimisation approach adopted by Contractors 2 and 3 resulted in a notable variance between candidate hullforms. Whilst respecting design constraints, both the AI and optimisation software approach resulted in a number of evenly distributed hullform designs to be created within a wide design space. In particular, this was noticed by the generation of 500 hullforms by Contractor 2. This formed the training data for the neural network, where defined design parameters were assigned upper and lower bounds whilst remaining within design constraints to ensure the design space was both extensive and compliant. As a result, a significant number of compliant hullform designs could be created in a short timeframe ready to be assessed.

6.3 Barehull Resistance

Despite resulting in the same cost as Contractor 2, Contractor 1 with the traditional method produced the least efficient hullform for both the top speed condition and also across the overall speed range taking into account the operational profile for the design condition. This is reflective of the limited design space explored, with little variance between the design iterations and the baseline hullform.

Contractor 2, with the operational profile as the main focus of the optimisation across the entire speed and displacement range, produced the greatest reduction in barehull resistance across the analysed speed range.

Contrary to the approach taken by Contractors 1 and 2, the operational profile was not considered for the optimisation and solely focused on optimising for the top speed requirement for the approach taken by Contractor 3. Despite showing the greatest improvement in barehull resistance at top speed, the resistance at lower speeds in the design condition suffered as a result and lead to an increase in resistance from the baseline design. Consequently, the increase in resistance for lower speeds offset the improvement in resistance performance at higher speeds, with the results of Contractor 3 being the worst overall across the assessed speed range.

This creates a dilemma for future designs. At present, the focus is primarily on top speed requirements, not taking into account the operational profile of the ship in reality. For ship designers, this is beneficial as it will help to define the internal machinery required with the installed power and therefore informs the general arrangement. The lower resistance at top speed consequently leads to a reduction in installed power and associated systems, therefore a reduced capital cost (CapEx).

However, as shown by Contractor 3's optimisation results, the customer would suffer from a substantial penalty in terms of increased through-life costs in terms of fuel consumption (OpEx). This is proven by the fact that the ship will spend the majority of its operational life transiting at lower speeds, as presented in Figure *2*.

7. Conclusions

With the advancement of modern technology and optimisation techniques, it is evident that by using traditional methods, optimal results cannot be achieved to meet efficient fuel consumption targets while considering the limited timeframes and budgets imposed by project on ship designers.

Going forward, ship requirements should take into consideration through life costs and fuel efficiency, rather that typically aiming to maximise performance, whether this is achieved through higher sprint speeds or reduced power requirements. With the ever more prevalent need for efficient design due to the industry commitment to net-zero emissions, it is evident that moving away from the traditional approach of design optimisation is required to achieve an effective design.

Reducing the hullform resistance reduces the effective power requirement and can lead to a number of advantages to a project depending on the optimisation goals, such as improving performance, allowing for an increase in design margins (reducing risk), and/or reducing installed power (reducing cost).

In addition, using efficient optimisation techniques to reduce ship resistance leads to a reduction in emissions and environmental benefits from having a lower Energy Efficiency Design Index (EEDI); increased viability for future fuels due to the ability to store lower energy dense fuel within the same tank volume; increased range due to the lower fuel consumption, increasing the platform capability; and lower propeller loading due to a reduction in delivered power required, reducing the risk of cavitation.

Ultimately ship design should be a holistic approach, combining optimisation for multiple performance areas (resistance, stability, seakeeping, manoeuvring etc.) to ensure overall performance is improved in its entirety. By adopting an optimisation process using AI techniques and optimisation software, the ability is created to conduct such an optimisation in an automated way, exploring a large design space, combine performance areas, all in a feasible timeframe, all of which simply cannot be achieved using the traditional approach.

Physical Resistance Components of a Hydrofoil as a Function of Submergence

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Synopsis

Hydrofoils have become a popular design addition to different kinds of vessels, particularly yachts and race boats. Predicting hydrodynamic forces acting on hydrofoils remains challenging, due to a wide operating regime and complex hydrodynamical phenomena. In this paper we investigate methods of decomposing the total drag force of a hydrofoil from high-fidelity Reynolds–Averaged Navier Stokes (RANS) and low-fidelity lifting line computational fluid dynamics simulations into its physical components. Namely, these are the wave-pattern, induced, and viscous drag components. These components were calculated using wake surveys in RANS, while a separation of downwash coefficients was used in the lifting line formulation. Reynolds numbers between 2.57×10^5 and 2.06×10^6 were simulated, which corresponded to chord Froude numbers between 0.5 and 4. We present various Froude number-dependent trends in these components which we observed from RANS. Lifting-line models were modified to account for free surface effects using a mirror image of the hydrofoil as well as free surface Green's function for the wave pattern; and benchmarked against RANS results to gauge their accuracy. A parameter study of submergence depth was also carried out using the lifting line model. Strong submergence-dependence of the induced and wave drag components was observed. Higher submergences led to overall lower total drag except at Froude numbers below around 1.5. In this intermediate regime, strong wave effects acted to increase the total drag compared to even shallower submergences. The efficiency of the numerical LL model here, demonstrated through an extensive parameter study on submergence depth, can be greatly exploited for exploring a large design space to optimise candidate designs during preliminary conception. However, great care should be taken in interpreting these results as the theoretical models employed, especially for the free surface effects, can be difficult to validate and still shows significant discrepancies with CFD.

Keywords: Hydrofoil, computational fluid dynamics, lifting-line, resistance, waves.

1 Introduction

Hydrofoil-equipped craft have become popular in many fields of yachting and boating. In yacht racing, their adoption became widespread after Emirates Team New Zealand introduced them as a design element for their 2013 America's Cup campaign. There are a myriad of other race classes that also incorporate hydrofoils (henceforth "foils") such as the IMOCA60, Waszp, and Olympic Nacra 17. In such cases, foil design is dictated by the class rules - a set of technical regulations that impose geometrical, structural and/or hydrodynamic restrictions on design. Aside from racing, foiling craft find uses in recreational and general-use boating and sailing: on superyachts, sport boats, multihulls, passenger ferries, and others. Here their design is less constrained and has more scope. The use of foils on watercraft adds substantial design complexity and challenge that requires significant effort from designers to overcome.

The use of foils on watercraft may serve different purposes depending on the application. On some craft, foils are used principally to provide an enhanced righting moment to permit greater sail power (Oliver and Gauvain, 2022). On others, the vertical lift foils generate helps significantly reduce the hydrodynamic resistance of the hull by raising it out of the water. Some craft, such as the IMOCA60 class, use foils for a hybrid purpose, combining these benefits. Craft that use foils for the latter purpose operate in two distinct regimes: hull-borne and foil-borne. The first occurs when the boat's speed is insufficient to generate enough lift to raise the hull out of the water, and the boat is supported by its buoyancy. When the boat passes through a threshold take-off speed, it becomes supported by its foils and enters the foiling regime (Acosta, 1973).

Foils used on race yachts face a large spectrum of hydrodynamic phenomena, since the boat speed varies greatly depending on wind speed, direction, and whether the boat is foiling or not. The operating regime encompasses lift

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coefficients from zero up to near stall. Furthermore, the lift and drag forces are affected by the presence of the free surface. Typical Froude numbers for contemporary America's Cup yachts range from <1 to >10 depending on their speed. This range encompasses a shift in wave kinematics from subcritical to supercritical, as well as the possible onset of cavitation and natural ventilation at higher speeds(Acosta, 1973; Faltinsen, 2005). In parallel, the Reynolds numbers range from about 5×10^5 up to over 3×10^6 - hence appendage flows are often in the transitional regime. In addition, foil forces are highly sensitive to foil orientation, immersion, and interactions with other hull appendages (Oliver and Gauvain, 2022; Turnock and Holroyd, 2001). Such a wide operating regime makes it challenging for foil designers to carry out holistic hydrodynamic analyses of candidate foil designs. This kind of analysis is especially important for America's Cup teams due to the current generation of technical regulations, which restrict the degree of physical testing allowed for built foil prototypes.

Characterising the hydrodynamics of foils is typically done using computational tools with varying degrees of fidelity. Computational fluid dynamics (CFD), such as Reynolds-Averaged Navier–Stokes (RANS) formulations, are sought for their versatility and acceptable accuracy for a wide range of flows. They have seen extensive use in for yacht design (Turnock and Holroyd, 2001; Graf et al., 2009; Jones and Korpus, 2001). However, their drawback is high computational cost, especially for evaluating hundreds of candidate designs during conceptualisation. As a remedy, potential flow models such as panel methods (Giesing and Smith, 1967) or lifting line (LL) models can be used. These too are already widely used in naval architecture (Rosen and Laiosa, 1997; Oliver and Gauvain, 2022). They tend to be less accurate than CFD but offer improved computational efficiency.

The aim of this paper is to investigate two things: the discrepancies between RANS-based and LL-based simulation of simple hydrofoils; and the decomposition of drag forces acting on such hydrofoils within the framework of both modelling approaches. With the former, a numerical LL model is benchmarked against a RANS model of a fully submerged hydrofoil, followed by an analysis of different physical components of drag as a function of flow conditions. With this, the aim is to determine the usefulness of analysing drag decomposition with LL models during, for example, preliminary design. Such a decomposition could offer greater insight into the performance of a hydrofoil, since a designer could look to refine the design with a deeper understanding of how different drag mechanisms would be affected.

2 Implementation of CFD-based drag decomposition

A rectangular NACA4412 foil model with an aspect ratio of $\lambda = 6$ and chord of $c = 0.3$ m was used for simulations. No fillet radii were used at the wing tips. A geometric angle of attack of $\alpha = 5^\circ$ was prescribed for all runs, with the foil's leading edge (LE) submerged one chord length beneath the undisturbed free surface. Figure 1 shows the domain dimensions and inlet/outlet boundary condition specifications.

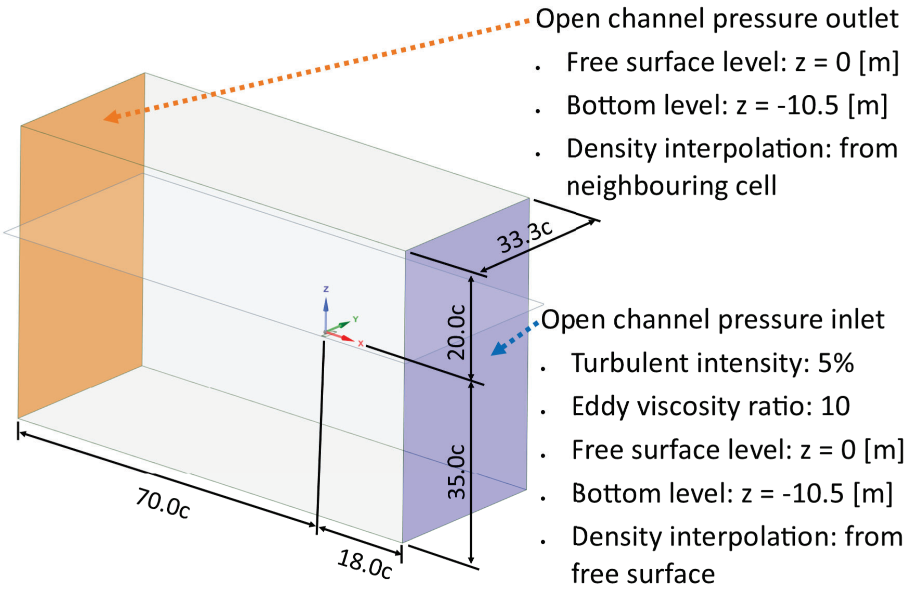

Figure 1: Computational domain used for simulations, with indicative dimensions and the inlet/outlet boundary conditions labelled. Detailed descriptions of the volume-of-fluid settings can be found in Inc. (2020).

The CFD implementation used to benchmark the lifting line (LL) results is described in Chernyshev et al. (2023a), and omitted here for conciseness. Flows were analysed at chord-based Froude numbers F_c of 0.5, 1, 2 and 4, which corresponded to inlet velocities of 0.858 ms^{-1}, 1.716 ms^{-1}, 3.431 ms^{-1} and 6.862 ms^{-1} respectively. The corresponding Reynolds numbers were 2.57×10^5, 5.15×10^5, 1.03×10^6 and 2.06×10^6.

The drag force, or resistance, experienced by foils moving through water has numerous physical sources. The most common way of extracting the drag force from CFD simulations is by integrating the normal and tangential stresses on the foil projected in the direction of motion (Hoerner, 1965). This way, components usually termed "pressure drag" and "skin friction drag" are obtained. Figure 2 depicts how further decompositions may be performed, along with the known ways of calculating each component. The methods used in this study were based on various forms of wake surveys that can calculate the wave, induced and viscous drag components. Their implementations are described in detail by Chernyshev et al. (2023b). Based on prior sensitivity analyses from the same reference, the wake plane location for the surveys was placed at 1.5 chord lengths downstream of the trailing edge. Due to the absence of any surface-piercing geometry in the present study, spray drag was not considered.

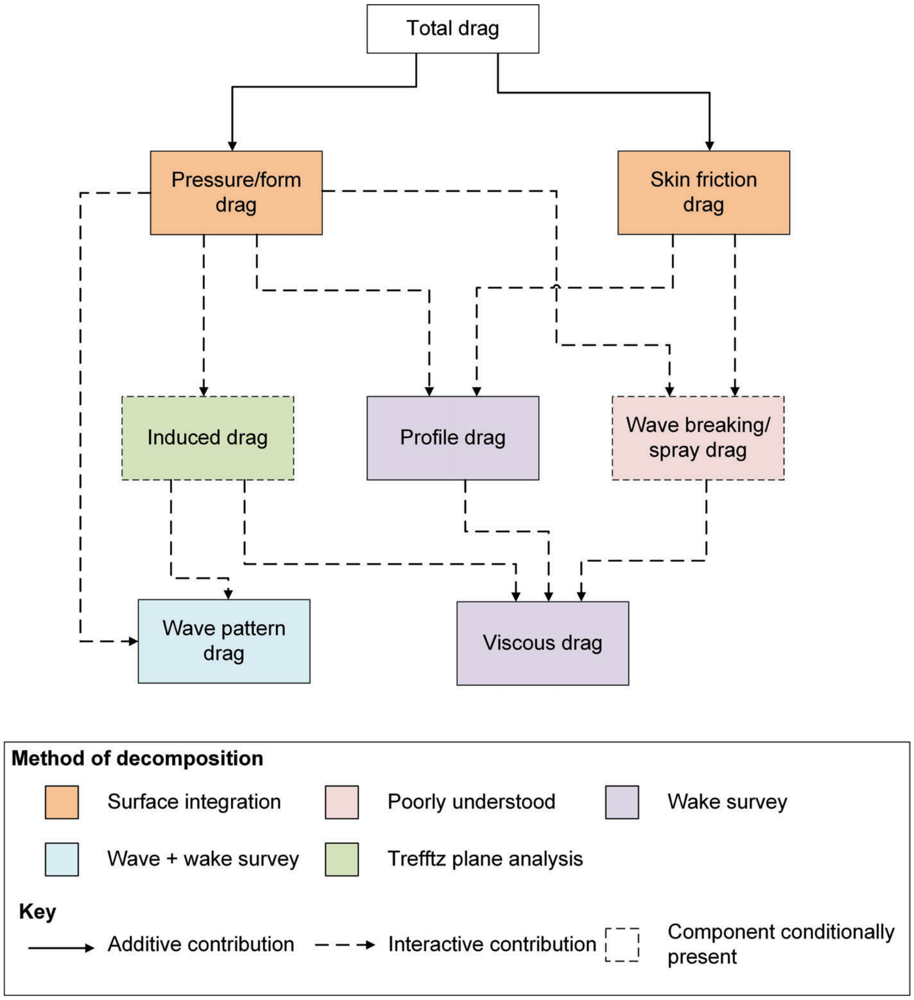

Figure 2: Hierarchical decomposition of drag forces on sailing yacht foils and appendages.

3 Methods - lifting line implementation

The lifting line model used in this paper is a numerical version of the analytical lifting line model of wings originally developed by Goates and Hunsaker (2019). This model is suitable for hydrofoils and airfoils with moderate to large aspect ratios - greater than about 4 - and small angles of attack where there is little to no flow separation. We used a package called "MachUpX" (Goates and Hunsaker, 2022), but modified it to account for the free surface effects present when simulating hydrofoils. The modified package, called "MachUpHydro" is available online (Chernyshev, 2023). The core of our method is largely the same as that presented by Goates and Hunsaker (2022), so most details will not be reproduced here. Instead, a description of the setup used for this study is given in the following sections, alongside the key changes to some of the governing equations made to accommodate free surface effects. Unless otherwise specified, all other settings were default ones carried over directly from those suggested by Goates and Hunsaker (2022) based on their verification and sensitivity analyses.

3.1 Geometry and model settings

The simulated geometry was the same as that used in the CFD section above, except for the submergence h which was varied between $h/c = 0.25$ and $h/c = 4.00$. The input files used to specify this are shown in the appendix. The database used to compute the hydrofoil's section properties (lift, drag, moment) for each control point was pre-generated using XFOIL (Drela, 1989). This was implemented via the `airfoil-db` Python package. A separate database was generated for each Froude number simulated, ensuring a small buffer of $\pm 10\%$ above and below the nominal Reynolds number to account for variations due to the induced velocities at control points. Angles of attack between -12° and 15°, with a step of 0.1°, were simulated for each Reynolds number. Because the nominal Mach number was negligible (less than 0.005 in the simulated water medium), the flow was treated as incompressible for all cases. Using interpolation, the lift, drag and moment coefficient were calculated for each segment of the lifting line at the effective angle of attack seen by that segment (in line with the practice of Goates and Hunsaker (2022)).

3.2 Modifications to account for free surface effects

A biplane image formulation was utilised, wherein the simulated hydrofoil is reflected about the mean free surface but with the bound and trailing vortices assumed rotating in the same sense as on the parent foil. Figure 3 illustrates this idea. Previous studies that used lifting line models for hydrofoils in the presence of a free surface deemed this formulation acceptable for accuracy (Nishiyama, 2013; Wu, 1953; Wilson, 1978; Morch and Minsaas, 1991; Walree, 1999).

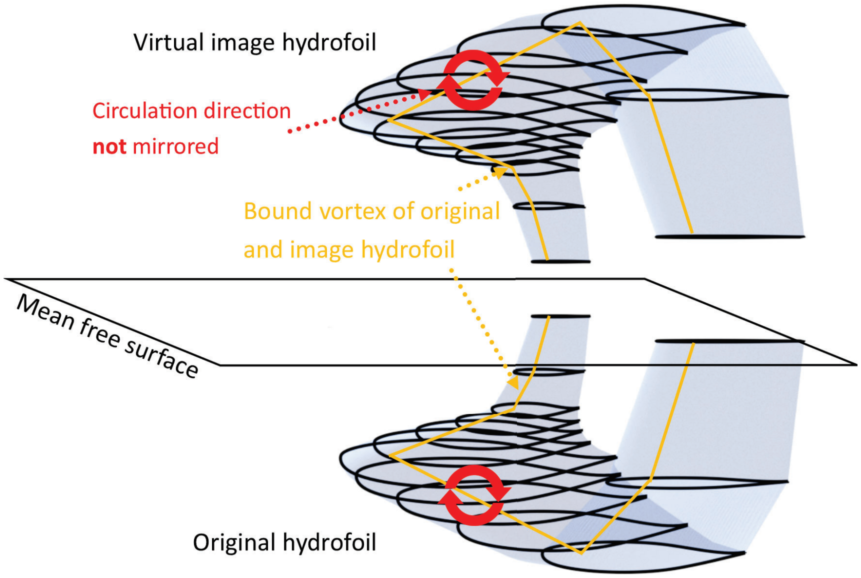

Figure 3: Illustration of biplane mirroring about the free surface to simulate interaction effects. The image was taken and modified from Kramer et al. (2018).

The biplane image was implemented by mirroring all of the vortex nodes about the mean free surface at $z = 0$ m. This was done using a standard vector mirror transform. The effect of this was to add additional terms to the expression of induced velocity v_{ji} at each control point. The original expression for v_{ji} is given as (eq. 36 in Goates and Hunsaker (2022))

$$
\begin{aligned}
v_{ji} = \frac{1}{4\pi}\Bigg[& -\frac{\vec{u}_{\text{trailing}_j} \times \vec{r'_0}}{r'_0(r'_0 - \vec{u}_{\text{trailing}_j} \cdot \vec{r'_0})} + \frac{(r'_0 + r_0)(\vec{r'_0} \times \vec{r}_0)}{r'_0 r_0 (r'_0 r_0 + \vec{r'_0} \cdot \vec{r}_0)} \\
& + (1 - \delta_{ij}) \frac{(r_0 + r_1)(\vec{r}_0 \times \vec{r}_1)}{r_0 r_1 (r_0 r_1 + \vec{r}_0 \cdot \vec{r}_1)} + \frac{(r'_1 + r_1)(\vec{r'_1} \times \vec{r}_1)}{r'_1 r_1 (r'_1 r_1 + \vec{r'_1} \cdot \vec{r}_1)} \\
& + \frac{\vec{u}_{\text{trailing}_j} \times \vec{r'_1}}{r'_1(r'_1 - \vec{u}_{\text{trailing}_{j+1}} \cdot \vec{r'_1})} \Bigg],
\end{aligned}
\tag{1}
$$

where $\vec{r}_0, \vec{r}_1, \vec{r'_0}$ and $\vec{r'_1}$ are the vector displacements between the ith control point and vortex node j and $j+1$, and vortex *joint* node j and $j+1$ respectively. The non-boldface variables represent magnitudes of the respective vectors. Trailing vortex direction vectors are denoted as $\vec{u}_{\text{trailing}_j}$ and $\vec{u}_{\text{trailing}_{j+1}}$ and δ_{ij} is the Kronecker delta function.

To calculate the induced velocities due to the mirrored lifting line, we would need to calculate new vector displacements to the mirrored vortex nodes and mirror the direction vectors of the trailing vortices. The former is done via

$$
r_{k,\vec{\text{image}}} = r_{\vec{\text{CP}}} - r_{\text{vortex},\vec{\text{image}}},
\tag{2}
$$

where $r_{\text{vortex},\vec{\text{image}}}$ is the mirrored counterpart of the jth and $j+1$th vortex node and $r_{\vec{\text{CP}}}$ is a given control point location from the *original* hydrofoil's lifting line locus. The subscript k is equal to either 0 or 1 depending on whether the jth or $j+1$th vortex node is being mirrored. To find the mirrored trailing vortex direction vectors, a simple vector mirroring operation was performed on the original vectors about the mean free surface.

With all the mirrored vectors now computed, the biplane correction to the induced velocities took the form

$$
v_{ji,\text{effective}} = v_{ji} \pm v_{ji,\text{image}}
\tag{3}
$$

where $v_{ji,\text{image}}$ is the same form as Equation (1) but using the mirrored counterparts of the displacement and direction vectors from the preceding calculations. The plus-minus sign is to be taken depending on whether the biplane or the wall boundary condition for the free surface was desired respectively.

3.3 Modifications to account for wave-making

In an effort to improve the fidelity of the lifting line model, wave-making effects were simulated in addition to the mean free surface effects described previously. This was done by adding the downwash produced due to the generation of the wave pattern by the hydrofoil using a method outlined by Morch (1992) based on free surface Green's functions – specifically Equation 2.3.1b and Appendix B. For brevity, the details of this calculation were not reproduced here. The resulting correction to the downwash coefficients from Equation (3) looked like

$$
v_{ji,\text{effective}} = v_{ji} \pm v_{ji,\text{image}} + v_{ji,\text{wave}},
\tag{4}
$$

where the last term of Equation (4) accounts for the effect of wave-making on the downwash coefficients.

4 Drag force decomposition from the lifting line model

Unlike for CFD, wake surveys cannot be used with lifting line solutions directly, due to the lack of a resolved wake flow field in the calculation. Instead, a simple separation of the downwash components, as per Equation (4), was used in combination with the Kutta-Zhukovsky theorem to calculate the inviscid – wave and induced – resistance components. The viscous component was calculated using the 2D viscous XFOIL simulations of each segment.

In MachUpHydro, the viscous drag force F_{Dv} was calculated as the sum of the discrete wing segment drag forces. For each segment, the local drag coefficient was computed by interpolating into the hydrofoil database created by XFOIL at the effective angle of attack (as defined in Section IV B of Goates and Hunsaker (2022)) and effective Reynolds number seen by that segment. After thus determining the total viscous drag force on the hydrofoil, the viscous drag coefficient was computed through

$$
C_{Dv} = \frac{2F_{Dv}}{\rho V_\infty^2 S}
\tag{5}
$$

where S is the planform area.

Assuming zero coupling between the induced and viscous drag components, the former could simply be calculated as the component of the total inviscid force acting in the freestream direction. In the numerical lifting line model, the inviscid force was calculated by applying the Kutta-Zhukovsky theorem to each discretised wing segment using

$$\Delta\vec{F}_{\Gamma_i} = \rho\Gamma_i\vec{V}_i \times \vec{dl}_i; \tag{6}$$

where $\Delta\vec{F}_{\Gamma_i}$ is the inviscid force vector acting on segment i; Γ_i is the segment's circulation; V_i is the total velocity vector at the segment's control point $\vec{V}_i = \frac{\Gamma_i}{4\pi}v_{ji}$, and $\vec{dl}_i$ is the bound vortex vector for that segment. Therefore, taking the component of this force acting in the freestream direction yields the inviscid drag $D_{\text{inviscid},i}$ acting on segment i,

$$D_{\text{inviscid},i} = \Delta\vec{F}_{\Gamma_i} \cdot \vec{u_\infty}. \tag{7}$$

The total inviscid drag acting on the hydrofoil is then the sum of $D_{\text{inviscid},i}$ from each segment. To decompose this further, it is necessary to assume that induced and wave drag are coupled with each other through the effect of the mean free surface via the biplane image formulation (judged to be a fair assumption based on prior studies (Chernyshev et al., 2023a)). Then the inviscid force from Equation (6) can be decomposed by breaking down $\vec{V}_i$ into three parts: self-induced downwash $\vec{V}_{si}$; downwash induced by the biplane image of the foil $\vec{V}_{bi}$; and downwash due to the wave-making correction $\vec{V}_{wi}$. Consequently, the inviscid force due to wave-making is derived from Equation (6) as

$$\Delta\vec{F}_{\Gamma_i} = \rho\Gamma_i(\vec{V}_{wi} + \vec{V}_{bi}) \times \vec{dl}_i; \tag{8}$$

and the force due to lift-induced effects is

$$\Delta\vec{F}_{\Gamma_i} = \rho\Gamma_i(\vec{V}_{si} + \vec{V}_{bi}) \times \vec{dl}_i. \tag{9}$$

Note the inclusion of the induced drag due to the biplane image in both Equation (8) and Equation (9). While it is not obvious how the wave drag and induced drag mechanisms interact, it is safe to assume that the biplane image influences both. For wave drag, this is because the biplane image approximates the effects of free surface's proximity, and the wave corrections of Equation (4) can be considered a subset of this. Meanwhile, the induced drag depends on the lift, which itself is altered by the presence of the free surface due to the downwash from the biplane image. Hence the biplane image factors into both components of inviscid drag.

After calculating the drag forces per Equations (8) and (9), the corresponding drag coefficient was found in a manner analogous to Equation (5).

5 Results and discussion

To ascertain the validity of the CFD simulations, in Figure 4 we examined whether, as suggested by the Froude hypothesis, the viscous and wave drag components sum to the total drag (Wu, 1962). Here, the sum of the viscous and wave drag coefficients is plotted alongside the total drag coefficient extracted directly from CFD via surface integration. The sum was remarkably close to the total at all simulated Froude numbers, which supported the Froude hypothesis. Figure 4 also shows that the strong decrease in the wave drag coefficient with Froude number led to an overall decline of the total drag coefficient. Likewise, the “hump” in C_{Dw} around $F_c = 1$ was reflected with a hump in $C_{D,\text{tot}}$ at the same location. This demonstrated that in the intermediate Froude number regime $0.5 < F_c < 2$ wave drag constituted a significant, if not dominant, part of the foil's overall drag.

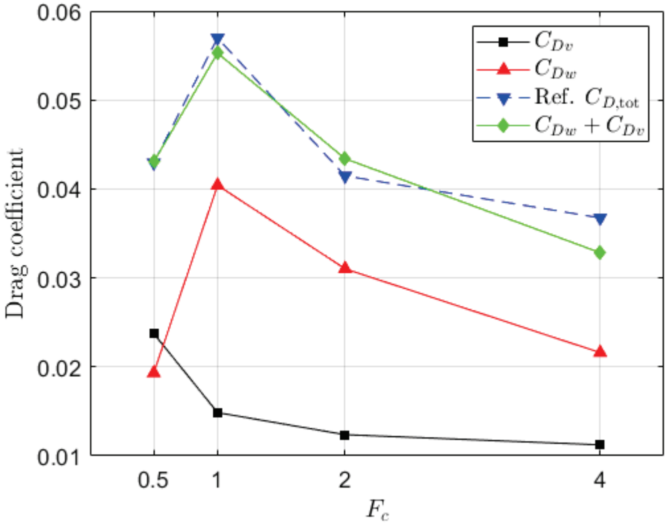

Figure 4: Examining the validity of the CFD drag decomposition through the Froude hypothesis.

5.1 Benchmarking lifting line calculations against CFD

Next, lifting line simulations were performed with the same geometry and conditions as for CFD. Figure 5 plots the total drag coefficients from both methods as function of the simulated Froude number. The overall trend from CFD was captured well by the LL model, with the drag sharply increasing up to a peak around $F_c = 1$ before slowly decreasing as F_c increased. However, the magnitude of the peak drag coefficient was underestimated by the LL model compared to CFD. This could be explained by strong non-linearities in the free surface wave pattern that were not accurately modelled by the wave-making correction applied to the LL model. Conversely, at $F_c \gtrapprox 2$, the LL model started overestimating the total drag, perhaps again due to differences between the theoretical (LL) and resolved (CFD) free surface deformations.

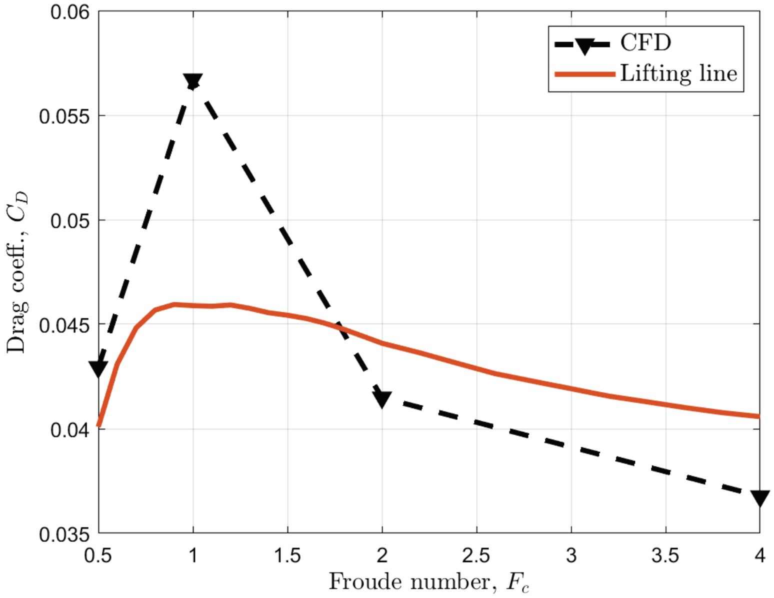

Figure 5: Calculated total drag coefficients with $\lambda = 6$, $h/c = 1$ and $\alpha = 5°$ using CFD and lifting line.

The viscous drag coefficient C_{Dv} was calculated for all simulated Froude numbers and is shown in Figure 6. Results are presented alongside the C_{Dv} from RANS CFD simulations. The main point to note here is that C_{Dv} from CFD was underestimated by the LL model at all simulated Froude numbers, by about half. This result showed that perhaps the induced velocities at the control points of the LL were not modelled very accurately. Most likely, the reason was that the XFOIL panel method used to calculate the section drag coefficient used rather rudimentary viscous flow models which did not account for additional viscous effects that were simulated in RANS – namely boundary layer growth and transition. These would have resulted in a greater pressure drag on each segment of the discretized wing, and increased the effective angle of attack seen by each control point.

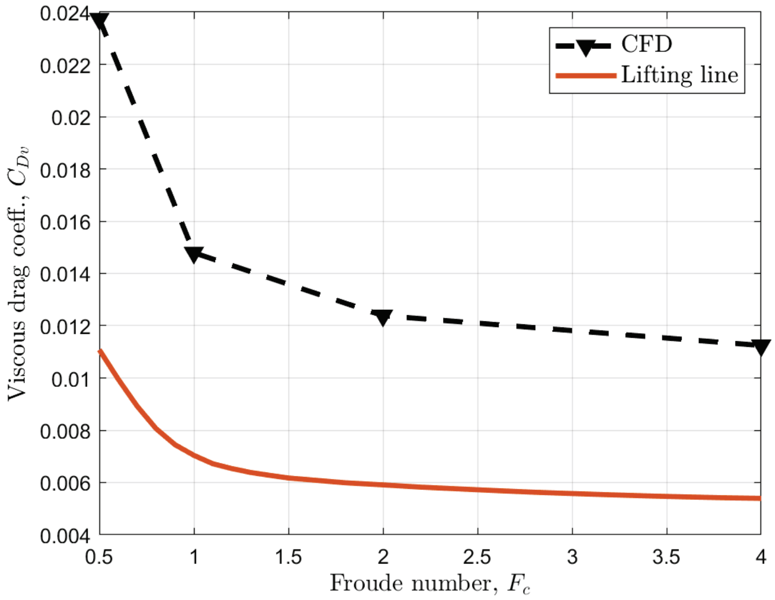

Figure 6: Calculated viscous drag coefficients with $\lambda = 6$, $h/c = 1$ and $\alpha = 5°$ using CFD and lifting line.

A comparison of the induced drag coefficient C_{Di} from CFD and LL is shown in Figure 7. At $F_c > 1$, the CFD model showed that C_{Di} approached a plateau of around 0.028 as F_c increased. The LL model was able to capture this trend reasonably well, though it appeared that the LL values of C_{Di} were still increasing at the highest simulated Froude number, suggesting the plateau point would be at higher Froude numbers than what were simulated here.

At $F_c = 0.5$, the LL model did not agree with CFD. While the LL model predicted a monotonically increasing induced drag coefficient through the whole range of simulated Froude numbers, the CFD simulations suggested the induced drag encountered a local minimum around $F_c = 1$ – granted, the resolution of Froude numbers in this area should be improved to elucidate this trend. This could be attributed to either an interaction with the free surface that changed the lift such as to reduce C_{Di}; or an inaccuracy with the wake survey. Through a previous sensitivity analysis (Chernyshev et al., 2023b), it was found that at $F_c < 1$ wake surveys were quite sensitive to the choice of downstream position for the wake plane. For consistency, the same position was used for all Froude numbers in the present CFD simulations, but for future studies perhaps the choice should depend on the Froude number to reflect the different nature of the wakes.

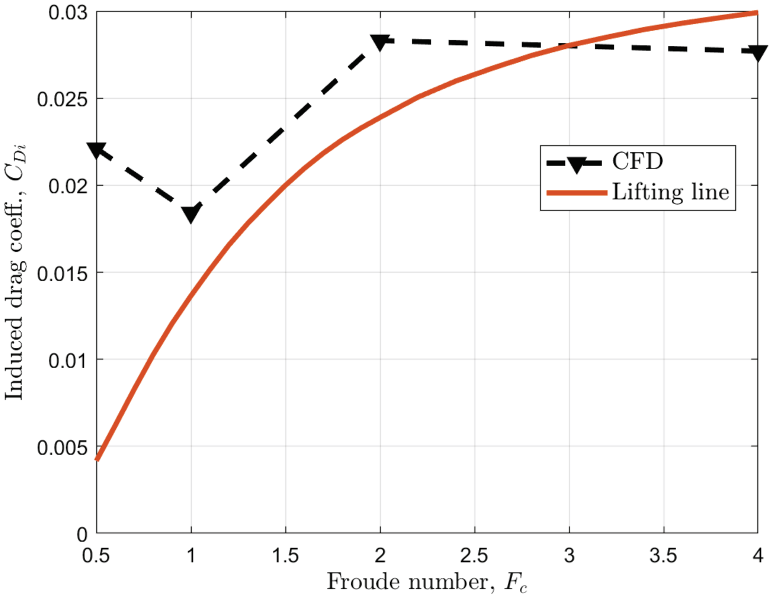

Figure 7: Calculated induced drag coefficients with $\lambda = 6$, $h/c = 1$ and $\alpha = 5°$ using CFD and lifting line.

Figure 8 shows a comparison between the wave drag coefficient C_{Dw} computed from the LL model and from CFD. In both cases, there was a "hump" in C_{Dw} at a certain F_c. In the CFD model, it occurred around $F_c = 1$ with a peak of 0.040; whereas in the LL model it was at about $F_c = 0.75$ with a peak of 0.028. Both cases reflected the approximate flow regime where wave drag is maximised due to the nature of the wave pattern on the free surface Wehausen (1973). After the hump, the wave drag was expected to gradually decrease as the Froude number went up, but to not reach zero. This is because in the high Froude number regimes, about $F_c > 2$, the transverse waves start to disappear and the only significant contribution to the wave drag comes from the diverging wave system (Nishiyama, 2013). This trend was seen in both models, with the wave drag from each steadily declining after the hump. However, there was still a large discrepancy between the predicted values due to the difference in peak C_{Dw} at the humps. This could be due to wave pattern structures that were resolved explicitly by the CFD model using a volume-of-fluid (VOF) model while only being theoretically modelled using the wave correction term of Equation (4) in the LL model. Addressing this would probably require a higher-fidelity theory for performing the wave correction.

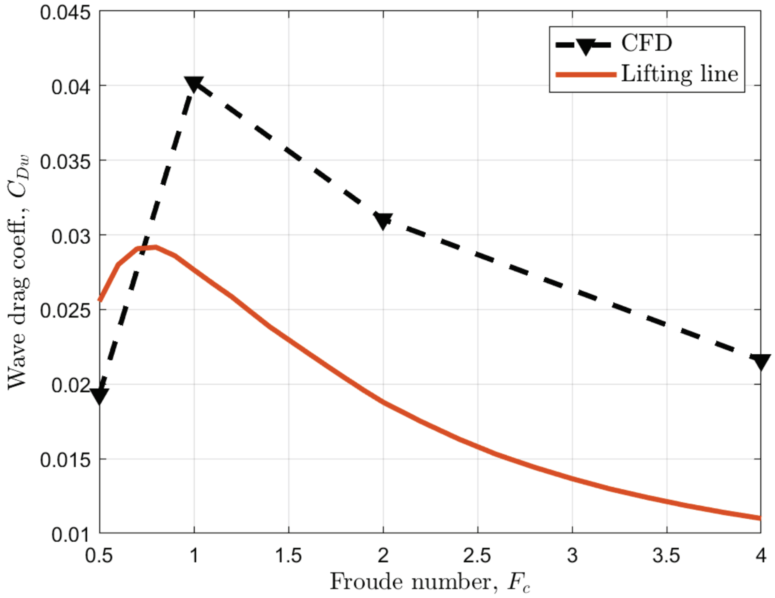

Figure 8: Calculated wave drag coefficients with $\lambda = 6$, $h/c = 1$ and $\alpha = 5°$ using CFD and lifting line.

5.2 Examining the influence of submergence depth on drag components

The submergence depth of a foil is known to drastically influence its hydrodynamics (Vladimirov, 1955). In this section, the submergence-dependence of the viscous, induced and wave drag components is examined using the LL model.

Figure 9 shows the total drag coefficient for submergence depths between $h/c = 0.25$ and $h/c = 4.00$ and F_c between 0.5 and 4. A strong submergence influence was evident. At the shallowest submergence, the total drag increased with Froude number up to a peak around $F_c = 1.75$, before slowly declining again. Also, as the submergence increased, the location of peak total drag coefficient shifted to lower Froude numbers and higher values. Such a peak was seen at all submergences except for the deepest ones of 3.00 and 4.00 chords. At these depths, the C_D was greatest at the lowest simulated Froude number, after which it monotonically decreased with F_c. Perhaps expanding the lower range of Froude numbers to around 0.25 would also reveal a peak in C_D for the greatest submergences.

It can also be observed in Figure 9 that the total drag at $F_c = 0.5$ increased as the submergence increased. This meant the total drag at lower Froude numbers was lower when the submergence was shallower. Looking to the highest Froude numbers, it was seen that the total drag attained at intermediate submergences was greater than that at the lowest of the highest ones. The result at the shallowest submergence, $h/c = 0.25$, should be treated with caution though. At the intermediate and high Froude number regimes, strong interactions between the free surface and suction side of the foil could result in the onset of ventilation which cannot be explicitly resolved or accurately modelled by the LL method, unless utilising an empirical correction.

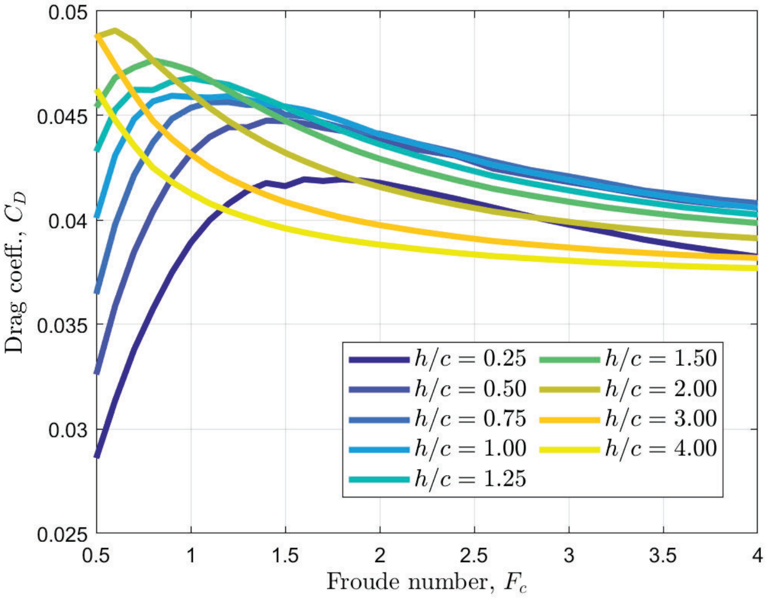

Figure 9: Calculated total drag coefficients with $\lambda = 6$ and $\alpha = 5^\circ$ at different LE submergences.

Further insight into the trends seen in the total drag coefficient can be obtained through drag decomposition. In Figure 10, the viscous component is presented as a function of submergence and Froude number. It appeared that submergence did not greatly influence C_{Dv} except for at the lowest simulated Froude numbers, $F_c < 0.75$. In this regime, the viscous drag was greatest at the shallowest submergences by around 33%. On the contrary, at the highest Froude numbers the viscous drag was greater the higher the submergence, with around 10% separating the drag at the highest submergence from that at the lowest one. In general, the viscous drag component decreased with Froude number because of the accompanying boundary layer transition at higher Reynolds numbers.

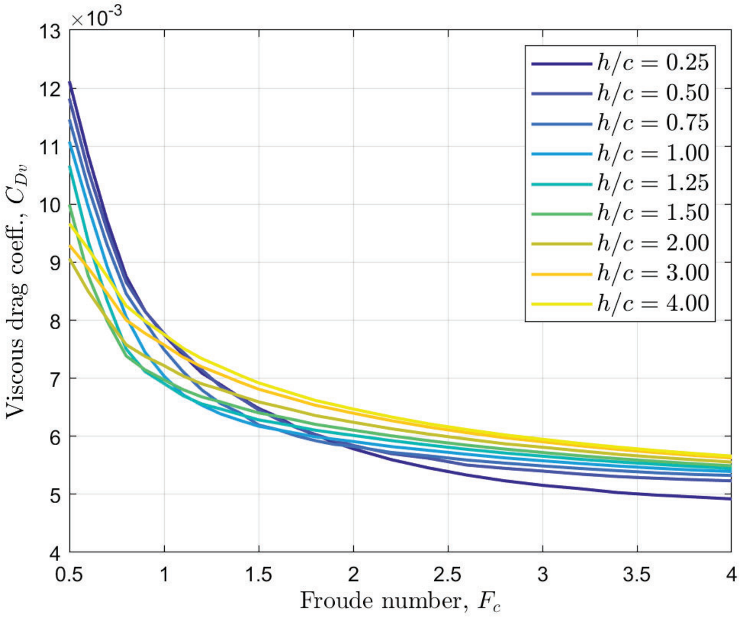

Figure 10: Calculated viscous drag coefficients with $\lambda = 6$ and $\alpha = 5^\circ$ at different LE submergences.

The induced drag coefficient C_{Di} is shown in Figure 11 for all simulated submergences and Froude numbers. It appeared that generally C_{Di} increased as the submergence increased, across all Froude numbers that were simulated. This was likely because these simulations were done with a constant angle of attack, instead of a constant lift. Because of this, the lift at shallower submergences was affected by the proximity of the free surface.

At shallower submergences, the induced drag increased more gradually as the Froude number went up. For example, at $h/c = 0.25$, C_{Di} increased from about 0.0025 to 0.025 over the whole range of Froude numbers – a 900% increase. By contrast, at the highest submergence, C_{Di} increased from 0.025 to only 0.032, which was a 28% increase. Furthermore, at this submergence C_{Di} attained a relatively constant value past a Froude number of around two, whereas at shallower submergence such a plateau was not observed. This showcased the significance of free surface effects on the induced drag coefficients across all Froude number regimes.

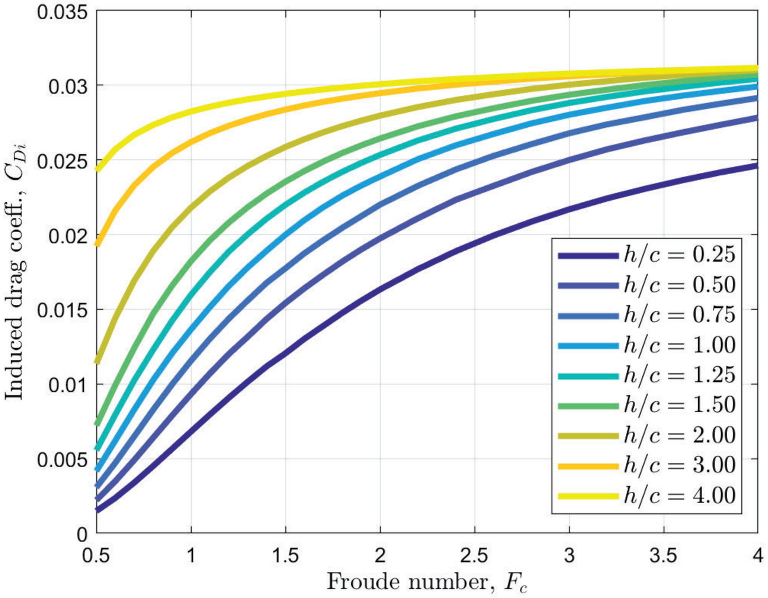

Figure 11: Calculated induced drag coefficients with $\lambda = 6$ and $\alpha = 5^\circ$ at different LE submergences.

Finally, the wave drag coefficient C_{Dw} is displayed in Figure 12. Here, the cause of the peaks in the total drag coefficient seen in Figure 9 is revealed, with C_{Dw} exhibiting similar peaks at intermediate Froude numbers. These shifted up and to the left on the plot as the submergence was increased. At a given submergence, the wave drag trended to a somewhat asymptotic value at high Froude numbers. This value decreased the greater the submergence was. This trend can be explained by the fact that wave drag depends on the free surface wave pattern generated by the foil's pressure disturbance. The closer the foil is to the free surface, the stronger its interaction with it becomes; hence the wave drag acting on the foil increases (Acosta, 1973). Hence the wave drag coefficient tended to be greater at shallower submergences.

Exceptions to this can be seen, however, at the lower Froude numbers. For example, at around $F_c \lessapprox 0.75$, the wave drag coefficient at $h/c = 2.00$ exceeded that at $h/c = 0.25$ despite the latter being at a shallower submergence. Other similar cross-over points can be observed for the other simulated submergences as well. As before, this was probably due to the nature of the wave correction formulation used and the corresponding physical implications – i.e. that the wave-induced downwash strongly depended on both Froude number and submergence. It would be desirable to perform another set of CFD simulations at a different submergence to see if these trends would be reflected in the higher-fidelity results.

Two distinct regimes could be seen in Figure 12 – one below the peak C_{Dw} and one beyond it. The drop in C_{Dw} as the Froude number decreased below the peak location was steeper than that when the Froude number increased past it. This reflected the shifting in the dominant source of wave drag from transverse to diverging waves.

These results are an example of one of endless parameter studies marine architects and naval engineers could employ to study the hydrodynamics of their proposed foil designs in great detail during the preliminary conception. However, care should be taken with interpretation of the results, as much of the numerical LL modelling relies on theoretical corrections that can be difficult to validate. For this reason, more detailed design analysis should be performed with a higher-fidelity approach such as CFD due to greater reliability of the results.

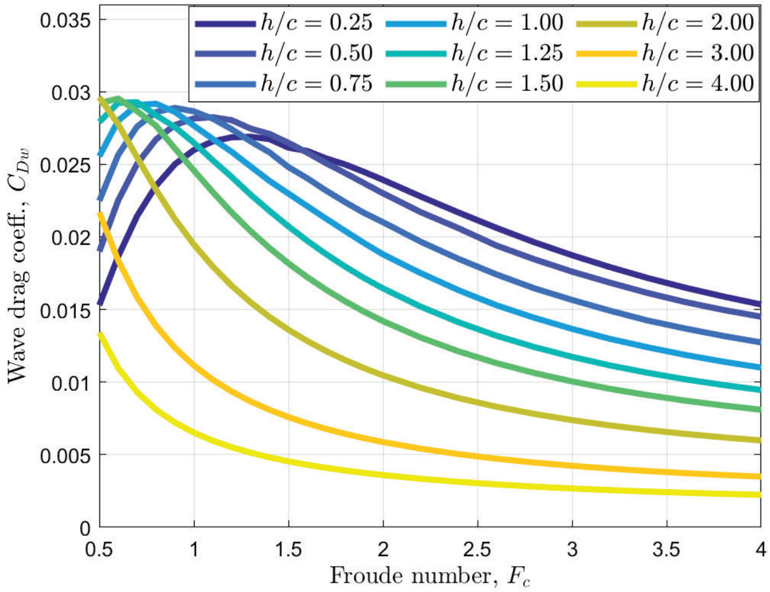

Figure 12: Calculated wave drag coefficients with $\lambda = 6$ and $\alpha = 5°$ at different LE submergences.

6 Conclusions and further research

A NACA4412 rectangular hydrofoil was simulated in a fully submerged configuration moving at a constant Froude number using both RANS-based CFD and a numerical LL model. Decompositions of the drag force acting on the hydrofoil were performed. From CFD, it was possible to extract the induced, viscous and wave drag components using various wake survey methods. Comparing the total drag force with the sum of viscous and wave drags yielded excellent agreement, supporting the widely accepted Froude decomposition of hydrodynamic drag.

The same drag coefficients were also computed from the numerical LL model. Significant discrepancies were seen when compared to the CFD model, but mostly those that would be reasonably expected due to the differing nature in which both methods function and their corresponding fidelity to real free surface flows. Otherwise, the trends were reflected in the LL model adequately. Building on this, a study of the effect of submergence depth of the hydrofoil was carried out. Strong submergence-dependence of the induced and wave drag components was observed. Higher submergences led to overall lower total drag except at Froude numbers below around 1.5. In this intermediate regime, strong wave effects acted to increase the total drag compared to even shallower submergences. It would be desirable to perform more high-fidelity CFD simulations at different submergences along with the corresponding drag force decompositions, to benchmark the trends predicted by the more simplified LL model. This would clarify the accuracy of these trends and whether they properly reflect the effect of waves and submergence on the hydrofoil's drag components.

The efficiency of the numerical LL model here, demonstrated through an extensive parameter study on submergence depth, can be greatly exploited for exploring a large design space to optimise candidate designs during preliminary conception. However, great care should be taken in interpreting these results as the theoretical models employed, especially for the free surface effects, can be difficult to validate and still shows significant discrepancies with CFD.

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References

Acosta, A., 1973. Hydrofoils and hydrofoil craft. Annual Rev. Fluid Mechanics 5, 161–184.
Chernyshev, L., 2023. Machuphydro.
Chernyshev, L., Kabaliuk, N., Jermy, M., Corkery, S., Bernasconi, D., 2023a. Determining the physical components of resistance acting on a hydrofoil. doi:`10.1115/IMECE2023-112475`.

Chernyshev, L., Kabaliuk, N., Jermy, M., Corkery, S., Bernasconi, D., 2023b. Developing methods of decomposing the physical resistance components acting on a hydrofoil. IOP Conf. Series: Materials Sci. Eng. 1288, 012038. doi:`10.1088/1757-899X/1288/1/012038`.

Drela, M., 1989. Xfoil: An analysis and design system for low reynolds number airfoils, in: Mueller, T.J. (Ed.), Low Reynolds Number Aerodynamics, Springer Berlin Heidelberg. pp. 1–12.

Faltinsen, O.M., 2005. Hydrodynamics of high-speed marine vehicles. Cambridge university press.

Giesing, J.P., Smith, A., 1967. Potential flow about two-dimensional hydrofoils. J. Fluid Mechanics 28, 113–129.

Goates, C., Hunsaker, D., 2019. Airfoil database documentation.

Goates, C.D., Hunsaker, D.F., 2022. Modern implementation and evaluation of lifting-line theory for complex geometries. J. Aircraft 60, 490–508. doi:`10.2514/1.C036748`.

Graf, K., Boehm, C., Renzsch, H., 2009. Cfd- and vpp-challenges in the design of the new ac90 americas cup yacht, in: SNAME 19th Chesapeake Sailing Yacht Symp., p. D011S001R001. doi:`10.5957/CSYS-2009-001`.

Hoerner, S.F., 1965. Fluid-dynamic drag. Hoerner fluid dynamics.

Inc., A., 2020. ANSYS Fluent Theory Guide. Report.

Jones, P., Korpus, R., 2001. International america's cup class yacht design using viscous flow cfd, in: SNAME 15th Chesapeake Sailing Yacht Symp., p. D011S001R004. doi:`10.5957/CSYS-2001-004`.

Kramer, J.V., Godø, J.M.K., Steen, S., 2018. Hydrofoil simulations–non-linear lifting line vs cfd, in: Numerical Towing Tank Symp.

Morch, J.B., 1992. Aspects of Hydrofoil Design; With Emphasis on Hydrofoil Interaction in Calm Water. Thesis.

Morch, J.B., Minsaas, K.J., 1991. Aspects of hydrofoil design; with emphasis on hydrofoil interaction in calm water.

Nishiyama, T., 2013. Linearized steady theory of fully wetted hydrofoils. Advances Hydroscience 3, 237–342.

Oliver, C., Gauvain, E., 2022. Practical performance prediction of foil-configured monohull yachts, in: SNAME 24th Chesapeake Sailing Yacht Symp., OnePetro.

Rosen, B.S., Laiosa, J.P., 1997. Splash nonlinear and unsteady free-surface analysis code for grand prix yacht design, in: SNAME 13th Chesapeake Sailing Yacht Symp., OnePetro.

Turnock, S.R., Holroyd, N.J., 2001. Appendage design for the america's cup using cfd, in: European Congr. on Comput. Methods in Appl. Sci. and Eng.

Vladimirov, A., 1955. Approximate hydrodynamic design of a finite span hydrofoil. Report. Central Aero-Hydrodynamical Institute.

Walree, F.V., 1999. Computational methods for hydrofoil craft in steady and unsteady flow. Thesis.

Wehausen, J.V., 1973. The wave resistance of ships. Advances Appl. Mechanics 13, 93–245.

Wilson, M.B., 1978. Lifting Line Calculations for Hydrofoil Performance at Arbitrary Froude Number and Submergence. Part 1. Fixed Shape Elliptical Circulation Distribution. Report. D. W. Taylor Naval Ship Research and Development Center.

Wu, J., 1962. Separation of viscous from wave-making drag ship forms. J. Ship Res. 6.

Wu, Y., 1953. A theory for hydrofoils of finite span. Report. California Institute of Technology Hydrodynamics Lab.

DC secondary distribution grids on future naval ships: a comparison with conventional AC distribution systems and their safety aspects

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Synopsis

Naval ships can use energy storage systems for the transition towards zero-emission technologies. The generation, storage and propulsion devices are connected to a DC grid to increase energy efficiency. However, smaller consumers and hotel loads throughout the ship are connected via a low-voltage AC distribution grid.

A DC distribution grid is expected to be more energy efficient, lighter and smaller than a conventional AC distribution grid. This paper aims to quantify the potential benefits of using a DC distribution grid and identify the risks of this new technology.

A conventional AC distribution grid design is compared with an equivalent DC distribution grid design for a typical surface combatant use case. Aspects included are energy efficiency, weight and footprint. Then, this paper delves into the various aspects affected by the choice of earthing, including common-mode voltages and currents, which can lead to electromagnetic interference.

It was shown that a DC distribution grid can save up to 25 tons of weight and 28 square meters of space for the specific use case. The energy losses are expected to be a factor of 2.5 less. Various earthing strategies, such as those involving the midpoint or negative terminal of the grid, yield different sets of advantages and disadvantages in terms of safety and availability. Unlike the relatively straightforward choices regarding the earthing strategy of the neutral point in AC grids, determining the best approach for the midpoint of DC grids is less obvious. It is shown that there is no earthing approach that gives the optimal solution for all investigated aspects. The adoption of new grid topologies brings about both advantages and risks. This paper elucidates the rationale behind these changes and underscores the importance of considering associated risks, particularly emphasizing the role of earthing. If the risks are properly mitigated, a DC distribution grid can be an improvement compared to a conventional AC distribution grid.

Keywords: DC distribution; Naval; Earthing; Energy Efficiency

1. Introduction

More and more naval ships use energy storage systems for the transition towards zero-emission technologies. Hybrid ships are gaining ground because of the integration of alternative sources such as methanol engines and fuel cells (Haxhiu, 2022). The generation, storage and propulsion devices can be connected to a DC grid to increase energy efficiency. However, the distribution grid usually remains AC because of the variety of loads and conservative design choices.

A full DC ship can potentially save costs and improve energy efficiency (Piazza, 2018). Additionally, using a DC distribution grid saves valuable space onboard of the ship. Besides, the availability of DC loads and components is increasing, making DC distribution a viable option. Most AC loads have an internal AC to DC conversion step anyway. DC distribution grids are upcoming. Applications are already found in office buildings, electric vehicles, smart cities, infrastructure projects and data centres (Dragičević, 2018). There are some challenges in the design of a ship's DC distribution grid. At this moment, there is no maturity in maritime standards that provide guidance in DC topics such as voltage level, grounding and power quality (Latorre, 2023; Xu, 2022). Also, it is not clear how much energy efficiency, weight and space can be saved.

This paper aims to tackle the above issues. The goal is to quantify the potential benefits of using a DC distribution grid and to identify the risks of this new technology. This is done by finding an answer to the following questions:

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- What is the benefit of using a DC instead of an AC distribution grid in terms of weight, energy efficiency and space?
- What are the possibilities of connecting AC consumers to a DC grid?
- How should the main and distribution DC grids be connected in terms of earthing?
- What other considerations need to be addressed in terms of earthing?

To answer the first question, Chapter 2 compares a conventional AC distribution grid design with an equivalent DC distribution grid design for a typical surface combatant use case. This chapter also addresses the second research question regarding the loads.

Then, in chapter 3, this paper delves into the various aspects affected by the choice of earthing, including common-mode voltages and currents, which can lead to electromagnetic interference. Given the presence of multiple power converters in a DC grid, which act as common-mode current sources, it is crucial to focus on mitigating this phenomenon.

Finally, chapter 4 draws a conclusion.

2. Quantitative Comparison Between an AC and a DC Distribution Grid

This chapter compares an AC distribution grid to a DC distribution grid. The use case consists of a fictional navy ship with a DC propulsion grid and four secondary distribution grids. Each distribution grid has different types of loads connected to it. The comparison is made by evaluating the difference in efficiency, weight and footprint of the components and loads. The boundaries of the evaluation are the connection terminals to the main DC grid and the connection points of the loads.

2.1 Use case

Figure 1 shows the simplified single line diagrams of the AC and DC use cases. Each of the four distribution grids has a rated power of 1 MW. The distribution grids are connected to a 1000 VDC main grid. The 440 VAC grids are connected with a 690 VAC grid converter, filter, cables and a transformer. The 700 VDC grids are connected with an isolated DC/DC converter.

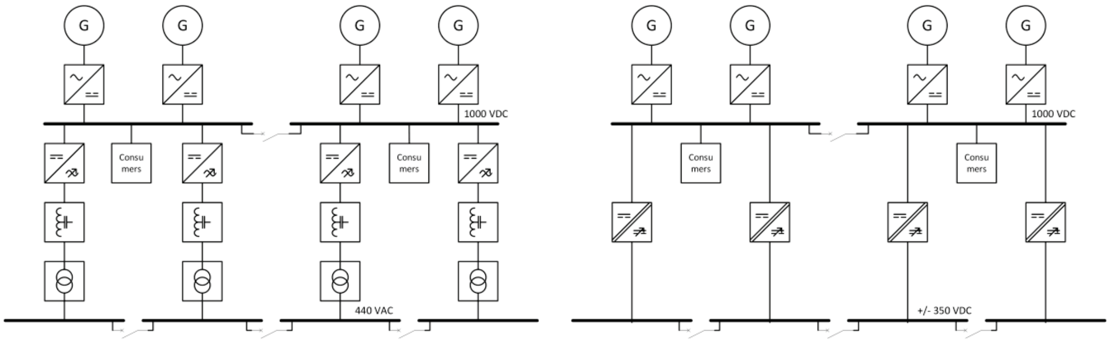

Figure 1: Single line diagram of the use cases. An AC (left) and DC (right) distribution.

The voltages for DC distribution grids on ships are not defined yet in standards. However, the electrical engineering community seems to converge to the voltages given in Table 1. The DC voltages are chosen so that:

1. they are doubled for every level,
2. they are different from the AC voltages so there is no confusion,
3. they are higher than the AC peak for that same level so the DC voltage can supply the AC consumer and
4. the highest level (1400 VDC) is lower that the threshold value for “high voltage” (1500 VDC), because for high voltage, different standards apply.

Table 1: DC grid voltage levels. The voltage for the DC distribution grid is chosen to be +/- 350 V for flexibility.

AC (RMS)	AC (peak)	DC equivalent	Unit
115	163	175	V
230	325	350	V
400	566	700	V

440	622		
690	976	1400	V

2.2 Components

This section discusses the grid components that are in between the propulsion grid and the connection points of the consumers for both the AC and the DC case. For every component, the efficiency, weight and volume are estimated. The following components are considered:

- grid converters,
- transformers and
- cables.

2.2.1 Grid converters

As will be discussed in chapter 3, galvanic isolation is necessary between the sections of the distribution grid. The grid transformer in an AC grid provides this isolation, but a DC/DC conversion step doesn't need a transformer. Therefore, a DC/DC grid converter with galvanic isolation is needed in the DC distribution grid. A major advantage of these converters is that the isolation happens in a high frequency transformer. These transformers are much smaller than the 50 or 60 Hz grid transformers. However, the demand for high power isolated DC/DC converters is recent. There are not many types on the market (yet). At this moment, the technology is mainly pushed by the electric vehicle market for fast charging. The assumptions for the grid converters are shown in Table 2.

Table 2: Assumed grid converters based on manufacturer data. The DC/AC conversion step consists of one large 1 MW unit, the DC/DC conversion step consists of several parallel 75 kW units.

	Parallel modules	**Efficiency**	**Weight [kg]**	**Size [mm]**
DC / AC	1	97 %	180	375 x 505 x 924
Isolated DC / DC	14	98.5 %	50	496 x 502 x 174

2.2.2 Transformers

There are transformers in the AC distribution grid. In the conversion step from the DC propulsion grid to the 440 VAC distribution grids there are four 1250 kVA transformers through which all the load on the distribution side is supplied. Then, on a lower level, every load centre is connected through one or two transformers which ensure the right voltage and an additional level of galvanic isolation. Some of the consumers are connected to the 440 VAC grid directly, so their loads only flow through one of the four large grid transformers. For the DC case, it is assumed that 20% of the loads still need to be connected to AC by means of an inverter and a transformer. Table 3 shows the assumed efficiency and weight (including cabinets and LC filter) of the transformers based on manufacturer data. The total footprint (including space around it) of the 1250 kVA grid transformer is assumed to be 9 m^2.

Table 3: Transformers in the AC and DC distribution cases

Voltage	**Efficiency**	**Rating**	**Weight**	**Amount (AC)**	**Amount (DC)**
115 VAC	98.5 %	30 kVA	275 kg	4	0
		20 kVA	230 kg	8	0
230 VAC	98.5 %	100 kVA	575 kg	2	0
		60 kVA	450 kg	4	0
		40 kVA	300 kg	4	0
		20 kVA	230 kg	4	4
		5 kVA	100 kg	8	0
440 VAC	98.5 %	100 kVA	575 kg	4	0
440 VAC	97.5 %	1250 kVA	3850 kg	4	0

2.2.3 Cables

The cables that connect the DC distribution switchboards to the main switchboard can be laid directly from the DC/DC converter (which is in the switchboard of the main grid) to the distribution grids. The cables in the AC case first go to the transformer and then to distribution switchboards, meaning they are longer. The assumptions based on manufacturer data are shown in Table 4.

Table 4: Cable parameters for the AC and DC distribution cases

	AC primary	**AC secondary**	**DC distribution**	**unit**
Length	40	10	40	m
Area	120	50	95	mm^2
Number of parallel conductors	8	9	7	
Resistance at room temp.	387	387	193	mΩ/m
Nominal current	240	153	209	A
Weight	4.85	2.17	3.76	kg/m
Efficiency at rated power	96	96	97.6	%

The cables are sized for the nominal power. For the analysis, the operational power is used. The conductor temperature dependent resistance, $R(T)$, of the cables is considered as follows:

$$T = T_0 + dT\left(\frac{I}{I_{nom}N_p}\right)^2$$

$$R(T) = R_0(1 + \alpha(T - T_0))$$

where T_0 is the ambient temperature, dT is the maximum allowable temperature difference, I is the conductor current, I_{nom} is the conductor current, N_p is the number of parallel conductors, R_0 is the resistance at ambient temperature and α is the temperature coefficient of copper. The nominal current is derived from the nominal power of the distribution grids.

2.3 Consumers

For every consumer, an assumption is made to which voltage point it is connected. With this information it is possible to determine the distribution efficiency per consumer for the AC distribution case. To find the distribution efficiency for the DC case, it must be known which consumer connects to which voltage. To make a generalization for the consumers, they are grouped as follows:

- motors,
- heaters,
- lighting,
- rack equipment and
- general equipment.

An assumption of the amount of consumed power during operation per group is shown in Figure 2. The grid components are sized for the nominal power.

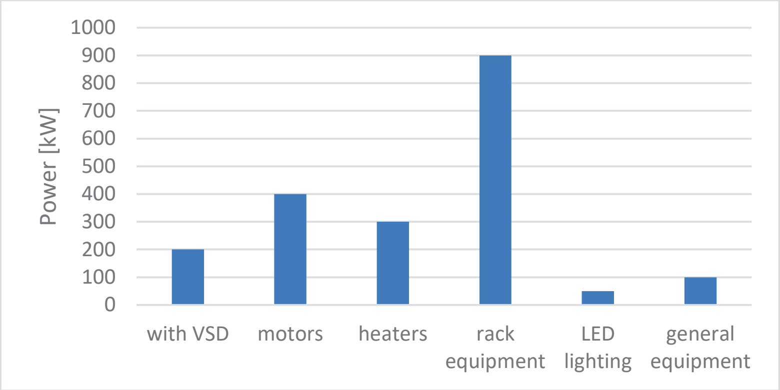

Figure 2: Assumed operational power use of the use-case. Rack equipment which includes weapon and radar systems.

In this section, every group is addressed. For every group it is discussed if it is possible to connect it to DC and what the implications and assumptions are.

2.3.1 Motors

Motors are either connected through a Variable Speed Drive (VSD), a Direct On-Line (DOL) or a soft-starter. For the AC case, most of the motors are connected with a DOL or soft starter. For the DC case, all the motors need to be connected with a VSD, which adds more losses. Connecting a VSD to DC is more efficient than to AC. For AC, the voltage is first rectified to DC, and then a three-phase variable frequency voltage is created. When a VSD is connected to DC, the rectifier step can be bypassed. An efficiency of 97.5 % is assumed for a VSD that is connected to AC and 98.5 % for a VSD that is connected to DC. DOL's and soft starters are assumed to have an efficiency of 100 %.

2.3.2 Heaters

A large part of the consumers consists of heaters which are used in HVAC, water treatment or other auxiliary systems. In this research, it is assumed that all the heaters are able to be connected to DC. On a technical level, this shouldn't be a problem. However, in practice it means that the suppliers of the systems that use heaters should reconsider their designs.

2.3.3 Lighting

The general lighting on the ship is LED. A LED driver is connected to the 230 VAC which converts the 230 VAC to a 24-48 VDC that powers the LEDs. A LED driver has a typical efficiency of 85 %. In the case of a DC distribution grid, the LEDs can be connected directly to the local 24 or 48 VDC connection points without LED driver losses (USDOE, 2013). The weight and volume of the LED driver are assumed to be negligible.

2.3.4 Rack equipment

A large part of the rack equipment consists of servers which are powered by 400/230 VAC. Datacentres are already moving towards DC distribution grids because the benefits are significant (Sterlace, 2020; Miller, 2016). The power supply cabinets that power other parts of equipment are designed to transform 440 VAC to another workable voltage. These cabinets can be redesigned to transform the 700 V DC voltage to another workable voltage. In this study it is assumed that all the 440 VAC cabinets and racks can be converted to DC. For the 400/230 VAC equipment it is assumed that 20 % still needs to be powered by an AC source.

2.3.5 General equipment

The general equipment category consists of bakery, galley, laundry, workshop, office etc. For this equipment it is assumed that most of it can be turned into DC by ordering specialized equipment. 20% of this load is still considered to be 400/230 VAC.

2.4 Results

Table 5 shows the results for the weight comparison between the AC and DC grids. It can be seen that most weight is saved due to the lack of grid transformers. The need for more converters adds more weight to the DC grid.

Table 5: Results of the weight comparison.

	AC [tons]	**DC [tons]**	**Difference [tons]**
Grid transformers	15.40	0	15.40
Small transformers	11.01	1.15	9.86
Cables	6.99	4.21	2.78
Drives	0.72	3.28	-2.56
Sum	31.65	8.89	25.48

The power dissipation in the AC and DC distribution grids is shown in Table 6. The results are based on the load profile which is defined in Figure 2. The DC distribution system is more than a factor 2.5 more efficient than the AC distribution system. The savings make up ~5% of the total power for a specific mode of operation.

Table 6: Losses in both the AC and DC distribution grids and loads.

Total power [kW]	**Losses AC [kW]**	**Losses DC [kW]**	**Savings [kW]**
1950	156	63	93

The lack of distribution transformers also has an impact on the total footprint of the distribution system. It is expected that an extra area of 36 m2 is available because of this. However, the extra drives which are needed in the DC distribution system are expected to take up to 8 m2 of space. The volume and area savings for the rest of the components is found to be insignificant.

3. Earthing considerations

Earthing plays an important role in an electrical installation. It influences its safety and functional behaviour. The choices may benefit one aspect but deteriorate another. That is why it is important to have a clear understanding of what influences earthing. Only if all impacts are known, it is possible to weigh pros and cons to make the best choice. This chapter discusses the most significant aspects related to earthing. Three different main aspects of earthing can be identified:

- Protective earthing, to prevent that accessible non-live parts can have a dangerous potential due to fault conditions, static electricity or leakage currents.
- System earthing determines whether a live part of the installation is connected to earth and where the protective earth is connected to earth in the system. In a Terra Neutral Separate (TN-S) system, the neutral point, midpoint or minus is connected to earth and the Protective Earth (PE) conductor is connected to that point. In an Isolated Terra (IT) grid, there is no intentional connection between a live part and earth, the PE conductor is locally connected to earth.
- Electro-Magnetic Compatibility (EMC) earthing or equipotential bonding.

3.1 Electrocution

Electrocution risks should be minimised by the proper application of insulation materials and protective earthing. The safest configuration of a DC network if a person would come into contact with a live conductor depends on a few aspects:

- Is there a ripple voltage present on the DC and what is the level and frequency of that ripple voltage?
- What is the capacitance to earth?
- Are there suitable DC residual current detectors (RCD) available?

If there are RCDs available, a TN-S approach is preferred since, in case of a leakage current, the voltage will be switched off immediately. Also, only 50% (2 wire system) or 66.6% (3 wire system) of the power conductors are at a dangerous potential, reducing the chance of touching a dangerous live conductor. In an IT grid all conductors are at a dangerous potential. If there is no RCD available and either the voltage ripple on the grid is low or the capacitance to earth is very low and an IT grid is less dangerous. Since an IT grid has no connection between a live part and earth, there is no obvious current loop created when a person touches a single live conductor. However, there might be filter capacitors connected to earth in the grid, and there will certainly be a parasitic capacitance between the grid and earth. In combination with a voltage ripple (which is usually significantly higher than 60 Hz) this enables a potentially dangerous current. Notion should be given to the fact that for higher frequencies the human body is less sensitive to exposure to currents (IEC 60479-2, 2019).

With high capacitance values, the least dangerous option is the TN-S grid since the chance on to coming into contact with a live conductor at a dangerous potential is smaller. In an IT grid touching any conductor will result in a discharge of all capacitance to earth in that grid.

3.2 Arc flash

From an arc flash point of view, an IT grid is a safer solution. The chance of a fault to earth is significantly higher than a fault between lines. In an IT grid, there is no short circuit in case of a single earth fault. In a TN-S grid there is. This could result in an arc. However, if an RCD is available, the risk is somewhat reduced since such a device should interrupt an earth-fault current within 40 ms if the fault current is 5 to 10 times the nominal current. If a protection system is used that will switch of the voltage before sufficient energy is released in an arc, there is no disadvantage in applying TN-S grids.

3.3 Fire hazard

Fires can be easily ignited by leakage currents even as low as 300 mA (IEC 60755-1, 2022). In a TN-S grid with suitable RCDs this risk is mitigated. Even TN-S grids without RCDs are relatively safe, since an earth fault will often result in a short circuit, triggering the breaker or fuse. IT grids have a higher risk of fire. They are designed to stay operational under single earth fault conditions. If a high enough ripple on the DC occurs and there is sufficient capacitance to earth, the impedance can be sufficiently low to conduct a fault current. This current will flow as long as the earth fault is there, which can be days. Also, faults are often not continuous connections but due to vibration on board. The fault is continuously made and interrupted resulting in sparks since the capacitance between earth and line is discharged every time the earth fault is made and recharged when the connection is broken.

3.4 Availability

The availability of system plays an important role. An IT system continues to be operational under single earth fault conditions, contrary to TN-S systems. So, from continuity of supply point of view it is better to use IT systems. However, an insulation monitoring system should be installed that indicates where the fault can be found, else significant parts of the installation might have to be switched off to localize the fault. Critical systems should not just rely on continuity of supply but should be built with redundant components where each component can be powered from multiple power sources.

3.5 Signature

A naval ship's signature should be minimised including its (electro)magnetic signature. In both grid configurations TN-S or IT, there shouldn't be a DC current flowing through the hull. In a TN-S grid, such a current could flow under single fault conditions if the current is too low to trip a safety device. This is the case for faults with a high impedance. In IT grids there are two faults required. If these faults are in the same line, the currents flowing through the hull could be much higher and no safety device will trip.

AC common mode currents are much more likely to flow through the hull, especially in TN-S grids where filters are applied to control common mode disturbance. In IT grids, the capacitance to earth (in filters) is minimised, but in practice there is still a lot of capacitance to earth enabling AC common mode current to flow through the hull. To summarise, a well maintained, properly designed IT grid, has a smaller signature then a TN-S grid.

3.6 Galvanic corrosion

Galvanic corrosion can be increased where current exits a metal into an electrolyte. DC is known to speed up galvanic corrosion, but also AC has an effect (Bergin, 2015). These currents can be common-mode currents or fault currents though the hull. The grid configuration has influence on the current level through the structural parts and hence on the level of galvanic corrosion.

The aspects that determine the amount of current that flow through structural parts is already discussed in section 3.5, but it is also important where the current flows through the structural parts. Only currents that exits the metal speeds up the corrosion. From that point of view, AC currents are less of a concern because their path is determined by impedance. Especially common mode currents, which usually have a higher frequency, will flow in the smallest loop possible since that path has the lowest impedance. DC currents will concentrate in the path with the lowest resistance, and it is quite likely that the hull is part of this current path since the thick steel offers a low resistance. Both types of grid configuration TN-S and IT could work well under the condition that for:

1. TN-S grids, residual current detectors are applied, if there is a leakage current below the tripping level it is small and the ratio between the resistance of the hull and that of sea water will reduce any current leaving the hull even further.
2. IT grids, earth faults are repaired immediately because two earth faults in the same line can result in very high current levels flowing through the hull and then still a significant level could leave the hull and speed up corrosion.

3.7 Electromagnetic compatibility

Below deck common mode currents are one of the main sources of interference. Capacitors to earth will improve both aspects, with their low impedance for higher frequencies they lower the common mode voltage on the grid and by placing the capacitors in the right positions, the size of common mode current loops can be decreased. To be allowed to use multiple capacitors to earth, a TN-S grid is preferred since in an IT grid the capacitance to earth should be minimised.

4. Conclusions

This paper aims to give insight in the use of a DC distribution grid instead of an AC distribution grid. The gain in efficiency, weight and footprint in using a DC distribution grid instead of an AC distribution grid is quantified. For a particular use-case it was shown that the use of a DC distribution grid approximately saves 93 kW of power, 25 tons of weight and 28 m^2 of space. The biggest difference is because there is no need for AC grid transformers in DC. DC still needs galvanic isolation in the DC/DC converters, but the high frequency transformers are more compact. Many of the loads are expected to be ready to be connected to a DC grid.

Assuming that soon DC RCDs and monitoring devices will be readily available, there is no clear preference for TN-S / or IT grids in general. This does not mean that the topic of power grid configuration is unimportant, but rather that it depends on priorities and additional measures. Table 7 shows the evaluated phenomena related to the grid's topology. "+" indicates if, from safety or reliability point of view, the grid's topology gives a good match with the considered phenomenon and "-" indicates that the match between phenomenon and grid's topology is less favourable.

Table 7: Preferred choice of grid topology

Phenomenon	TN-S	IT
Electrocution	++-	---
Arc flash	+--	+++
Fire hazard	+++	+--
Availability	+--	+++
Signature	+--	++-
Galvanic corrosion	++-	++-
Electromagnetic interference	+++	++-[*]
[*] Under the condition that the applied earth fault insulation monitors can deal with the present capacitance to earth.		

In conclusion, both grid topologies can work satisfactorily if the proper measures are taken to compensate for disadvantages.

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References

Haxhiu, A., Abdelhakim A., Kanerva, S. and Bogen, J., "Electric Power Integration Schemes of the Hybrid Fuel Cells and Batteries-Fed Marine Vessels—An Overview," in IEEE Transactions on Transportation

Electrification, vol. 8, no. 2, pp. 1885-1905, June 2022

Di Piazza, M. C., Luna, M., La Tona, G., Pucci, M., Accetta, A. and Pietra, A., "A New Method for Selecting the Voltage Level for an Advantageous Transition to DC Distribution in Ships," 2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), Nottingham, UK, 2018, pp. 1-5

Dragičević, T., Lu, X., Vasquez, J. C. and Guerrero, J. M., "DC Microgrids—Part II: A Review of Power Architectures, Applications, and Standardization Issues," in IEEE Transactions on Power Electronics, vol. 31, no. 5, pp. 3528-3549, May 2016

Latorre, A., Soeiro, T. B., Geertsma, R., Coraddu, A. and Polinder, H., "Shipboard DC Systems—A Critical Overview: Challenges in Primary Distribution, Power-Electronics-Based Protection, and Power Scalability," in IEEE Open Journal of the Industrial Electronics Society, vol. 4, pp. 259-286, 2023

Xu, L. et al., "A Review of DC Shipboard Microgrids—Part I: Power Architectures, Energy Storage, and Power Converters," in IEEE Transactions on Power Electronics, vol. 37, no. 5, pp. 5155-5172, May 2022

USDOE, March 2013. *Energy Efficiency of LEDs* [online] U.S. Department of Energy. Available from: https://www.osti.gov/biblio/1220089 [Accessed 7 June 2024].

Sterlace, D., February 2020. *Direct current in the data center: Are we there yet?* [online]. Available from: https://www.datacenterdynamics.com/en/opinions/direct-current-data-center-are-we-there-yet [Accessed 7 June 2024].

Miller, R., March 2016. *Google Unveils 48V Data Center Rack, Joins Open Compute* [online]. Available from: https://www.datacenterfrontier.com/cloud/article/11431310/google-unveils-48v-data-center-rack-joins-open-compute [Accessed 7 June 2024].

IEC 60479-2, “Effects of current on human beings and livestock - part 2: Special aspects”, edition 1.0, IEC, 2019.

IEC 60755-1, “General safety requirements for residual current operated protected devices – Part 1: Residual current operated protective devices for DC systems”, IEC, 2022.

Bergin, A., June 2015, Alternating Current Corrosion of Steel in Seawater, Norwegian University of Science and Technology (NTNU).

Enhancing Internal Battle Operations Through the Battle Damage Repair Tool

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Synopsis

In today's maritime industry, the operational environment is undergoing a significant transformation characterized by increasing complexity, smaller ship crews, and more sensor-generated information. As ships become more technologically advanced, the volume of data available to crew members will skyrocket, presenting both opportunities and challenges. Amidst this backdrop, there is a pressing need for streamlined communication channels and efficient data management systems to ensure the operational continuity.

To address some of these challenges, the authors have developed a digital solution within our 'Golden Triangle' of collaboration between knowledge institutions, industry and defence: the Battle Damage Repair Tool (BDR tool). Unlike traditional methods reliant on handwritten notes from defect managers, the BDR tool leverages advanced digital capabilities to streamline the reporting process. By digitizing defect reports and centralizing information in a user-friendly platform, the BDR tool eliminates the inefficiencies associated with manual documentation and enhances shared situation awareness. Now, critical information regarding ship defects is readily available to crew members and directors alike, facilitating swift decision-making.

The research aims to assess the effectiveness of the BDR tool in improving internal battle operations in a high stress environment. The authors have identified several key findings. Firstly, the implementation of the BDR tool has led to the development of the Mobile Support Tool (MST) which will lead to a significant reduction in reporting delays, enabling faster response times to prioritized issues. Secondly, the centralized nature of the tool has enhanced collaboration among crew members, fostering a culture of transparency. Moreover, the real-time accessibility of defect information has facilitated more informed decision-making processes at all levels of the organization. Overall, our research underscores the transformative potential of digital solutions like the BDR tool in optimizing maritime operations amidst an evolving operational landscape.

Keywords: Battle Damage Repair Management, Decision Support, Internal Battle, Lean Damage Control

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1. Introduction

Battle Damage Repair (BDR) on a naval vessel follows the OODA-loop (observe, orient, decide and act) (Geertsma, 2018). After impact an assessment of damage has to be done. Traditionally, this is done by the crew, in buddy pairs, checking each compartment; the so called Blanket Search (BS). In recent years, the Royal Netherlands Navy (RNLN) has adapted this procedure to fit business operation on specific ships (e.g. reduced crew size, lack of redundancy of system specialists or larger ships). However, the RNLN always relies on personnel on the spot to assess damage (incidents or malfunctions). Sensor or operator information can provide useful insights of the ship's status and remaining capabilities quite quickly, but can hardly provide detailed information on repairs required after a significant impact. Sending personnel to damaged compartments will always be part of business operations.

Once a team or specialist arrives at a (potentially) damaged compartment or system, they start gathering information in a structured way. To assure this structure, they use a so-called "5-point brief" to write down observations. All the information on the '5-point brief' is reported to a Defect Manager (DM) in the Engineering Office (EO). Current ships use a phone line or plotline for this. Having multiple teams on a BS- round, the single line of communication acts as a bottleneck and causes delays. To mitigate the effects (people shall only call once), much focus is put in training on first completing the ' 5-point brief', before calling in an incident or malfunction.

The DMs in turn report all damage to their Director, often using a plotline. Limiting here is the speed Directors can process (and write down) information, combined with the DM ability to prioritize information. Finally, the BDR officer combines the information of his or her Directors to the top-3 of most pressing issues at the moment. Hereby focusing in the first stage primarily on 'Command Aim killers'.

The use of digital technology has two distinct, immediately recognizable advantages: crew can share information whenever available and information is readily available for all crewmembers. This forms the starting point for the development of the BDR Support Tool (BDR ST). Section 2 of this paper describes the collaboration between Government, Knowledge Institutes and Industry, the so called 'Golden Triangle', that enabled the flexible and result-oriented development of the BDR ST. Section 3 outlines how the requirements have been drawn up by the knowledge institution and government, which have been implemented and adopted by the Industry (see section 4). Section 5 describes the conclusions and future ideas about the development process of the BDR ST.

2. Result-oriented development in collaboration

The traditional waterfall method, where the customer provides a set of requirements and a budget, only to receive a product several years later, is long gone. The result often ends up being a product that does not quite meet expectations or fails to satisfy revised insights. Furthermore, there are limited opportunities to prevent errors due to misinterpretation of specifications.

A more modern approach is the Agile methodology, which involves iterative work towards a final product. However, it is important to note that the budget is often static, and any changes entail risks. Typically, this means that if something new needs to be added, something else must be removed. This could involve removing a functionality entirely or stripping it down. It is crucial for all parties involved to understand that maintaining scope is vital to prevent an endless implementation cycle. The goal should always remain to develop a product that could add the most value with the minimal required effort. The 'Minimal Viable Product' (MVP) (just enough features to be useable on board a ship by users who can then provide feedback) should be rolled out as soon as possible.

To be flexible and result-oriented throughout the whole development phase it is necessary that government (defence), knowledge institutes and industry, which each of their specific contributions, work closely together. This collaboration, the so called 'Golden Triangle', allows efficiently aligning the strengths and weaknesses of the partners. The 'Golden Triangle' establishes a structural feedback loop. It is essential to clarify who needs to be briefed at what stage to track progress and brainstorm solutions to challenges collaboratively.

The Software is collaboratively developed with three key stakeholders: Defence as the client, Knowledge Institutes for theoretical expertise and specifications, and the industry to build an operational applicable product.

The strongest contribution for Defence in the creation of this product is domain knowledge. A risk is the frequent turnover within Defence. New individuals join a project with different priorities and perspectives on the challenges already addressed. In a development project like BDR ST, numerous such turnovers can occur.

Knowledge Institutes' key contributions are their scientific knowledge and fundamental approach to a problem. This enables a thorough analysis and complete consideration of all relevant factors. The outcome is a set of specifications, to serve as a guideline for implementation. A downside can be the time required and a too theoretical approach to the operational context. The result of the trade-off between writing specifications or documenting all researched alternatives and the rationale behind all decisions, can later lead to incorrect decisions when seeking a more 'efficient' way to implement a particular requirement.

The industry possesses the most knowledge of software development and the potential risks. A risk of the industry is the ambition to be able to re-use the software for a wider target, extending certain features or making certain parts more flexible at the cost of the current projects budget.

The collaboration between these three partners within the 'Golden Triangle' has led to the result-oriented development of a digital tool to manage Battle Damage Repair on board naval vessels; the BDR Support Tool.

3. Requirements decision for the Battle Damage Repair Support Tool (BDR ST)

The current internal battle damage repair procedure is robust and flexible. However, due to the great amount of communication required, there is a significant delay in information flow throughout the hierarchy and the chance of miscommunication is high. Currently, at every location involved in the internal battle damage repair process there is a paper overview to keep track of defects and incidents. The duplication of all these overviews requires a lot of verbal communication, is often messy, stressful, and does not provide any opportunity to connect information sources for technical support or automation. The current process thus poses the risk of providing incorrect or outdated information and advice to the Commanding Officer (CO), increasing the chance of setting incorrect priorities, and decreasing the chance of mission success.

The aim of the BDR ST is twofold: (1) the tool should improve rapid and accurate situational awareness for making the right decision in determining the top-3 ship repair priorities, and (2) to guide the onboard personnel to respond to emergencies to be resolved using the necessary information.

The BDR ST enhances situational awareness for the internal battle, since it supports digitally managing incidents and defects from combat damage. Therefore, the BDR ST facilitates a reliable and quick command advice (see Figure 1). The main goals of the BDR ST therefore are:

1. Coordinating damage assessment (Blanket Search (BS)) after weapon impact;
2. Recording system malfunctions and incidents as a result of impacts, and monitoring the resolution of these defects and incidents;
3. Prioritizing the repair of defects and incident response;
4. Managing electrical isolation in support of incident response;
5. Coordinating the deployment of personnel for incident repairs, incident response and electrical isolations.

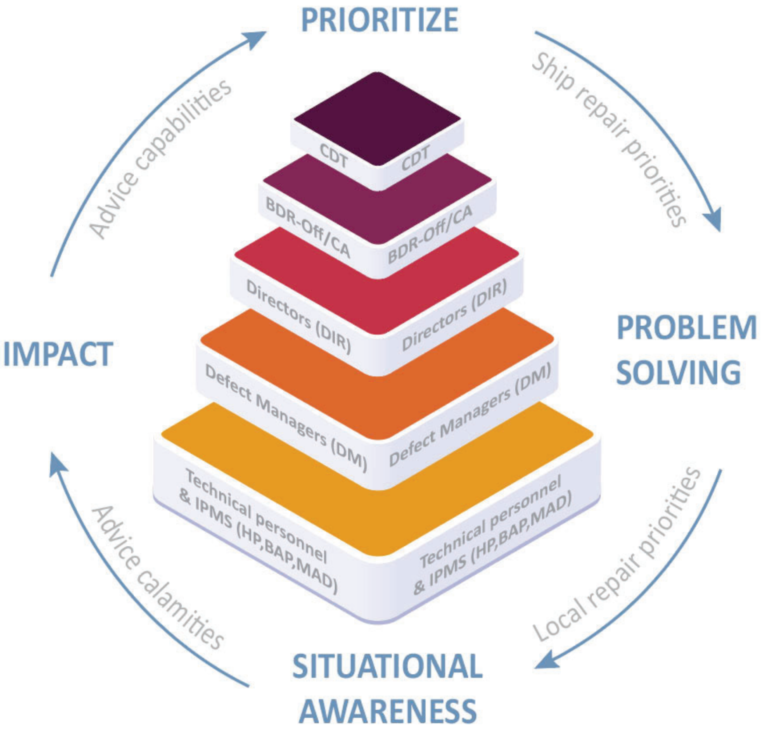

Figure 1: The internal battle repair process: illustration of decision making

In this paper the authors focus on giving more insight in the way the damage assessment is coordinated and managed. The process of collecting system defects and incidents by the BS-specialists has been further studied and specified with and without the use of a handheld device by each crew member. The three main parts to come to these clear requirements includes the approach, the challenges faced and the user tests.

3.1. Approach

The written requirements for the BDR ST have been iteratively developed in a methodology, in which part of the requirements were tested and visualised by prototyping. The knowledge institute TNO, the Defence Material Organisation (nowadays COMMIT) and a representative number of end users were involved intensively, which resulted into approved requirements. All the requirements were stored in Confluence (*ATLASSIAN, Confluence (www.atlassian.com)*), so that it can be used for bringing it in production.

From the beginning the ultimate product should reflect the predefined 10 golden rules. Some of these 10 golden rules are read as follows: (1) the user is always is control, the system should therefore facilitate and should not restrict the user, (2) the system must support business operations, not impose them, (3) the system should be flexible in use, (4) the user must stay informed at all times, (5) speed of entering information is leading.

After an impact on a ship the BS is a process in which the ship is systematically searched for incidents and defective systems by the crew. All irregularities are reported to the Defect Manager (DM). The progress of the BS is important in assessing the uncertainty that remains about the status of the ship and therefore of the situational awareness.

3.2. Workflow

As already mentioned in the introduction, the functionality of the BDR ST is to increase internal situational understanding during damage control. After mapping the system malfunctions and incidents such as fires, flooding and injuries the ship's status is known, increasing the crews situational understanding. The internal situational understanding enables decision making and prioritizing the system malfunctions and incidents, based on the Command Aim. The Defect Managers and the higher echelons (directors, BDR officer, Command Advisor and CO) are involved in this process (see Figure 1). It should be noted that everyone (whether dispersed or not) on board has the same information. The BDR ST makes this possible, because real time information is digitalized and everyone can also expand the tickets with relevant information. Initiating the malfunction-tickets or incidents-tickets can be done by the DM, but also by technical personnel.

At every level, except local, priorities can be set in the system. Each DM had a top-3 tickets, which go one echelon up, where a director combines the top-3 of all his DM's into his own top-three of incidents and malfunctions. The BDR-officer in turn, combines all top-3 from his directors into the overall repair priorities, which the BDR-officer proposes to the Command Advisor and CO).

Once priorities are set, the repair process begins by resolving the overall repair priorities first. The technical personnel will be assigned by the DM to the system malfunction- or incident tickets. The progress of resolving these tickets will also be monitored so that the DM and higher echelon are aware of the progress of the repair process. This is done by means of, among others, the Estimated Time Back on Line (ETBOL).

The BDR ST consist of workstations (fixed monitors) for the DMs and the higher echelon. The technical personnel will be equipped with the handheld, because they have to do their work spread across the ship. The user interfaces are optimized for the role of personnel, so they can immediately see where their responsibilities lie and how they can manage the status of "their" tickets.

3.3. Challenges

Of the challenges during the requirements phase (specification phase), the available hardware was an important aspect. Some users are stationed at a fixed post, while others are expected to gather information by surveying the ship. Depending on the readiness state of the ship, users wear gloves and other protective equipment. The personnel who are surveilling the ship may even carry firefighting equipment or "prop" kits for the first attack of incidents such as leaks and fires. The DM up to the Command Advisor (see Figure 1) will be using fixed monitors, with touch screens, mouse and keyboard. The engineering personnel will be equipped with handhelds, touch screens, and preferably using voice commands. Figure 2 shows possible user interfaces related for fixed monitors and handhelds (Mobile Support Tool (MST)).

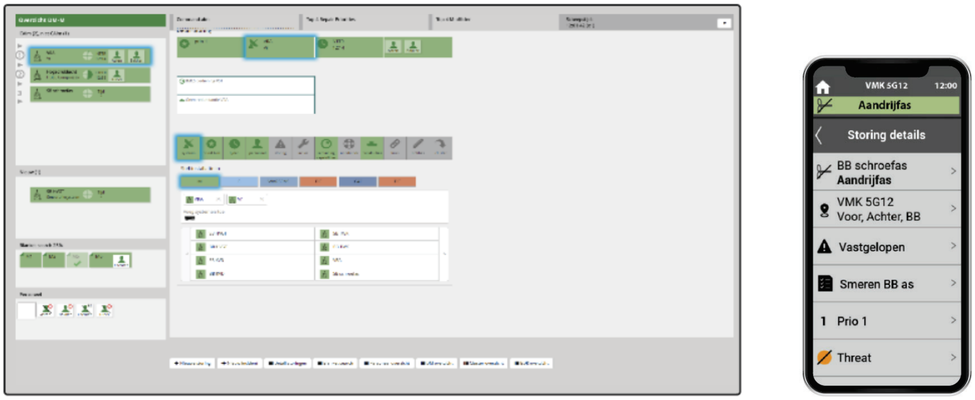

Figure 2: Snapshots (ticket view) of the BDR ST from a fixed monitor and handheld (an example)

The functionalities of the static stations were first investigated, next specified and finally tested before the handheld was included, since the information and tasks on a static workstation are the most extensive. Special attention has been paid to the HMI (Human Machine Interface), including incorporation of communication integration (Voice or Text) and integration with other applications such as an Electronic Incident Board and Automatic Decision Support applications. (Geertsma R.D. and Badon Ghijben N.A., 2014)

Crewmembers performing Blanket Search (BS) must be guided through the ship (from initial predefined known BS route map to flexible route map), the DM and higher echelon want to see the progress of all the BS-routes, and the BDR ST should be fed with all the defects and incidents. All requirements regarding the processes have been established via clear user stories. Examples of visualizations on fixed screens and handhelds were considered, where interaction was an important facet. Tickets should be generated by the BS specialist during the BS with the help of the handheld. The BS specialist, but preferably her or his device, should be aware of its location in the BS route. At any time, the BS specialist can be ordered to do something else by receiving a new command or assignment. A change in tasking must be confirmed. Interactions between crew in the ship and the DM is primarily through the BDR ST, but the mobile support device can also be used for communication by voice. All this, must not distract a crewmember from his most important task, finding, reporting and execute first response actions.

3.4. *User tests*

Before testing the ideas of a digitalised BDR ST, workshops and explorations were held in 2016. The DM-level of the BDR ST (without the interaction with higher echelon or the technical personnel) has been pilot-tested at the Royal Netherlands Navy Engineering Training Centre “Koninklijke Marine Technische Opleidingen” (KMTO) with experienced instructors as users. The focus was on the digitization of the information collected by the Defect Manager and how the information can be optimally presented for the user, in this case the Defect Manager. The results of the test were both positive and constructive. Especially situation awareness of officers increases as all information is readily available for everyone. The stand-alone prototype BDR ST (without the handheld) has been tested by the Zr.Ms. Evertsen crew in an experiment at the end of 2017. In this case the total decision process to come to the top-3 repair priorities by the BDR Officer was tested, based on information and assessment of the Defect Managers and directors. The experiment signaled the need to convert the demonstrator into a usable (integrated) tool on board naval vessels. These have led to the specifications for creating a BDR ST, as drawn up by TNO. Finally, the stand-alone prototype BDR ST including the handheld (Mobile Support Tool) has also been successfully tested by the HNLMS (Zr.Ms.) Evertsen crew in an experiment at the end of 2018. Figure 3 illustrates the successive test and evaluation moments towards the production of the BDR ST.

Figure 3: Evaluation / user test moments of TNO and DMO (COMMIT) during the BDR ST specifications.

After the specification had been sufficiently developed and user tests yielded positive results, the implementation of the BDR ST began. The determination of scope and approach for the implementation is described in the following section.

4. Implementation of the BDR ST

The next phase of the development of the BDR ST is the implementation phase, in which the software is developed. First, scope was determined at both hardware and software level. Subsequently, communication lines were established to ensure that what was specified was created and possible deviations were addressed through proper consultation. How this was done is described in this section.

4.1. *Approach*

After completing the thorough specification, the practical implementation phase could finally commence. Due to financial limitations, this was later than from an engineering perspective would have been optimal. Given the extensive scope of the specification, which encompasses multiple applications, a deliberate strategy was employed to break it down into more manageable segments. This section provides insights into the methodology employed to achieve this segmentation, emphasizing the significance of this approach in navigating the complexities of the implementation process.

4.2. *Determining Milestones*

The overarching objective is to enhance stakeholder engagement on a regular basis. Empowering training centers to contribute their insights on the readiness of the software for training purposes accelerates the progress towards the goal. One pivotal milestone is to enhance the software's functionality to a level where it can seamlessly integrate into a demonstration setup at the training centers, encouraging active participation in the process. Another critical milestone involves preparing a version capable of engaging the training center students actively, facilitating practical training sessions leveraging the demonstration setup. The final milestone before reaching the Minimal Viable Product (MVP) is a version that enables the crew to start using it. The MVP will be considered successful once the software can be deployed operationally.

4.3. Where to begin

As previously mentioned, the specification encompasses two major applications: a desktop application for the DMs and higher echelons, and a mobile support tool application for engineers. Both applications share a considerable amount of functionality and data, thus they will share a backend. During the requirements phase, it became evident that the initial focus would be on the Engineering office (EO), where various defect managers administer and prioritize defects and incidents. Therefore, it seemed logical to commence development here, since here the base of the process is preformed; collecting and managing ‘5- point briefs’.

Within the desktop application, there is a vast array of functionalities to choose from. To make decisions about which functionalities fit within the milestones, significant cuts were made. Priority was given to building a shared situational understanding: capturing the current situation as comprehensively as possible to determine priorities for resolving the issue.

The MVP constitutes of ticket creation, prioritization and personnel deployment. With this functionality, a complete BS would not be directly supported. Instead, the results of the blanket search could be utilized to create a shared situational awareness. All ‘5- point briefs’ generated from the blanket search can be logged and prioritized, allowing for the assignment of personnel accordingly.

After defining the scope of the MVP, the method for feedback to ensure seamless communication could be established. In the next section this feedback loop is covered.

4.4. Future Proof architecture

Transitioning from a paper-based process to a digital system involves more than just digitizing forms; it requires rethinking the entire architecture to support scalability, flexibility, and integration. The BDR ST had to be designed to handle increasing demands, Future integration with various applications, and react to real-time events. This chapter explores the technical challenges involved, focusing on microservices architecture, event sourcing, virtualization and Kubernetes, and data redundancy.

4.4.1. Microservices Architecture

The BDR-ST adopts a microservices architecture, breaking down the application into smaller, independent services. Each microservice handles specific functionality, allowing for greater flexibility and scalability. However, this shift introduces challenges such as managing inter-service communication, ensuring fault tolerance, and orchestrating distributed transactions.

4.4.2. Event Sourcing

Event sourcing is implemented to capture every change as an immutable event, enabling precise state reconstruction at any time. This approach, while providing a comprehensive audit trail, requires careful management of large event volumes, consistency across services, and handling the evolution of event schemas.

4.4.3. Virtualization and Kubernetes

Virtualization is crucial for resource efficiency and scalability. Containers are used to standardize the environment across different deployments, while Kubernetes (www.kubernetes.io), automates the management and scaling of these containers. This setup, however, brings challenges such as complex configuration management, security, and ensuring reliable storage.

4.4.4. Data Redundancy

The architecture of the BDR ST incorporates data redundancy through distributed databases, and replication to ensure data availability and resilience. A key challenge is balancing strong consistency for data accuracy with eventual consistency, which enhances performance during peak demand.

4.5. Feedback loop

Within the Industry partner, a development team has been established with various disciplines to develop the different functionalities. Development is conducted using the Scrum methodology in iterations (sprints) of 3 weeks each. During these sprints, work is estimated, developed, and tested. This team is led by a Product Owner who reports to the stakeholders.

Every 6 weeks a stakeholder meeting takes place to demonstrate progress, determine upcoming tasks, and address inquiries from the development team. A software developer attends to ensure transparency regarding the hidden effort in 'simple changes'. Every 13 weeks, the entire ‘Golden Triangle’ convenes. During these meetings, specific features are clarified by discussing the rationale behind them, and the Knowledge Institute can assess if their ideas are becoming reality.

Once the first milestone is reached and enough product is available for practical use, trainers from the Royal Netherlands Navy Engineering Training Centre (KMTO) are added to the working group. As progress moves towards the second milestone, more input is sought from personnel within the training division. Additionally, it becomes possible to undergo certain (adjusted) training sessions using the software. As the final milestone approaches, it becomes increasingly important to actually train crew members. Trainers can gather feedback and share it in the stakeholder meetings. It is crucial to ensure that the scope remains broad enough to be genuinely operationally deployable at all times.

After a certain foundation of the BDR ST was established and the process became digitally available, various ideas for automation and opportunities for more efficient manpower management emerged. These opportunities will be addressed in the following section.

5. Conclusions and the way forward

What is currently set with the MVP is merely a foundation that is already usable for operational deployment. The desktop application of the MVP needs to be expanded to the full application in order to, for example, support the full-fledged blanket search but also to gain insight into and utilize capabilities and the command aim. Additionally, the mobile application for the technicians also needs to be fully developed.

As result of the MVP of the BDR ST, the following conclusions may be drawn in general:

1. Verbal communication reduces;
2. Quicker distribution of information;
3. Minimal chance of mistakes and miscommunication;
4. Simplification of the BDR management process becomes possible;
5. A tool can be created that is as easy to use as the current paper process.

The MVP of the BDR ST applications was not so much intended to reduce manpower but rather to reduce stress and communication during the mapping of the current situation. When all information is available for everyone, it is much easier to assist a colleague who is struggling and get him or her back on track. A downside is that is also enables micromanaging. Directors must be aware of this risk and focus on their role.

5.1. Adding automation and intelligence

Working digitally, even at MVP level of software, automation can easily be applied. For instance, automatic ticket generation based on platform alarms, and with a command aim integration, they could even be prioritized to a certain extent. Integration with other applications, such as *smart rooms* or *indoor positioning* can ensure that incident tracking, for example, happens integrally. An overall process optimization made possible by utilizing smart room and location tracking is a dynamic BS.

When it becomes possible to partially automate building the shared situational awareness, it brings the possibility of making the BS dynamic. Instead of going through predetermined routes and determining whether there are defects or incidents to report per room, the system, with the help of smart rooms, can determine which rooms do not need attention, thus generating a shortened route and forming a overview more quickly. With every crew member's location known using an indoor positioning system, the routes can be further optimized by sending crew who are closer.

5.2. Enhance collaboration

Throughout the process the value of close cooperation between the Defence, Knowledge Institutes and Industry has proven valuable. The flexibility and result-oriented approach provides the best possible product for crews on board. In future projects, it is foreseen to further intensity the cooperation and integrate the specification and development phase. For this project, the decision was made to initially elaborate on the specification and then allow the industry partner, in consultation with the Navy, to cherry-pick an MVP.

In future projects, the specification will consider staged delivery, enabling potential MVP definition at an earlier stage. This approach also enables the industry to start development earlier in the process, which enhances collaboration.

References

Geertsma F.D.: "Integration of Battle Damage Repair management in an Integrated Mission Management System", proceedings INEC 2018.

Geertsma R.D. and Badon Ghijben N.A., 'Experiences on implementation of electronic incident boards in the Royal Netherlands Navy', proceedings INEC 2014

Atlassian, Confluence, https://www.atlassian.com/software/confluence

Kubernetes, https://www.kubernetes.io

Improving the internal battle in a navy ship by adding situation awareness by means of using a 3D geospatial model combined with a linked data model of this ship.

Design phase

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Synopsis

Modern Navy ship operations are undergoing significant transformations, marked by three key changes. Firstly, ships become increasingly complex, characterized by advanced systems generating vast amounts of sensor data. Secondly, crew sizes become smaller, placing greater responsibility on individuals to oversee a multitude of systems. Lastly, as warfare becomes faster, naval forces are compelled to make quicker decisions in response to rapidly changing and complex situations. Consequently, there is a pressing demand for integrating information from diverse sources and providing clearer, comprehensive overviews to facilitate decision-making.

In the event of a calamity, it is crucial to rapidly assess the impact of the calamity on the ship's capabilities. This study introduces an innovative approach for enhancing situation awareness of the situation inside navy ships. By employing 3D geo-information and a knowledge graph we evaluate the consequences of calamities on the operational capabilities of the ship.

We construct a detailed 3D model of both exterior and interior parts of a ship using three dimensional geometric data, which includes static elements such as rooms, (weapons) systems, and cable & pipe networks. This model also contains logical data describing functionality and interconnectivity of the physical objects in the ship. To do this, the data elements are connected through a linked data approach.

In this research project the 3D model will be used in two key ways: firstly, to generate a realtime 3D common operational picture of the "internal battle" that visually represents the calamities and their impacts in 2D, 2.5D and real3D, all representing the same situation; secondly, as a 3D computational model equipped with a comprehensive set of business relating events in the ship. This model enables realtime assessment of calamity impacts using data gathered from sensors, personnel, and systems throughout the ship, to be used in a 3D decision support system. Data from smoke and temperature sensors are integrated with the static 3D model, as are simulated positions of personnel. Users can choose their own views (depending on their roles) but can also continue with the already existing views of other users. A view of the ship is shown in Figure 1.

The conclusion is that a knowledge graph in linked data and a 3D representation of the same ship in realtime will give a basis for better decision-making. The effectiveness of this approach is tested with personnel from the Royal Netherlands Navy with data and models of one navy ship. The current state of the project is that the spatial and semantic relationships, the different visualizations, and interfaces have been developed. This first paper will report on the design of all this, the scientific approach and the first results of user testing.

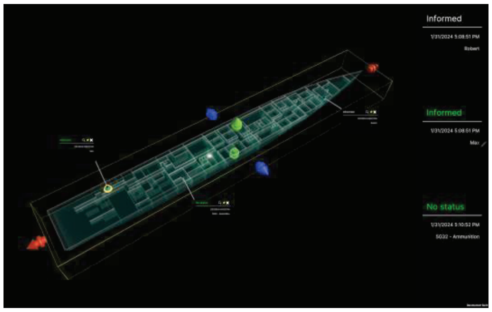

Figure 1: 2.5 D visualization of the internal ship (Voûte & Smit, 2024)

Keywords: Situation awareness; Indoor 3D; Linked data; Navy vessel; Realtime modelling; Marine systems; Lean Damage Control

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1. Introduction: Introducing 3D decision making in the internal battle of a navy ship

In the current ships of the Royal Netherlands Navy decisions for the internal battle are not based yet on any 3D digital systems. In most of the ships an Electronic Incidents Board is being used for battle damage assessment, displaying all decks from a top-down perspective. The spatial awareness is something that takes place in the imagination of the users and has so far proven to be acceptable. As ships will increasingly use multi-skilled minimal crews, meaning there is less personnel available for dedicated roles, it is important to research the potential improvement of the Situation Awareness (SA) by adding real 3D digital support, including Augmented Reality (AR) decision support. Command and control needs to be maintained at all times, but at the same time the smaller size of the crew means the increased value of the human factor. Can this one person rightly apply for all roles, given the support of IT in this highly dynamic environment?

The system (furthermore named as Proof of Concept) that is being built for research is based on a type of modularity. Not one hull for many ships but one general computational model that can be applied to many types of ships, based on semantic data and computations. The visualizations follow the ship itself, but are being taken from the same synchronized datasets. At startup the systems reads in all data and configures itself. This Proof of Concept will be used to test the adoption 3D by measuring the changes in the amount of Situation Awareness.

2. Research goals: the first part of measuring the effects of 4D decision support

This paper is part of a larger study researching the added value of three-dimensional data on board of navy ships. The research goal for this paper is to assess the added value of three-dimensional data for calamity control in the ‘internal battle’ by using a multi-dimensional information system. This information system combines a computational model with a visualization model, with the aim of supporting human operators in the process of situation assessment. The research uses the situation awareness model of Endsley (1995) as a basis, while extending on navy-focused human factor research such as the work of Post et al. (2014) and Tate et al. (2022).

The focus in this research will be on the added value of presenting multiple (4D) dimensions by an information system. The first dimension relates to text, tables and schematics. The second dimension relates to 2D geographic coordinates, for example a floor plan representation of multiple decks. The third dimension relates to 3D geographic coordinates, such as an integrated 3D model of the ship. The fourth dimension relates to time.

The research question is the following:

To what extent does Situation Awareness (SA) increase in the internal battle in times of calamities by integrating system components of a naval vessel into one four-dimensional spatial information system?

The main question is split into three sub-research questions that will be answered during the study:

1. *From which elements do you build a four-dimensional spatial information system of a naval vessel in order to be able to determine the impact of a calamity on the ship?*
2. *In what computational ways can you combine these elements in a four-dimensional spatial information system to gain a better understanding of the impact of a calamity on the ship?*
3. *In what ways does it help the construction of Situation Awareness to represent a calamity in a ship in a user interface that consults the three-dimensional spatial information system?*
    a. *How does a 3D representation of the ship contribute to the interpretation of a calamity on board a naval vessel compared to the usual 2D visualisations?*
    b. *How can you get to level 2 of Situation Awareness (comprehension) with these elements at any point?*

The first and second sub-questions relate to a conceptual and a computational model, while the third sub-question relates to the visualization model and the interpretation of the information system by human operators. The result section will provide insights into the creation of the three aspects of the proof of concept. See Figure 2.

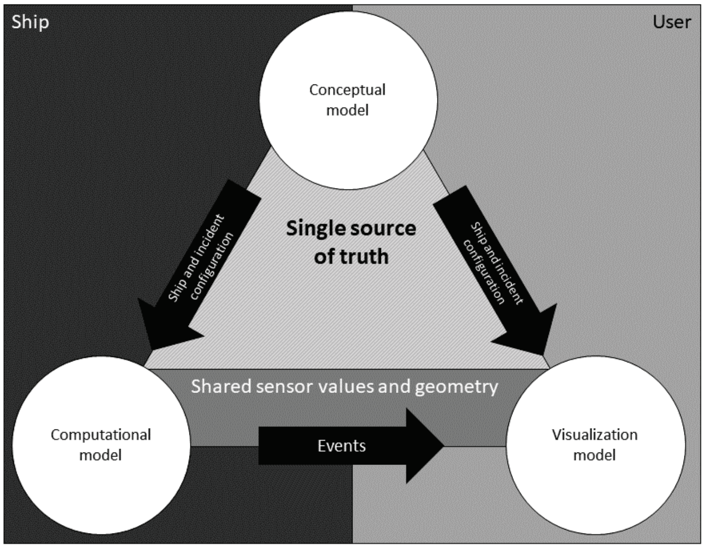

Figure 2: Connection between conceptual model, computational model and visualization models (Voûte & Smit, 2024)

3. Methods

To test the research question, a proof of concept has been developed. The purpose of the proof of concept is to design a conceptual model of the ship and to combine this with a computational model and with a visualization model. The conceptual model and the computational model will together form one single source of truth, holding information about the state of the ship and insights about potential incidents within. The information from the single source of truth is distributed to the visualization model. Together, the conceptual model, the computational model, and the visualization model will be used for creating situation awareness following the model of Endsley (1995). The method to do this is described below.

First, the purpose of the conceptual model is to describe the ship in data, while testing a linked data approach to relate data entities with hierarchical, semantical and spatial relationships. Several interviews with navy experts are conducted for this purpose. Special focus was given to modelling the ships in a flexible way, in order to use one model for describing multiple types of ships in a similar way. The conceptual model can thereby be seen as a fundamental layer, defining the scope of what can be perceived through data.

Secondly, the interviews will also be used to identify meaningful relationships between ship components, incidents, personnel, and operational systems. By doing so, the aim is to draw incident management reasoning from navy personnel into the information system. By modelling logical reasoning from navy personnel onto the conceptual model of the navy ship, a knowledge graph is created, enabling to draw conclusions from events that occur simultaneously and throughout the ship. These conclusions can subsequently be used to draw attention to important aspects of the ship, and to support human operators in assessing impact of events within the ship. The computational model can thereby be seen as a reasoning layer, enabling the system to support assessment of situations in the internal battle.

Thirdly, a visualization model will be created by creating visualizations of ship components, personnel, incident aspects, and system components. This is done by creating so-called ‘building blocks’. Building blocks are highly flexible visualizations of data entities that exist in the conceptual model. According to Van der Meer et al. (2018) it helps to have 3D visualizations for detailed and integral indoor incident visualizations, while 2D floor plans are better for maintaining an overview of the situation. Therefore, a 2D/3D toggle will be integrated within the proof of concept. This means that all of the building blocks will also have both a 2D, and a 3D visualization. In feedback sessions, the building blocks are evaluated and incrementally improved by using an ‘optician model’. With this model, this research aims to quickly determine the best visualization of a building block, by incorporating feedback immediately within the feedback sessions, asking the question 'is this better, or worse than before?'. The building blocks are flexible in the way that they can be changed through configuration rather than development on the subjects of 1) colour, 2) transparency, 3) shape (Surface, Volume, point), 4) symbols (outline and filling), 5) actions, 6) states, 7) pop-ups, 8) location (rooms/surfaces/3D points). The visualization model can thereby be seen as a presentation layer, determining the way in which data elements and assessments are presented to end users in order to make the actual decisions to intervene in case of calamities.

4. Results

As presented in this paper the results exist of all the preparations for the tests that will be executed with the Navy crews. A later publication will follow up on that with descriptions of the actual tests, the ways of measuring and the data that came out of those.

4.1. First level of situation awareness: perception

To come to any level of situation awareness about the internal battle of a navy ship, a description of the situation aboard in data elements is needed. As a conceptual model for the ship configuration and describing incidents was not available right off the shelf, a data model of the ship had to be created. One of the sub-goals here was to describe not just one navy ship, but to create a data model structure that can be used across multiple ships with their own configuration, or even different types of navy ships.

4.1.1. Conceptual model

What qualifies a ship as a ship? The Royal Netherlands Navy has many types of ships. In order to describe an internal battle of a navy ship in data, this research aims to present a conceptual model that describes the ships and it's incidents accurately and completely. A ship being a small floating village and it has many functions and properties aboard. This makes it difficult to generate a holistic view on the vessel. In order to view functions, properties and relationships of the ship from different perspectives, the problem was approached from a linked data perspective. This approach enabled to link data sources and ship components together in a meaningful way via a graph structure. To build the graph, the entities needed to describe the ship, in a ship configuration model with the aim of controlling incidents, were identified. Based on interviews with the Royal Netherlands Navy, it was decided to model the ship in four interconnected spaces: ship spatial layout, incidents, personnel, and systems. Then, the relationships between those entities were identified in a hierarchical, semantical and spatial way, as these relations came up frequently when discussing events within the internal battle.

Hierarchical relations

The hierarchical relations help to quickly switch between levels of detail. An example of this is the hierarchical structure of the ship: all Dutch navy ships exist out of two sections (front and back), divided into multiple zones, which are divided into multiple compartments over multiple decks, which are divided into one or multiple rooms. Using this structure allows to quickly draw focus to what is important regarding incidents aboard the ship, and to filter out areas of lesser importance.

Semantic relations

To know what is important, a semantic model is used that reasons about states of singular and/or multiple entities. This was done by translating knowledge of personnel of navy ships into IT, by interviewing personnel and by creating business rules from their insights. The business rules are modelled as triple relationships, connecting two entities via a semantic relation. For example, a single sensor observation does never lead to the conclusion that there is a confirmed fire somewhere in the ship. For this, two separate sensor values (such as an exceeded smoke detection threshold, and an exceeded temperature threshold) are needed. The threshold values for these entities are decided by business rules as well, creating a complex web of interconnected semantic relationships that lead to conclusions that are taken from the ship.

Spatial relations

Leaning on an OGC (Open Geospatial Consortium) standard, IndoorGML version 1.1, (https://docs.ogc.org/is/19-011r4/19-011r4.html) that describes indoor environments in different but coherent ways. It uses both adjacency and connectivity between and among indoor spaces. A included duality makes it possible to use both at the same time, describing one space on several ways at the same time.

Finally, our research uses spatial relationships to draw conclusions on what is important to decide on. For this, two spatial relationships are recognized: connectivity, and adjacency. Connectivity reasons about explicit relationship, for example that two rooms that share the same door are connected for personnel routing. These relationships can be modelled explicitly in the data model as well, by creating direct links between two physical entities. Adjacency is more abstract, as it depends largely on interpretation what is adjacent. For example, two rooms that are next to each other but do not share a door can be regarded as adjacent. However, an explosion that happens somewhere within the ship may well have a larger impact on the ship than just the rooms that are next to each other, depending on the power of the explosion. This is why adjacency often is defined via spatial buffers, that can be dynamic of size.

Physical data

Entities describe the ship in a conceptual way. The hierarchical, semantic and spatial relations are applied on the entities to understand relationships between entities better. However, a spatial description was still needed to describe the ship in a physical way: the way in which the entities are physically represented in the ship, what states they are in, and what events are occurring in the ship.

- Physical representation: An example of this is the many rooms that are present in the ship, each with their own place in the ship, their own function and systems, and their own 3D room layout. As implicit spatial relationships about adjacency can't be modelled in the knowledge graph structure, a separate tabular geo database was used that holds the spatial properties of the ship. This database can be easily queried on spatial properties, such as distance calculations from a certain point in the ship. This geo database is linked to from the linked database, to still hold the benefits of the hierarchical, semantic and connectivity models.
- Sensor data: Many sensors collect a lot of data points within the ship, which is difficult to store in a linked data in a performing way. This is why sensor data is stored in a separate tabular sensor database as well, which makes it more easy to create levels of detail in the sensor database and search for exceeded value thresholds. The sensor database holds information such as states of doors, valves, smoke levels, and electrical distribution.

4.1.2. Preliminary conclusion

By using business rules to monitor the current situation aboard, the system knows what is happening, and where it is happening. It was found that the business rules can be used up to a certain extent to indicate why a state is reached, for example in the situation where both temperature and smoke detectors are triggered. This gives some insight into the situation. Also, preliminary tests with the navy have indicated that the linked data model describes the situation aboard completely, with enough detail, and in a flexible way. It was noted the hierarchical, semantical and spatial relations within the computational model help immensely with creating insight on the internal battle, describing the situation, and drawing conclusions. It is even possible to use these insights to partially predict the impact of incidents on the operational capabilities. An example of this is that the effect can be predicted of a fire in a room on the electrical distribution that runs through cables in the ceiling of that room, and to warn of an upcoming outage of connected operational systems.

4.2. Second level of situation awareness: comprehension

Although it was observed that it is possible to describe a situation in data and draw conclusions, it would go too far to state that the situation is fully understood in the computational model. For more complex situations, a human operator is still needed in order to interpret the situation and fully comprehend the situation and its operational consequences. To test the value of 3D relations in the description of the ship, a visualization model was built: can the proof of concept to be used by a team of navy vessel operators? The proof of concept is aimed on facilitating personnel in the 'technical control room' of the ship, where incidents are managed in accordance with the current command aim of the ship.

The visualization model heavily relies on the accompanying computational model, as the computational model provides one single source of truth about describing the ship. The visualization model can be used on multiple clients, which can run on a variety of devices. To test the value of 3D spatial relationships fully, both regular 2D screens and 3D holographic projections are used to visualize the entire visualization model in 3D.

4.2.1. Views

Although the data about the ship is fully 3D, it doesn't mean that all of the views on the model have to be 3D as well. Within this studies, the idea derived from Van der Meer et al. (2018) that 3D is good for detailed and integral views was strengthened, while also strengthening our idea that 2D views are good for creating quick overviews of a situation. By using 2D and 3D views of the ship alongside each other, it is possible to provide both the details and the overviews that are needed to manage the incidents efficiently and effectively.

It is also possible to present data in other ways compared to geographic visualization, such as by generating text, schematics, and instructions. These presentations of data were not tested within this research project, and offer opportunity for further exploration of the subject.

4.2.2. Flexible building blocks

3D models give the opportunity to view a navy ship as a whole in one integral view. However, this comes with a risk of information clutter and information overload. Clearing the visualizations are therefore key, which should draw attention to the right aspects of the situation. A model of the ship including the systems within the ship and incident information (such as fires and boundary cooling) has been made.

Preliminary results indicate that it helps to be able to vary in the visualization of different elements within the ship, especially if configured together with navy personnel.

4.2.3. Multiple Devices: one uniform user interface

Multiple interfaces have been tested on usability and interpretability. Special interest was drawn to holographic interfaces, to view digital data of the ship blended with a physical working environment. This follows the hypothesis that people work together better in a physical environment, even when relying more and more on information with a digital source.

To enable testing of this hypothesis, a similar interface is built for both a Microsoft HoloLens 2 and traditional 2D screens. The HoloLens is controlled via gestures, while the screens can be controlled via both keyboard and mouse, as well as via a touchscreen. The screensize is dynamic, enabling for switching from tablet/laptop sized devices to a large 65 inch overview screen. This enables for dynamic setups for test environments.

To deliver a unified user experience to users on different devices, a user interface has been implemented with a uniform look and feel. The interface displays information in 3 dimensions: 3D, 2D, and text. The user interface supports various views, such as switching from 2D to 3D views.

For data interaction, popups on various objects are implemented, giving detailed information about the various components in the ship. Furthermore, a 'view selector' widget has been created to filter data related to the data spaces that are presented in the ship, respectively related to spatial configuration (decks and zones), Incidents, personnel, and systems.

4.2.4. Shared situation awareness

In the navy ship, the internal battle is managed not by a single person, but by a team. In this way, incident managers can share tasks to manage incidents more effectively, for example focusing on managing specific damage to mobility systems or defensive systems. Having a shared level of situation awareness is essential here, as multiple users are collaboratively managing aspects of one situation. The information system can run on multiple instances simultaneously to facilitate this team-oriented way of working. During the development phase of the proof of concept, two principles for facilitating team situation awareness have been identified:

1. As the shared instances are meant to only act as an interaction and visualization model, all data elements are fed through the single source of truth that is hosted in the computational model. If information is added to the system by a user, that information is added to the computational model and distributed from there.
2. As all users have their own information need, they can set their own filters to create their own dedicated view from the overall data source. However, sometimes quick it is important to share a specific view with the rest of the team. To facilitate this process, users are able to share their personal screen to a shared team screen to share their observations and plans with the rest of the team.

5. Conclusions

For the conclusion we focus on the two aspects of the demonstrated four-dimensional information system. First, the computational model will be discussed, then the visualization model.

5.1. Computational model

The computational model proves beneficial in describing the internal battle in data elements. According to the expert interviews we have conducted, the model describes the data elements of the internal battle completely. This leads to believe that the computational model is able to reach the first level of situation awareness as described by Endsley: perception. To reach the second level of situation awareness, we need to be able to connect the data elements in a meaningful way. With the proof of concept a linked data approach proved to create meaningful relations between data elements, while being flexible in choosing between hierarchical, semantical and spatial relations. This enables to model complex relationships between entities in the ship, such as the relation between sensor readings (smoke and temperature), leading to the conclusion that a fire has started in a certain room, endangering a specific electricity cable that facilitates the working of a specific operational system (such as a radar system). As was agreed with the Royal Netherlands Navy, it was concluded that aspects of the second level (comprehension) of situation awareness were met by the computational model.

5.2. Visualization model

For the visualization model it is more difficult to conclude on certain levels of situation awareness reached. With the building blocks it was proven that all aspects of the internal battle can be visualized in both 2D and 3D. This enables to view the aspects in detail and in an integral view in 3D, while also offering a clear overview of the situation in 2D. However, further testing is required to assess whether human operators are able to perceive all aspects of the internal battle which are relevant for them, and if they can bring these aspects together to gain understanding of the situation.

6. Discussion and recommendations

The research that this paper reflects on is still ongoing. There are several improvements that are still to be made. These improvements are thought to be in two main aspects of the research, namely the testing strategy and the temporal component of situations.

6.1. Testing strategy

For this paper we have focused on testing individual building blocks in group sessions to discuss merit and improvement points. In future research we will focus on testing integrations of building blocks into incident scenarios. We will do this with individuals first, after which we incrementally improve the information system. Finally, we will test the improved information system with groups of users to assess the extent to which shared situation awareness can be reached. For this, the SAGAT technique will be used during the tests, in combination with user interviews which happen after the tests.

6.2. The fourth dimension: time

Currently we are able to present information about the current situation via text (one dimensional), floor plans (two-dimensional) and in a 3D model (three-dimensional). For incident management, the temporal component of a situation is a large aspect of knowing why things happen as they happen. This means that it is not just important to know what is happening in the moment, but also what events have led to the current situation and for how long certain elements in the situation have been present. This includes both looking back at a situation, and looking forward at projections of a situation into the near future.

Due to time constraints this functionality wasn't ready in time for this paper, leaving a research gap for future research.

References

M. Endsley, "Toward a theory of situation awareness in dynamic systems." human factors journal 37(1), 32-64", Human Factors: The Journal of the Human Factors and Ergonomics Society,vol. 37, pp. 32–64, Mar. 1995. doi: 10.1518/001872095779049543.

Meer, T. van der., Verbree, E., Oosterom, P. van,: "Effective cartographic methods for assisting tactics choice and indoor deployments during building fires – a casestudy the Dutch fire brigade", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Delft, Netherlands, October 1 – 5 2018.

Post, W., Schreurs, J.C., Rakhorst, M., Badon Ghijben., N.A.: "Human factors in operational maintenance on future naval vessels", 12th International Naval Engineering Conference and Exhibition, Amsterdam, Netherlands, May 20 – 22 2014.

Tate, A., Purvis, E., Froom, C., Jaya-Ratnam, D.: "The UK's Intelligent Ship project – Exploring Future Human-Machine and Machine-Machine Teaming", International Ship Control Systems Symposium 2022, Delft, Netherlands, November 8 - 10 2022.

Dynamic potential of naval nuclear power generation: modelling of a high-temperature reactor with a supercritical carbon dioxide power conversion cycle

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Synopsis

There is a renewed interest in nuclear power generation within the maritime sector as a low-emission power source. As other renewable sources or alternative fuels contain a lower energy density than conventional fossil fuels, and the energy demand of naval vessels will rise due to implementation of unmanned assets and direct energy weapons (DEW), a problem occurs for the limited volume onboard of a naval vessel. Nuclear power generation could play a supplementary role due to its high energy density, while improving the duration of the vessel and thus enhancing operational flexibility and strategic autonomy.

The generation IV very high temperature reactor (VHTR) was selected for implementation due to its enhanced efficiency, safety and relative high TRL compared to other generation IV reactors. The combination with the high efficiency and compact sizing of a supercritical carbon dioxide (sCO_2) Brayton power conversion cycle, could produce an economically, social and technical feasible option for nuclear power generation.

Nuclear energy is however commonly used as a stable power source, and therefore the question arises if nuclear power generation can provide the dynamic power transients common to a naval vessel. By proposing a novel dynamic model of the nuclear reactor, its power conversion cycle and the vessel itself, the paper investigates the dynamics of a nuclear vessel and determines if implementation of nuclear energy is technologically feasible.

With the proposed model, the transient speed of the nuclear power plant will be compared to conventional prime movers of naval vessels, specifically the diesel engine and gas turbine. Three different control scenarios were analysed; (1) transient reactor control, (2) constant reactor power with dynamic bypass control, and (3) constant reactor power with bypass and additional cooling for reactor temperature management. Results indicate that operating the reactor in transient mode will limit the system dynamics to the dynamics of the reactor, which were deemed not sufficient for power transients in naval vessels. Keeping the reactor at constant power output therefore limits the system dynamics to the bypass in the secondary cycle, but this control method is capable of achieving power transients up and equal to gas turbine level. However, it requires additional cooling of the reactor to prevent a temperature increase within the reactor. Dynamic limitations with this control method do not occur due to the nuclear power plant installation, but by the limitation in the operating envelope of the electric motor. Final results also indicate that fixing the reactor power output to its maximum and thus providing maximum thermal input to the secondary cycle, while operating the secondary cycle itself at part load, significantly lowers the overall plant efficiency. The overall plant efficiency can be improved by modulating the reactor output to match the demand of the secondary cycle, but this again limits the system dynamics to the dynamics of the reactor.

The paper therefore concludes that a VHTR with a sCO_2 Brayton cycle is a promising option for nuclear power generation in naval vessels. With appropriate control strategies and safety measures, nuclear systems can match the dynamic performance of conventional propulsion and power generation systems. Further research should however be committed to improving cycle efficiency at part load and enhancing safety evaluations before nuclear power generation could be deemed a feasible option for naval nuclear power generation.

Keywords: Nuclear power generation; nuclear propulsion; high temperature reactor; supercritical carbon dioxide power conversion cycles; dynamic modelling; power simulations.

Authors' biographies

Sub-Lt (E) Tom Wien is a Naval Officer who graduated in 2022 at the Netherlands Defence Academy for a BSc. in Military Systems and Technology. He is now finishing his MSc. in mechanical engineering at Delft University of Technology, focusing on Energy, Flow and Process Technologies. In his MSc. thesis, he focuses on the dynamic power behaviour of a nuclear power plant installation for implementation on naval vessels. After his thesis, he will finish his Officer's training at the Royal Netherlands Naval College institute and will serve as Technical Officer on the vessels of the Royal Netherlands Navy.

ir. Gert-Jan Meijn is currently the innovation lead for marine and electrical systems at the Research Development and Innovation department of Damen Naval. He received his BSc. and MSc. in mechanical engineering at Delft University of Technology in 2013 and 2015 respectively. In his current role, he is responsible for identifying new technology, initiating innovation projects, and ensuring that new technology is embedded in products and future projects. Experiences in previous roles include the concept design of propulsion plants, vessel performance evaluation, simulation of system dynamics, and the development of novel control algorithms. His research interests include the development of future power and propulsion systems, holistic system simulation, control systems, energy management and sustainable power generation.

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1 Introduction

Nuclear power generation has recently gained increasing interest within the maritime sector in the Netherlands and Europe. According to the Dutch maritime sector policy report ”No Guts, No Hollands Glorie!” 2023, nuclear energy can help reduce dependency on fossil fuels and provides a potential high-energy density source for ships without emitting carbon dioxide (CO_2). One of the project goals is to develop a standardized, modular nuclear reactor for ship integration within 10 years Dutch maritime sector (2023). The resurgence of interest in nuclear power generation for maritime applications comes at a crucial time when the global shipping industry is aiming to reduce its environmental impact.

Due to the implementation of unmanned assets and direct energy weapons, it is expected that energy usage on naval vessels will not decrease in the coming years Royal Dutch Navy (2023). However, renewable energy sources, like wind and solar, and alternative fuels, like methanol, have a lower energy density compared to conventional fossil fuels van Zalk and Behrens (2018) U.S. Department of Energy (2024). An increasing energy demand while energy density is decreasing results in an energy mismatch problem, presenting an issue for the volume limited environment of a vessel. Nuclear energy could play a major role in solving this issue, as it offers one of the highest available energy densities.

In addition, operational advantages of nuclear power generation arise for naval vessels, as sufficient power for long operation times can be guaranteed. As a result, nuclear vessels can ensure high vessel speeds without losing operational endurance. Operational flexibility is improved compared to conventional vessels, as nuclear ships can respond to crises quicker and can operate longer with fewer logistic support, improving the strategic autonomy of the operator U.S. Department of the Navy and Department of Energy (2015).

Nuclear power generation has been implemented in military ships, such as aircraft carriers, submarines and cruisers by several countries, and has been implemented on merchant vessels like icebreakers and cargo ships, although successes differ significantly Freire and de Andrade (2015). Despite previous usage of nuclear power generation, implementation of the technology in future vessels will present challenges, especially for countries not possessing this classified technology. As nuclear reactors typically operate as stable constant power sources, which contrasts with the fluctuating power demands of (naval) vessels, issues could arise in providing the dynamic power profile of the vessel. To determine the possibility of nuclear power generation as a replacement of conventional fossil fuels, the power dynamics of a nuclear power plant installation must be assessed.

This paper investigates a) the dynamic possibilities of a nuclear power plant installation on a naval vessel, and compares it to dynamics of conventional prime movers of a naval vessel, and, b) indicates potential safety issues during power dynamics of such a power plant and provides preliminary solutions to ensure safe operation. The paper proposes a novel power plant model for dynamic power simulations of a nuclear reactor, its power conversion cycle and the vessel’s propulsion system.

In the investigated scenarios, the modelling results demonstrate the power transients that can be achieved with different control methods and which considerations should be made to realize optimal power transients for the nuclear power plant installation. With the proposed modelling strategy, the dynamic possibilities of a nuclear power plant are determined, and additional insights at system level are obtained for further cycle designs.

Lastly, the power transients are projected on a notional frigate design, based on the work of Geertsma (2019), analysing the impact on ship performance. Noting that the requirements for power transients on board of naval vessels are increasingly demanding due to new (direct energy) weapon and sensor technology, this paper also aims to demonstrate the competitiveness of nuclear technology with respect to the conventional prime movers.

2 System description

Nuclear power plants function by using the heat released during nuclear fission inside a nuclear reactor. This heat is converted into mechanical power by means of a thermodynamic power cycle such as a Rankine or a Brayton cycle. Depending on the application, this mechanical power is used directly (e.g. direct mechanical propulsion) or converting the mechanical power first into electrical power using a generator. There are different types of reactors and possible cycle configurations for nuclear power generation, but the most common type of reactor is the pressurised water reactor (PWR). PWR technology is used in over 70% of all operable land based reactors, as it is used in 307 out of the 437 worldwide reactors in 2022 World nuclear association (2023). The typical cycle efficiency of such a power plant (from thermal power to electrical power) is around 33% IAEA (2023), but this depends strongly on the specific type of reactor.

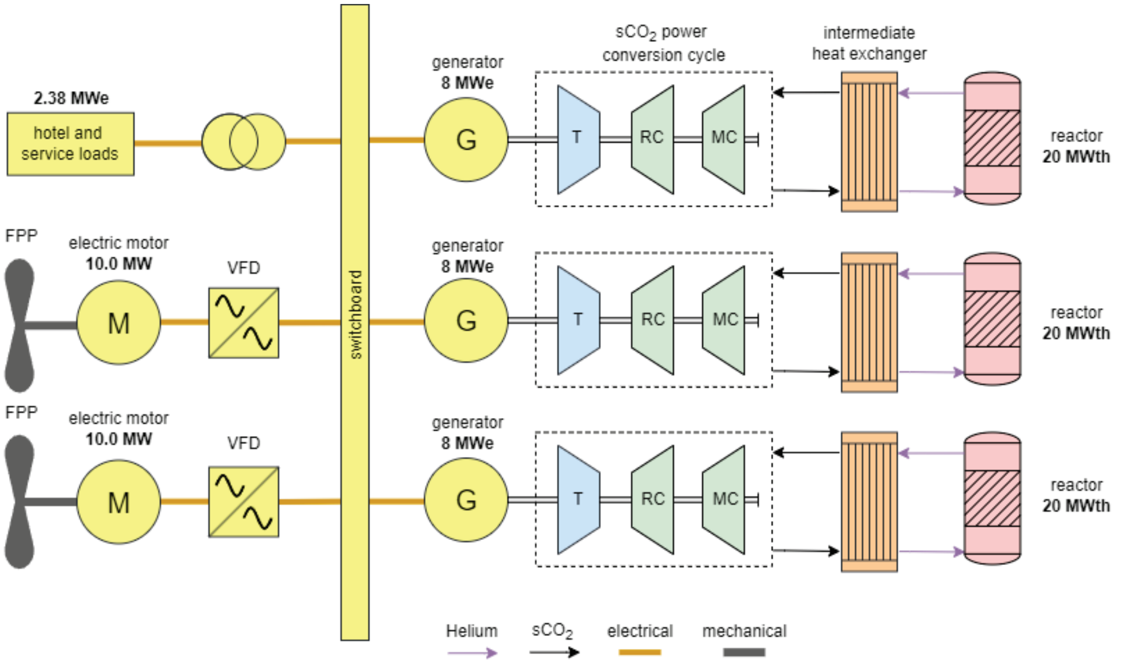


Figure 1: Schematic overview of the electric propulsion plant fed by multiple nuclear power generators

2.1 *Ship overview*

To determine the dynamic potential of a nuclear power generation system, integration within a naval vessel should occur. For this research, the vessel proposed by Geertsma (2019) was implemented as a preliminary design choice, representing a notional frigate. The design values of this vessel are presented in Table 1. A full-electric propulsion system is proposed, with two large propulsion electric motors driving fixed pitched propellers. The nuclear power generation is split in three individual generator modules (3 x 8 MWe), which together provide power to both the propulsion (2 x 10 MW) and to the vessel's hotel and service loads. The resulting electric propulsion plant is presented in Figure 1, of which the nuclear reactor and its power conversion cycle will be further explained in the sections 2.2 and 2.3. With the current sizing, the installed power is sufficient to fully utilize the propulsion motors and approx. 2+ MWe of hotel and service loads. The notional frigate can reach a speed of 26+ knots.

2.2 *Propulsion choice*

As reactor, the generation IV very high temperature reactor (VHTR) Zohuri (2020) was selected for implementation. The VHTR is a graphite-moderated reactor operating on the thermal neutron spectrum. Its design focus in on maximizing safety and thermal efficiency, the latter by having a high outlet temperature between 700°C and 850°C Zohuri (2020). The reactor applies the TRISO layered particles with UO$_2$ kernels Olander (2009) IAEA (2023), which has been specifically made for the high temperature environment of the VHTR. The selection of a

Table 1: Design values of the notional frigate

Parameter	Value
Ship length [m]	135.0
Displacement [tonnes]	5400
Type of propulsion	Full electric
Max. speed [knots]	26+
Propeller type	2 x FPP (Wageningen C5-75)
Propeller diameter [m]	4.90 m
Propeller pitch (P/D) [-]	1.450
Nuclear power generators [MWe]	3 x 8
Propulsion motors [MW]	2 x 10
Propulsion motor speed [RPM]	120 (nom.) / 135 (max.)

VHTR is contradicting with the fact that historically almost all the nuclear propelled reactors on board of vessels apply pressurized water reactors (PWR) as energy source. However, the potential of the VHTR regarding a more efficient Olander (2009)Zohuri (2020), passive safe Zohuri (2020), economically feasible Steigerwald et al. (2023) and relative high technology readiness level (TRL) compared to other gen. IV reactors Gen IV International forum (2014), provides the question if PWRs will be used solely on nuclear vessels in the future.

Naval vessels are permitted to use highly enriched uranium (HEU) in contrary to merchant vessels which can only use low enriched uranium (LEU) fuel, containing an enrichment up to 20% of U-235 World nuclear association (2023). Still, it was decided to implement a LEU fuelled reactor for naval applications as nuclear proliferation risks are reduced and the potential for naval and merchant collaboration towards nuclear vessels remains possible.

Supercritical carbon dioxide (sCO_2) is an attractive fluid for a nuclear power conversion cycle implemented on a naval vessel due to its attractive properties in supercritical state. Above the critical point (73.9 bar and 31.1°C), CO_2 has a liquid-like density, while still having a gas-like viscosity, which ensures power production is more efficient and compact Marchionni et al. (2019). The volume on a (naval) vessel is limited compared to land based applications. The amount of volume needed for sCO_2 turbomachinery is less than other types of turbomachinery. Ming et al. (2023) state that at the same power level, the sCO_2 Brayton cycle is only one-tenth in size compared to the steam Rankine cycle. Further on, at higher turbine inlet temperatures, corresponding to the temperature range of a VHTR, the cycle efficiency of sCO_2 is higher than any other working fluid Wu et al. (2020). Experience with nuclear vessels shows that economics are crucial for successful nuclear ship design Freire and de Andrade (2015), which are improved with a higher cycle efficiency. A higher cycle efficiency also results that less fuel is needed for the same amount of energy production, ensuring that the amount of nuclear waste decreases, improving public trust in this technology. Finally, the lower shaft and turbomachinery inertia of the sCO_2 cycle, compared to turbomachinery of other fluids Michael A. Pope (2006) Carstens (2007), could turn beneficial for dynamic power behaviour.

2.3 Cycle design

Implementation of a VHTR within the simulation requires a sufficient developed reactor design. The 10 MWth U-battery was therefore selected, as Atkinson et al. provide the required design parameters within their research Atkinson (2018) Atkinson et al. (2019a) Atkinson et al. (2019b) Atkinson et al. (2021) Atkinson and Aoki (2024). A single 10 MWth reactor will not provide the required power output for typical naval applications, so it was therefore decided to combine two single 10 MWth U-battery as power source for one power conversion cycle, resulting in a 20 MWth power source for a single power conversion cycle. An overview of the generic U-battery is presented in Table 2. Additionally, a cross section of the reactor is presented in Figure 2, showing the various layers of the reactors, the flow path through the reactor, and a general indication of the outer dimensions.

Table 2: Design values of the U-battery Atkinson (2018)

Parameter	**Value**
Reactor type	VHTR
Neutron spectrum	Thermal
Core layout	Prismatic
Moderator	Graphite
Coolant	Helium
Fuel type	UO_2 (TRISO)
Capacity [MWth]	10
Inlet temperature [°C]	400
Outlet temperature [°C]	750
Pressure [bar]	40

Although developments are still ongoing towards the optimal sCO_2 power conversion cycle, the indirect recompression cycle is deemed the most efficient cycle configuration while being relative simplistic Dostal (2004) Carstens (2007) Brun et al. (2017), and was therefore selected as the first tested cycle design configuration. The indirect nuclear sCO_2 recompression cycle designed for naval power generation is presented in Figure 3.

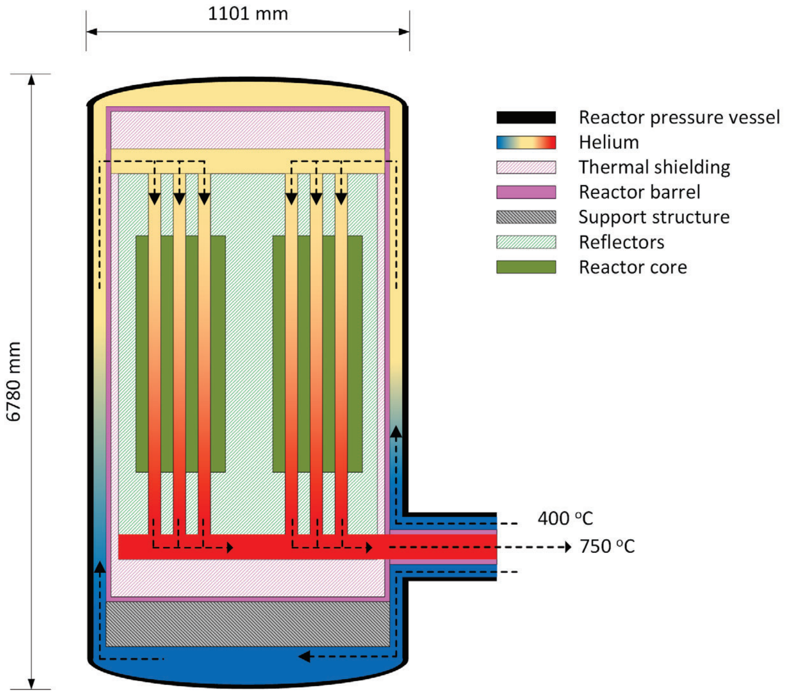


Figure 2: schematic cross section of the U-battery based on Ding et al. (2011), design values and sizing taken from Atkinson et al. (2019b) - **note:** figure not drawn to scale

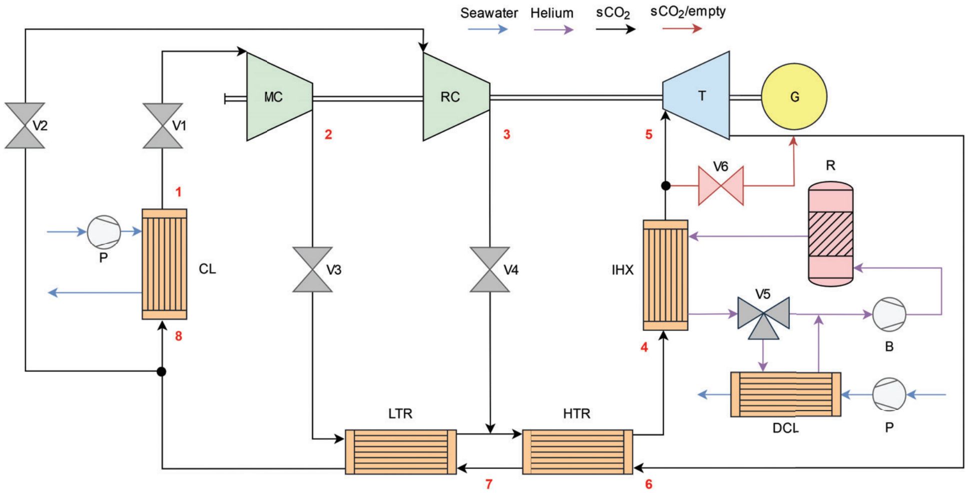


Figure 3: Schematic overview of the designed recompression cycle with a nuclear reactor

The recompression cycle applies a nuclear reactor (R) as heat source, using helium as working medium. This heat will be transferred by the intermediate heat exchanger (IHX) to the sCO_2 cycle. The sCO_2 cycle applies a single stage turbine (T), but adds another separate compression stage, resulting in a main compressor (MC) and a re-compressor (RC). This turbomachinery is all connected to a single shaft, applying a Turbine-Alternator-Compressor (TAC) configuration, which also drives the generator (G). For optimal cycle efficiency, two recuperators will be implemented after each compressor, resulting in a low and high temperature recuperator (LTR and HTR). A cooler (CL), and an optional dump cooler (DCL), must be implemented to transfer waste heat from the cycle to the seawater. While cooling using an intermediate fresh water circuit would also be a valid option, especially given the high pressures and integrity requirements of the sCO_2 cycle, the choice for a seawater cooling loop has been made for the sake of simplicity and reducing the overall number of (intermediate) heat exchangers. The primary loop (reactor loop) and the cooling loops also need an additional pump (P) or blower (B) to ensure sufficient mass flow and pressure within the system. Further on, for dynamic power control multiple valves are present within the system. Throttle valves are placed before and after the compressors (V1-V4) to maintain pressure within desired limits, a three-way valve (V5) is implemented to control mass flow going through the DCL and a bypass valve (V6) is placed around the turbine for load control.

All the heat exchangers within the power conversion cycle are wavy channelled printed circuit heat exchangers (PCHE). This is a widely chosen heat exchanger type for (nuclear) sCO_2 power conversion cycles due to its high efficiency Olumayegun et al. (2017)Jiang et al. (2018), capability to withstand high pressures and temperatures Carstens (2007)Wang et al. (2021) and being relatively small compared to other heat exchangers (compared to a shell and tube heat exchanger it needs only 20% of the volume for the same heat load capabilities Ming et al. (2022)). PCHEs also have faster thermal dynamic responses, due to their lower mass and higher heat transfer coefficients compared to shell-and-tube heat exchangers Deng et al. (2019), which makes them beneficial for naval implementation.

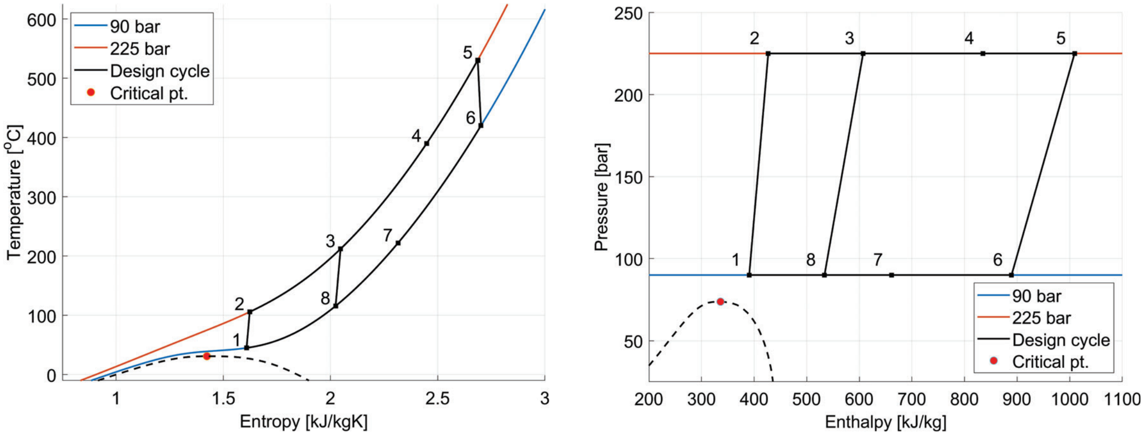
Before testing the dynamic behaviour of the recompression cycle, specific design conditions must be selected. The results of this cycle design are presented in Table 3 and Figure 4 Wien (2024). This cycle design is based on the following approach. Firstly, the lower cycle pressure is fixed at 90 bar, as this ensures a sufficient margin is realised from the critical point of CO_2. The characteristics of the selected turbomachinery result in a pressure ratio of 2.5, resulting in a high cycle pressure of 225 bar, which is within pressure limits of a sCO_2 power conversion cycle Olumayegun and Wang (2019). To ensure that the notional frigate design can operate globally, a seawater inlet temperature of 35°C was selected as the worst case scenario Seatemperature.org (2024). Furthermore, a terminal temperature difference (TTD) for the heat exchanger must be selected, which was assumed to be equal to 10°C for all heat exchangers Olumayegun and Wang (2019). Although a smaller TTD could be beneficial for cycle design, this would increase heat exchanger sizing.

Only a full cycle design for implementation on a vessel could determine if additional heat exchanger sizing is permissible, and therefore identification of the optimal TTD balance is not considered in this work.

Table 3: Design values of the power conversion cycle Wien (2024)

Parameter	Value
Working fluid	Supercritical carbon dioxide (sCO_2)
Cycle type	Indirect recompression
Turbomachinery type	Radial/centrifugal
Thermal power [MWth]	20.0
Electrical power [MWe]	8.0
Efficiency [%]	40.0
Shaft speed [RPM]	20,000
Cycle pressure [bar]	90–225
Cycle mass flow [kg/s]	114.78
Split ratio [-]	0.71
Seawater inlet temperature [°C]	35
Heat exchanger terminal temperature difference [°C]	10

The eight design points, as presented in Figure 4, are determined based on the following reasoning. Thermophysical property databases only require two of the thermodynamic states to be known to determine any other thermophysical property. As pressure is known for each design point, it is only required to determine one other thermophysical property. The sea inlet temperature, and the TTD, provide the temperature in point 1, which is set to 45°C, ensuring fluid conditions above the critical point of CO_2. Design point 2 can then be determined based on the enthalpy difference that results from the performance characteristic of the compressor. The temperatures between point 2 and 8 require a minimal difference equal to the TTD. Repeating this process once again results in the design points 3 and 7. As the U-battery has an inlet temperature equal to 400°C, design point 4 should have a temperature equal to 390°C to account for the TTD. To determine the design points 5 and 6, an iterative process regarding optimal cycle efficiency and energy balance must be applied. For optimal cycle efficiency, the mass flow should be as high as possible, as this increases the power output of the turbomachinery. However, three energy balances related to three heat exchangers should be considered as constraints for identifying the optimal cycle efficiency. Firstly, the IHX must balance the 20 MW_{th} heat input from the reactors with the energy difference between point 4 and 5. Secondly, the energy balance over the HTR, design points 6 and 7 in comparison with design points 3 and 4, should be equal. Lastly, the energy balance over the LTR, design points 7 and 8 in comparison with design points 2 and 3, should be equal. Using these constraints, while focusing on optimal cycle efficiency and implementing the turbine characteristic, results in design points 5 and 6, followed by the cycle mass flow and design split ratio.



(a) T-s diagram

(b) P-h diagram

Figure 4: Cycle design points for the power conversion cycle

3 Simulation model

Within this section, the dynamic model of the components for the sCO2 closed Brayton cycle for nuclear naval power generation is presented. In order to study the transient performance of the sCO2 plant, and its dynamic possibilities, a dynamic model of the whole system needs to be developed. This includes the nuclear reactor, heat exchangers, turbomachinery, control valves, shaft dynamics and the vessel's propulsion system. It is assumed that the impact of piping is negligible on the dynamic possibilities of the power conversion cycle.
In this work, the individual models are created and connected within the Matlab© and Simulink© working environment, of which an overview is presented in Figure 5. Since Matlab© does not have any thermodynamic and transport property functions, CoolProp© was implemented to calculate the thermophysical properties of the fluids. CoolProp© can be used if there are two known thermodynamic properties, so for example the temperature T can be determined if the thermodynamic properties pressure p and enthalpy h are known, which is stated in equation 1.

$$T = f(p,h) \tag{1}$$

3.1 Reactor model

For dynamic power simulations of a nuclear reactor, it is important to simulate the neutronics and the thermal hydraulics of a reactor. Neutronics accounts for the fission process occurring within the fuel, while the thermal hydraulic process explains the process of heat being transferred from the fuel to the helium coolant. To control the fission reactions within the reactor, the control rods can be raised or lowered based on the required power output of the reactor.

3.1.1 Neutronics

The process of fission occurring within the reactor is explained by the neutronics of a reactor. A common preliminary modelling method is applying the so called point-kinetics equations (PKEs). The PKEs assume that the spatial dependence of the reactor can be described by a single shape, removing the spatial dependence of the more general neutron diffusion equation Duderstadt and Hamilton (1976). As a result, the neutron density at each point of the nuclear reactor core therefore only varies with time, ensuring dynamic power changes can be simulated by raising or lowering the control rods of the reactor. The PKEs are presented in equation 2 and 3 in their six-group form Duderstadt and Hamilton (1976) Atkinson et al. (2021), and were validated according to Henryk Anglart (2011).

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{j=1}^{6} \lambda_j c_j \tag{2}$$

$$\frac{dc_j}{dt} = \frac{\beta_j}{\Lambda} n - \lambda_j c_j, \text{ with j = 1,2, ... 6} \tag{3}$$

Here n is the neutron population, which is related to the thermal power of the reactor, ρ is the change in reactivity, β is the total effective delayed neutron fraction, Λ is the prompt neutron generation lifetime, λ is the effective decay constant and c_j is the concentration of a delayed neutron group Atkinson et al. (2021). Based on a reactor analysis within Serpent, Atkinson et al. (2021) provide the required point kinetic parameters for the U-battery. Furthermore, in addition to the PKEs, the model applies a thermal reactivity feedback system based on a temperature change of the fuel rods. This passive safety feature ensures that reactivity will drop as fuel temperature increases, ensuring power output will lower and fuel temperature will stabilize.

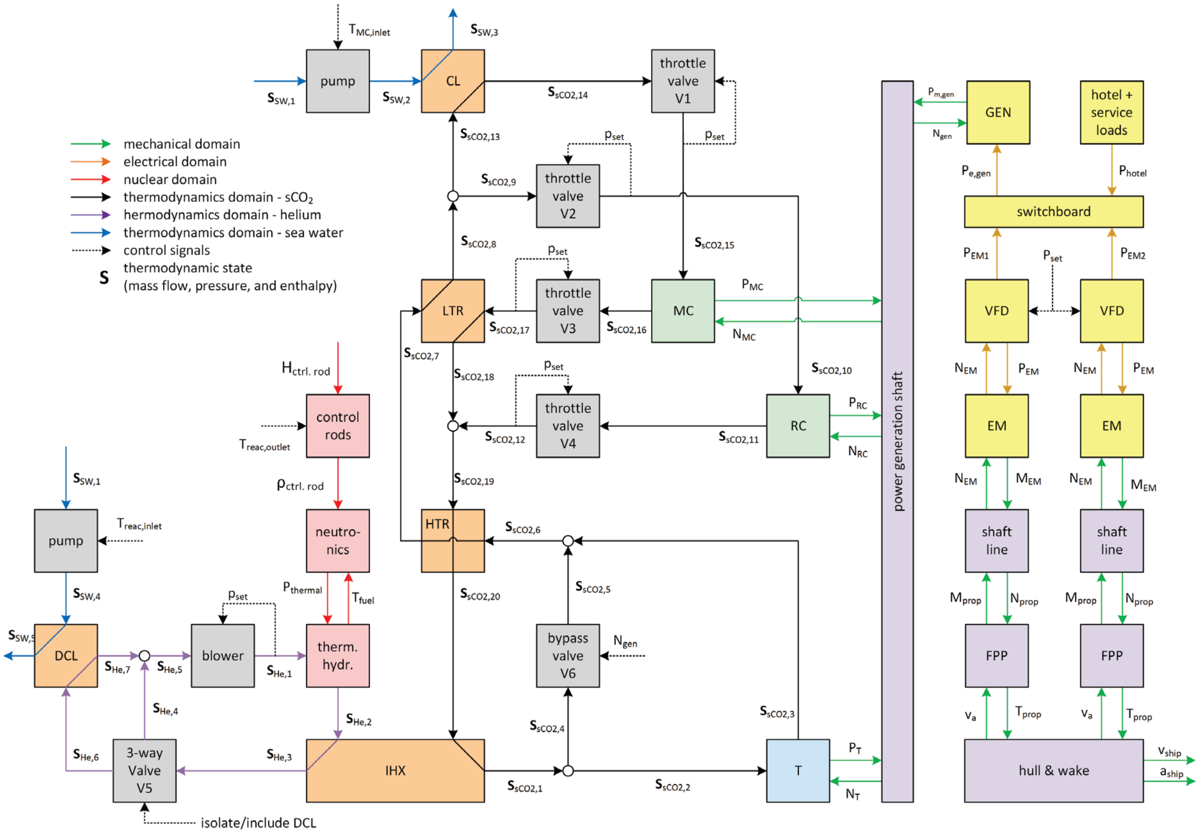


Figure 5: Model overview of the created nuclear naval power generation system

3.1.2 *Thermal Hydraulics*

The heat generated within the fuel must be transferred to the reactor coolant, which occurs through heat transfer between the different reactor components. To simulate this behaviour, a 1D lumped thermal hydraulics scheme was implemented and validated based on the component structure of the U-battery Atkinson et al. (2019b) Atkinson et al. (2021). The structure of the thermal hydraulics model is presented in Figure 6, which is based on the structure of the reactor as shown in Figure 2. Each component (reactor segment) is modelled by applying mass and energy conservation equations, of which an example for the fuel elements is presented in equation 4.

$$M_F C_F \frac{dT_F}{dt} = Q_{reac} - UA(T_F - T_M) \tag{4}$$

Here, M_F is the mass of the fuel elements, C_F is the specific heat capacity, T_F the fuel temperature, Q_{reac} the heat produced within the fuel elements (determined by the PKEs), U the overall heat transfer coefficient, A the heat transfer area and T_M the temperature of the moderator, which surrounds the fuel elements. Within the reactor, conduction is the main method of heat transfer between the reactor components. Only by interaction with the flowing coolant will convection be part of the overall heat transfer coefficient.

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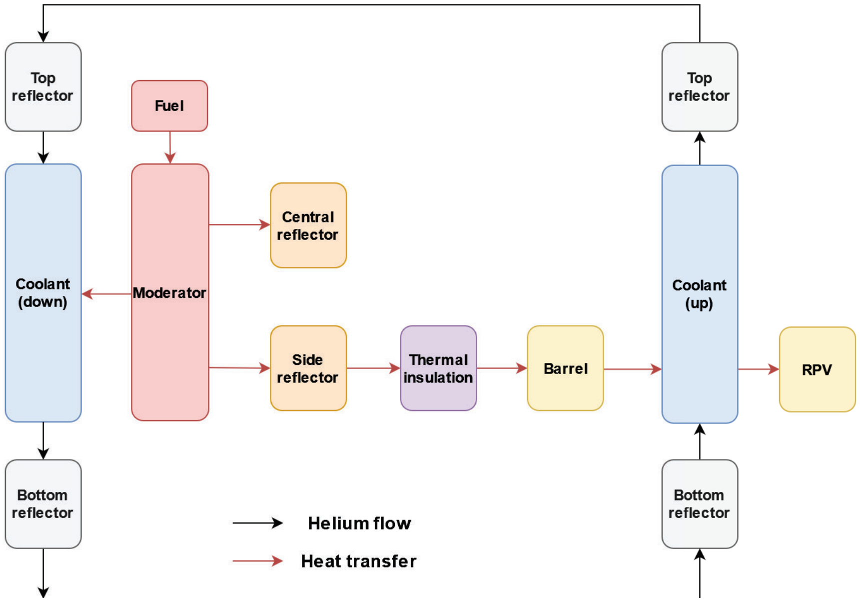


Figure 6: Schematic diagram of the lumped thermal hydraulics of the U-battery

To calculate the overall heat transfer coefficients between the different reactor components, equation 5 is applied Ming et al. (2022). Here, the impact of convection depends on the region in which the fluid operates, which is accounted for by a changing heat transfer coefficient h according to equation 6 Ming et al. (2022). This equation depends on the thermal conductivity k and the thickness t_e of the material, the hydraulic diameter of the channel d_H and the Nusselt Nu number, which is determined by the Gnielinski correlation.

$$\frac{1}{U} = \frac{1}{h_h} + \frac{t_e}{k_w} + \frac{1}{h_c} \tag{5}$$

$$h = \frac{Nu\,k}{d_H} \tag{6}$$

Furthermore, the helium within the reactor flows through channels made within the reflector and hexagonal fuel blocks. As a result, a pressure drop will be realised, which can be calculated according to equation 7. Here, the pressure drop Δp is related to the pressure drop due to a height difference Δh and a friction component. For the friction component holds that the pressure drop depends on the friction factor f, which is calculated by the Petukhov relation, the density of the fluid ρ, the flow speed u, the length of the channel L and the hydraulic diameter d_H of the channel.

$$\Delta p = \Delta p_{height} + \Delta p_{friction} = \rho g \Delta H + \frac{f \rho u^2 L}{2 d_H} \tag{7}$$

3.2 *Heat exchanger model*

To ensure the thermal inertia of the heat exchangers are accurately implemented within the system, it is of importance to construct a dynamic heat exchanger model. It is common to split the model of the heat exchanger into several nodes and apply a 1D finite volume method on only two channels (one hot and one cold) of the heat exchanger. These channels will be separated by the wall of the heat exchanger and will also be divided into several nodes (n) along the length of the channel, to ensure accurate calculations of the thermal properties. The heat exchangers are modelled as a 20 node structure as this results in the best optimum regarding accuracy and simulation speed Wien (2024), and were validated based on the PCHE of Marchionni et al. (2019).

$$M_h \frac{dh_h}{dt} = \dot{m}_{h,i} h_{h,i} - \dot{m}_{h,o} h_{h,o} - Q_{hw,n} \tag{8}$$

$$M_c \frac{dh_c}{dt} = \dot{m}_{c,i} h_{c,i} - \dot{m}_{c,o} h_{c,o} + Q_{wc,n} \tag{9}$$

For the energy balance within the channels, the energy conservation equations 8 and 9 are applied to each node for the hot (h) and cold (c) channel. In these equations h_i and h_o are the enthalpy of the inlet and outlet fluid of each node. Furthermore, M_h and M_c are the mass of the fluid in the hot and cold side of the heat exchanger. The heat transfer between these two channels occurs between the hot channel and the wall $Q_{hw,n}$ and between the wall and the cold channel $Q_{wc,n}$ according to equations 10 and 11. Ming et al. (2022)

$$Q_{hw,n} = U_{h,n} A_{h,n} (T_{h,n} - T_{w,n}) \tag{10}$$

$$Q_{wc,n} = U_{c,n} A_{c,n} (T_{w,n} - T_{c,n}) \tag{11}$$

In equation 10 and 11 the temperature of the fluid in the heat transfer elements ($T_{h,n}$ or $T_{c,n}$) is equal to the average temperature between the inlet and outlet temperature of the node. To calculate the wall temperature ($T_{w,n}$) of the heat exchanger, the energy conservation equation is applied to the wall, which is presented in equation 12 Ming et al. (2022).

$$M_{w,n} C_{w,n} \frac{dT_{w,n}}{dt} = Q_{hw,n} - Q_{wc,n} \tag{12}$$

The overall heat transfer coefficient is calculated based on equations 5 and 6, but this time applying the Gnielinski correlation corrected for a wavy channel for the Nusselt number, as described by Marchionni et al. (2019). The pressure drop along the channels of the heat exchanger can be calculated according to equation 7 Ming et al. (2022) Furlong et al. (2024). Here, the friction factor is calculated according to the Serghides's solution, which is an approximation of the Colebrook–White equation Marchionni et al. (2019).

3.3 Turbomachinery model

Due to the fast response time of the turbomachinery, compared with the heat exchangers and reactor, it is common to neglect the response time of turbomachinery in dynamic simulations Brun et al. (2017)Wang et al. (2021). Therefore, the compressors and turbine are modelled by employing performance characteristic maps for the prediction of the efficiency and pressure ratio, of which the implementation was validated according to Oh et al. (2016). Based on the performance maps of sCO_2 turbomachinery created by Oh et al. (2016), presented in Figures 7(a-d), a normalization approach results in the needed performance maps for the designed power conversion cycle. However, as the performance maps are created by specific inlet conditions (pressure and temperature) and dynamic simulations could result in different operating conditions, and thus different turbomachinery performance, a correction equation must be applied to justify the use of the performance maps. Due to the real gas properties of CO_2, and the significant changes in thermophysical properties especially near the critical point, the correction equations created by Pham et al. (2016) were implemented. As a result, the performance maps can be used according to equations 13 and 14.

$$\pi = f_{map}(\dot{m}_{corr}, N_{corr}) \tag{13}$$

$$\eta = f_{map}(\dot{m}_{corr}, N_{corr}) \tag{14}$$

Here, the corrected mass flow $\dot{m}_{corr}$ and the corrected shaft speed N_{corr} are used to obtain the pressure ratio π and efficiency η of the turbomachinery. The pressure ratio ensures pressure at the outlet of the compressors and turbine can be determined. Furthermore, enthalpy h at the outlet of the turbomachinery can be calculated according to equations 15 and 16 Alsawy et al. (2024). Here, the isentropic enthalpy h_{isen} can be determined according to equation 17, which uses the fact that for a reversible process entropy s is constant.

$$h_{C,o} = h_{C,i} + \frac{h_{C,o,isen} - h_{C,i}}{\eta_C} \tag{15}$$

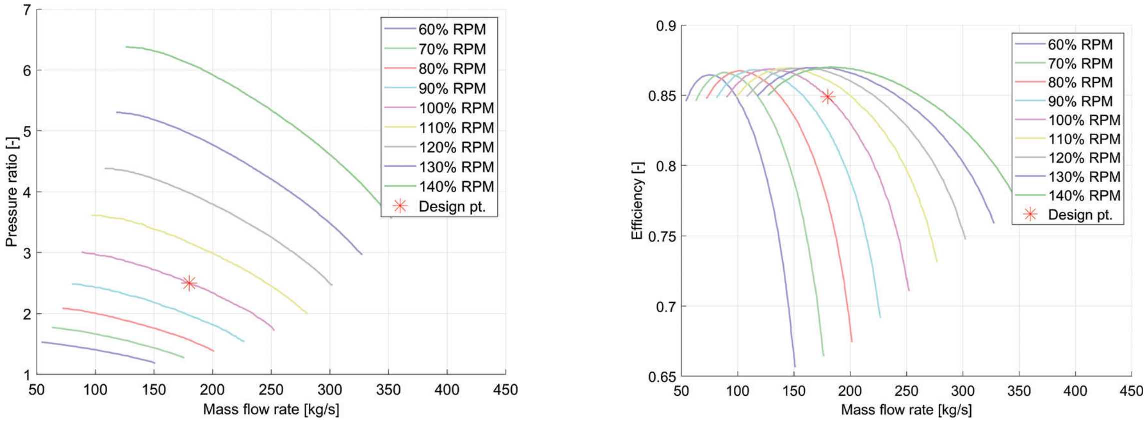
$$h_{T,o} = h_{T,i} - \eta_T (h_{T,i} - h_{T,o,isen}) \tag{16}$$

$$s = f(h_i, p_i) \rightarrow h_{o,isen} = f(s, p_o) \tag{17}$$

Finally, the total power produced/consumed by the turbomachinery can be determined according to an energy balance over the system, which results in equations 18 and 19 for the compressor and turbine respectively. Here, the power P of the system is calculated according to the mass flow $\dot{m}$ going through the system and the enthalpy difference between the inlet and outlet.

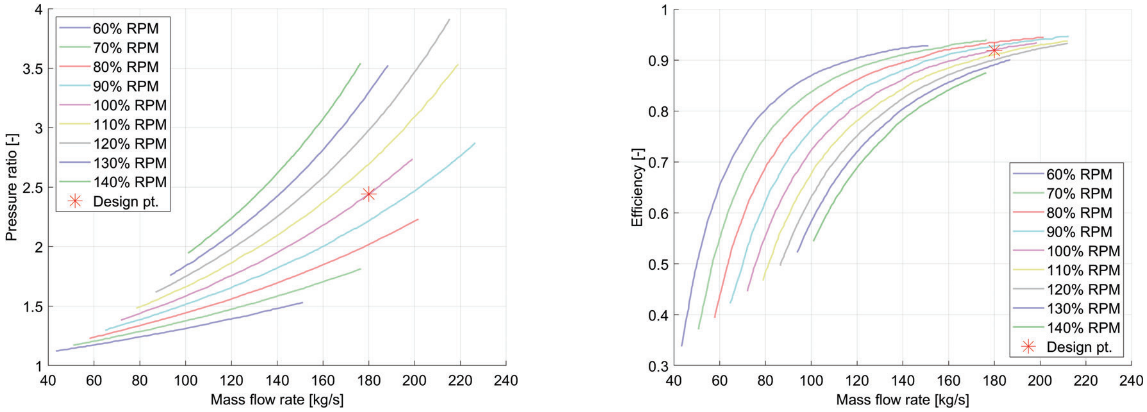
$$P_C = \dot{m}_C (h_{C,o} - h_{C,i}) \tag{18}$$

$$P_T = \dot{m}_T (h_{T,i} - h_{T,o}) \tag{19}$$



(a) Pressure ratio map of the compressor

(b) Efficiency map of the compressor



(c) Pressure ratio map of the turbine

(d) Efficiency map of the turbine

Figure 7: Performance maps of the sCO_2 turbomachinery Oh et al. (2016)

3.4 *Shaft and generator model*

For a recompression cycle applying a TAC configuration, the rotating speeds of the turbine, compressor and external load are the same. As a result, the shaft speed will only change by a change in positive torque generated by the turbine or a negative torque generated by the compressors or external load Ming et al. (2022). Therefore, the transient behaviour of the shaft can be determined according to equation 20 Oh et al. (2016) Olumayegun and Wang (2019) Ming et al. (2023).

$$I\omega\frac{d\omega}{dt} = P_T - P_{MC} - P_{RC} - P_G \tag{20}$$

The shaft speed dynamics of the power conversion cycle can be calculated according to the inertia I, the shaft speed ω and the power P of the different components connected to the shaft. Although load demand is an electrical power demand, the generator power P_G refers to the mechanical power required by the generator. It is further assumed that the dynamics of the generator can be neglected. Michael A. Pope (2006) determined the shaft inertia belonging to a 2400 MWth nuclear power plant connected to a sCO_2 power conversion cycle. To determine the inertia values for the selected power conversion cycle, the inertia values of Pope can be scaled based on the thermal power of the nuclear reactors Oh et al. (2016).

3.5 *Control valves*

The pressure difference over a throttle and bypass valve is significantly different. Throttle valves are located between pipes that contain similar pressure levels, resulting in low pressure differences, while bypass valves are connected between the high and low pressure side of the power conversion cycle, resulting in large pressure differences. For a throttle valve, it is common that the pressure drop is equal to 0.3-0.6 of the total pressure drop over the piping in which it is located Bian et al. (2022). For a small pressure difference, the case of a throttle valve, equation 21 can be used. For a bypass valve, the mathematical model of an orifice plate flow with a large pressure difference can be used, which is presented in equation 22. In these equations the mass flow is related to

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a constant valve construction coefficient C_v, the relative opening area of the valve f_{open}, the flow density ρ, the pressure difference between the inlet p_i and outlet p_o of the valve and the specific heat ratio γ Bian et al. (2022).

$$\dot{m} = C_v f_{open} \sqrt{2\rho(p_i - p_o)} \tag{21}$$

$$\begin{aligned} \dot{m} &= C_v f_{open} \sqrt{\frac{2\gamma}{\gamma - 1}\rho_i p_i ((\frac{p_o}{p_i})^{\frac{2}{\gamma}} - (\frac{p_o}{p_i})^{\frac{\gamma+1}{\gamma}})}\text{, for } (\frac{2}{\gamma+1})^{\frac{\gamma}{\gamma-1}} \leq \frac{p_o}{p_i} < 1 \\ \dot{m} &= C_v f_{open} (\frac{2}{\gamma+1})^{\frac{\gamma+1}{2(\gamma-1)}} \sqrt{\gamma \rho_i p_i}\text{, for } \frac{p_o}{p_i} < (\frac{2}{\gamma+1})^{\frac{\gamma}{\gamma-1}} \end{aligned} \tag{22}$$

3.6 Propulsion plant

In order to investigate what the power dynamics of the indirect sCO$_2$ Brayton cycle would provide in terms of ship performance, a simplified presentation of the full-electric ship propulsion plant and 1 Degree Of Freedom (1-DOF) ship model is included. The electric power generated by the three nuclear generator units is distributed, transformed and partially converted into mechanical power for propulsion. Variable Frequency Drives (VFDs) regulate the mechanical power output of the propulsion motors.

3.6.1 Electric grid and motors

It is assumed that the dynamics of the AC-grid can be neglected, reducing the model to a power balance with fixed efficiencies assumed for each of the components, as presented by equation 23. The electrical power provided by the generators $P_{Gj}\eta_G$ is equal to the power P_{hotel} consumed by hotel and ship service, considering transformer efficiency η_{trans}, added to the power consumed by the electric motors P_{EMj}, considering VFD efficiency η_{VFD} and motor efficiency η_{EM}.

$$\sum_{j=1}^{3} P_{Gj}\eta_G = \frac{P_{hotel}}{\eta_{trans}} + \sum_{j=1}^{2} \frac{P_{EMj}}{\eta_{EM}\eta_{VFD}} \tag{23}$$

The VFDs, as shown in Figure 5, also ensure that the power target setting P_{set} is reached while also being constrained by a certain power ramp rate. Based on the rotational speed of the motor N, the VFDs also enforce that the torque and power limits $P_{EM,lim}$ of the motors and converters are not exceeded, after which the electric motor torque M_{EM} is directly calculated based on the current shaft speed and (mechanical) motor power P_{EM}, as presented by equations 24 and 25.

$$P_{EM} = min(P_{set}, P_{EM,lim}(N)) \tag{24}$$

$$M_{EM} = \frac{P_{EM}}{N\frac{\pi}{30}} \tag{25}$$

3.6.2 Propeller and hull

To simulate ship performance, the mechanical power provided by the electric motors is converted into propeller thrust, providing the driving force for the hull of the ship. The model is considering both the rotation mechanics (i.e. the shaft lines), and the translation mechanics (i.e. hull and ship mass). The torque balance in the rotational domain is presented by equation 26, where inertia I dictates how quickly shaft speed ω can change, depending on the difference between propeller torque M_{prop} and electric motor torque M_{EM}.

$$I\frac{d\omega}{dt} = M_{EM} - M_{prop} \tag{26}$$

Similarly, the force balance in the (1-DOF) translation domain is presented by equation 27. Here, the ship's speed v_{ship} depends on its mass M, the propeller thrust T_{prop}, the number of propellers k_p, and the speed dependent ship resistance R_{ship}. A thrust deduction factor t is included to compensate for propeller-hull interactions.

$$M\frac{dv_{ship}}{dt} = k_p T_{prop}(1-t) - R_{ship}(v_{ship}) \tag{27}$$

Propeller thrust T_{prop} and torque M_{prop} are calculated using the four quadrant representation of propeller performance data, presented in equations 28 and 29, where thrust coefficient C_T and torque coefficient C_Q are obtained from the propeller performance diagrams. The density of the surrounding (sea)water ρ and propeller diameter D are constants. Wake fraction w relates the ship speed to the advance speed v_a, the velocity of the inflowing water as observed by the propeller, as presented by equation30. Shaft speed N is equal to shaft speed ω after accounting for unit conversion (i.e. from $[rpm]$ to $[rad/s]$).

$$T_{prop} = C_T({v_a}^2 + (0.7\pi\frac{N}{60}D)^2)\rho\frac{\pi}{8}D^2 \tag{28}$$

$$M_{prop} = C_Q({v_a}^2 + (0.7\pi\frac{N}{60}D)^2)\rho\frac{\pi}{8}D^3 \tag{29}$$

$$v_a = (1-w)v_{ship} \tag{30}$$

All parameters related to propeller and hull models, including ship resistance and hull interaction parameters, are directly based on the work of Geertsma (2019) without any further modifications. Propeller performance data is based on the well-known Wageningen (C5-75) C-series stock propeller Dang et al. (2013).

3.7 Controls

To realise the power transients for the nuclear power plant, controllers must be added. Not only should controllers change the power output of the system, but controls should also ensure operating conditions within the cycle do not impact the dynamic load changes of the cycle, and keep the cycle within safe limits. Therefore, controls are categorised in safety control, which includes main compressor inlet temperature control, compressor in- and outlet pressure control and reactor temperature control, and load controls includes bypass control, reactor control, and power control of the propulsion electric motors. If controllers are implemented in the model, a version of a PID controller has been selected, which has been tuned manually.

3.7.1 Safety control

Near the critical point of CO_2 do slight operating conditions result in drastic thermophysical property changes. As the operating region of the main compressors is the closest to the critical point, it is of importance to control the inlet conditions to ensure a stable working regime. To control the inlet temperature of the main compressor, a PID controller adjusts the mass flow through the cooler Bian et al. (2022).

Furthermore, throttle valves are placed around the compressor to ensure a stable and safe operating regime. Before the compressors, the valves ensure that the flow entering the compressors has a pressure of 90 bar, equal to the lower cycle pressure. Throttle valves placed after the compressors ensure that the cycle pressure does not exceed the maximum cycle pressure of 250 bar Olumayegun and Wang (2019). In addition, the throttle valve after the recompressor ensures the flow entering the mixer has the same pressure as after the LTR, preventing flow reversal that could damage the machinery Carstens (2007).

To control the reactor temperature, two control systems are present. At first, the addition of a dump cooler before the reactor controls the reactor inlet temperature, acting the same as the main compressor inlet temperature controller. Second, the control rods of the reactor can be used to control the reactor output temperature, limiting the power output of the reactor if the temperature increases.

3.7.2 Load control

At first, reactor control is performed by raising or lowering the control rods, based on the required power output of the reactor. As one controller cannot control two different things, using this option will reduce the option for reactor temperature outlet control. Furthermore, the speed of the control rods is tightly regulated to provide a stable power transient of the reactor Atkinson et al. (2021). If the controls rods were raised too fast, the reactor could turn prompt critical. As this results in an uncontrolled and rapid increase of fission reactions, and thus power increase, the consequence could be severe overheating that can lead to a meltdown or explosion, which should be prevented in all cases Duderstadt and Hamilton (1976).

Secondly, bypass control is used by implementing a bypass valve parallel to the turbine. This is a common bypass location for steam cycles. Although other bypass locations could be beneficial Carstens (2007)Wang et al. (2021)Wien (2024), for simplicity this common bypass location was selected. The bypass valve controls the shaft speed of the power conversion cycle. As a change in load power will result in a change in shaft speed according to equation 20, this results in that bypass control indirectly controls the power output of the cycle Bian et al. (2022). Opening the bypass will result in a reduction of mass flow entering the turbine, this way lowering the power output of the turbine. If the cycle operates at maximum power, the bypass should be fully closed to ensure maximum mass flow enters the turbine for maximum power production.

Lastly, the electric load demand is regulated using power electronics which are capable of following a fixed and prescribed power ramp. The overall electric load demand consists of two components, 1) the power required by the two electric propulsion motors, and 2) the power required by hotel and ship service loads. For the hotel and services loads, the required electrical power is assumed to be constant and is therefore not actively controlled. Variable frequency drives feeding the electric motors ensure that the propulsion load is controlled, reaching the desired power target while not exceeding the desired ramp rates.

4 Scenario description

4.1 Scenario introduction

To determine the dynamic behaviour of the nuclear power plant installation, it is of importance to investigate different scenarios. A distinction will be made between three different scenarios, of which an overview is presented in Table 4. Scenario 1 investigates the possibility of dynamic power control based on the transient of the reactor. Here, the reactor operates at low power and will increase its power based on the demanded power increase of the vessel. Scenario 2 investigates the possibility in which the reactor operates at constant power level and the dynamic power demand is realised by the secondary cycle. Bypass control will here solely control the load demand, but in this case the dump cooler placed in the primary circuit will not be present. Finally, scenario 3 will also operate with constant reactor power and a dynamic power change in the secondary cycle, but in this case a preliminary dump cooler will be added to the system ensuring reactor temperature control.

Table 4: Scenario conditions

Scenario	**#1**	**#2**	**#3**
Control			
Main compressor inlet temperature	Yes	Yes	Yes
Throttle valves (V1-V4)	Yes	Yes	Yes
Bypass valve (V6)	Yes	Yes	Yes
Reactor temperature inlet/outlet	No	No	Yes
Power transient			
Load speed	Fast as possible	Slow (0.75%/s)	Fast (3.00%/s)
Nuclear reactor output	Controlled	Fixed	Fixed
Dump cooler active (V5)	No	No	Yes

4.2 Ship manoeuvres

The three different scenarios will be investigated based on specific ship manoeuvres. It was decided to only look at a full linear power demand going low-high-low (10%-100%-10%), as this presents the most challenging power transient of a naval vessel. For the vessel, the 10% only corresponds to the load of hotel and ship services (base load) and the increase of 90% corresponds to accelerating from zero propulsion power to full propulsion power. To determine if a nuclear power plant installation can achieve similar power dynamics to conventional prime movers, two different transient speeds will be investigated. As the diesel engine and the gas turbine are the most common types of prime movers of a naval vessel, these will act as comparison for the transient speed of the system. It is common for a diesel engine to achieve 10-100% load changes in 120 seconds, while the transient of a gas turbine is even faster, being capable to achieve a load transient of 10-100% in 30 seconds. Therefore, this paper will apply two power transients to test the dynamic possibilities of the different scenarios; a slow transient of 0.75%/s and a fast transient of 3.00%/s. Note that these values are generic and aim to represent what is considered typical engine performance for naval applications, and do not include the impact of specific control strategies or any type-specific modifications made to the engines.

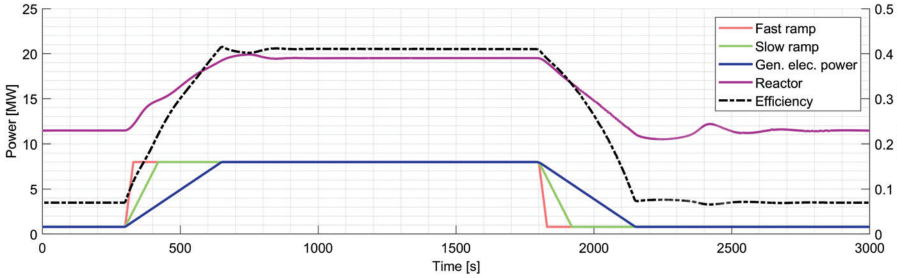
5 Results

5.1 Reactor limitations

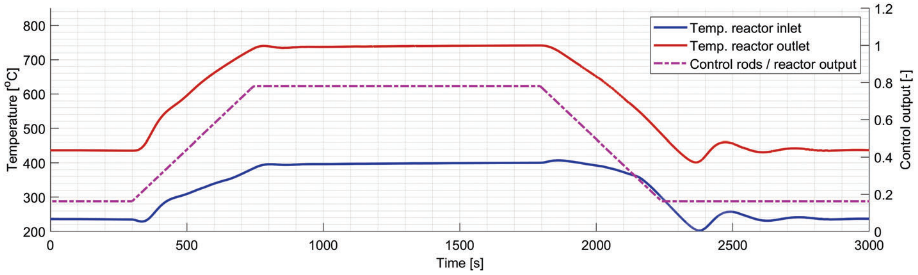
Within this scenario, the power dynamics of the reactor will be presented in combination with a bypass. The reactor is limited in its dynamics, by the previous mentioned control rod speed, and therefore the bypass is implemented to control the shaft speed. The simulation applies the maximum allowed control rod speed if the power demand on the cycle changes. If this change in power of the reactor is not sufficient, then bypass control will aid the power dynamics as much as possible. It was decided to limit the speed of the load in such a way that the shaft speed does not change more than 3%, as this indicates the limits of the bypass within the created scenario.

As a result, the power transient presented in Figure 8 can be achieved. Here, the power transient corresponding to the diesel engine and gas turbine are plotted for reference. The power transient presented in Figure 8a starts at 300 seconds and ends at 650 seconds. Within this time frame, a power change of 90% is realised compared to the rated power, resulting in a power transient of 15.4%/min. This is however the result of bypass and reactor control operating at the same time. Solely looking at the reactor power output of the simulation, presented in Figure 8a, the simulated ramp rate of the reactor is approximately 4.6%/min. This corresponds to ramp rate values presented in literature of VHTRs, which are between 3-10% min IAEA (2022) IAEA (2023) NRG (2023). Although the implementation of the bypass increases the ramp rate of the reactor slightly, it is not able to come close to the required power dynamics of a naval vessel.

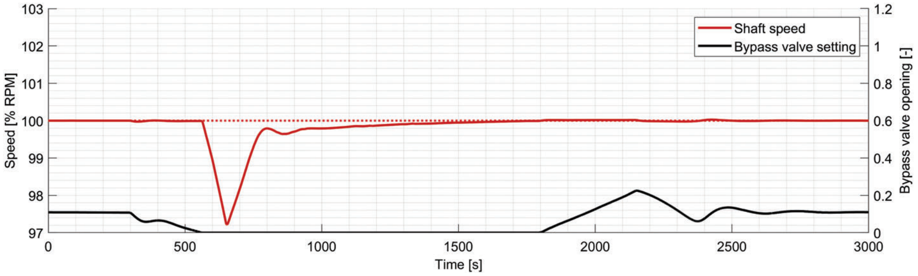
It must be noted, that during the simulation, the power dynamics of this scenario are limited by the first stage of the power transient, which goes from 10-100% cycle power. At the start of the scenario, the reactor is scaled down in power output as the cycle is operating in part load. Although this is beneficial for cycle efficiency, as less heat will be produced that will just be wasted, it also results that during the load increase the reactor must increase its thermal power output. Increasing reactor power output is strictly limited by the reactor dynamics and as a result faster power dynamics cannot be achieved by the bypass. To limit the impact of the reactor dynamics, the next scenario will discuss power transients during stable reactor power.



(a) Power balance (thermal and electrical)



(b) Reactor temperature control



(c) Shaft speed control

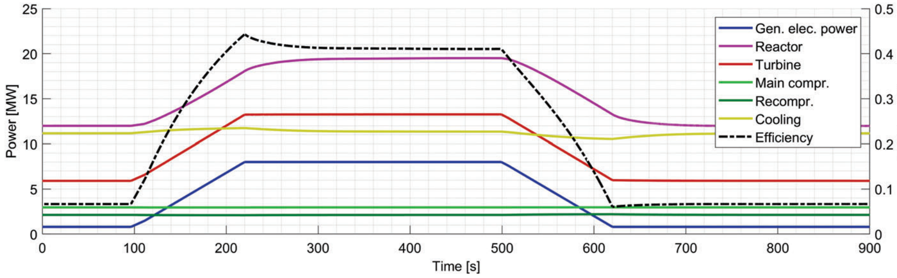
Figure 8: Simulation results scenario 1, reactor limitations

5.2 *Secondary cycle performance*

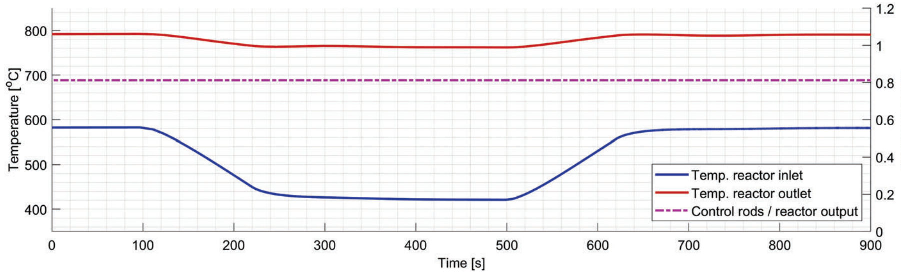
As scenario 1 indicates that the dynamics of the reactor are the limiting factor for the power transient, scenario 2 tries to achieve the power transient with a constant reactor control. To realise constant reactor control, the height of the control rods will be constant at the level belonging to a reactor output of 20 MWth. This limits the influence of the reactor dynamics on the system, but the secondary cycle is now responsible for achieving the required power dynamics, which is realised by the bypass valve controlling the mass flow through the turbine.

The results of the power transient are presented in Figure 9. Here, the slower ramp rate of the diesel engine is tested on the power conversion cycle, and the model is capable to run the simulation before large shaft speed changes start to occur. At full cycle power, the reactor produces its expected power of 20 MWth, as the secondary cycle is now absorbing all the required heat of the reactor. As a result, the inlet and outlet temperature of the reactor are within the expected region of 400°C and 750°C respectively. However, although the control rods are maintained at the same height, the power of the reactor does not stay constant if the cycle enters part load. This is the result as temperature control on the reactor is not guaranteed. During low part load, not all the heat produced in the reactor is used by the power conversion cycle. Although cooling power starts to increase slightly, most of the heat is returned to the reactor through the recuperators, resulting in an increased inlet and outlet temperature at the reactor side. This pushes the reactor into a temperature region for which it is not designed, as the temperature at the inlet of the reactor increases up to 590°C. As shown in Figure 2, the helium flows between the outer wall of the reactor barrel and the inside of the reactor pressure vessel before entering the reactor core, effectively cooling the reactor barrel and preheating the helium. Atkinson et al. (2019a) states that the temperature of the reactor barrel should not exceed 425°C, as material regulations imposed by the ASME state that graphitization of steel occurs at these temperatures. Therefore, the inlet temperature of helium is limited to around 400°C at steady state, but according to Figure 9b these safety limits are (excessively) breached during power transients.

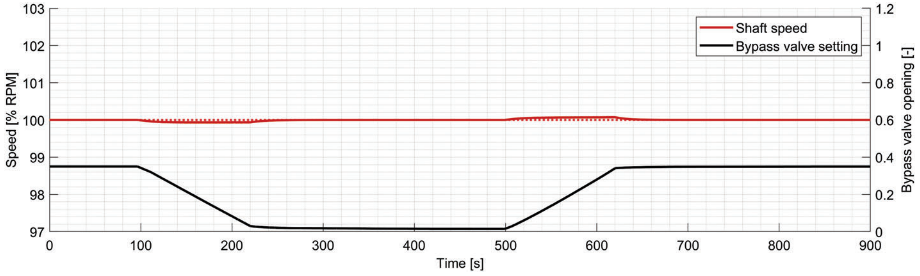
Compared to scenario 1, is scenario 2 able to provide the power dynamics corresponding to the transient of a diesel engine, due to operating the reactor at constant level. However, the temperature limits of the reactors are exceeded as reactor temperatures are not controlled. Scenario 3 will therefore continue by operating the reactor at constant power, but will add additional temperature control for the reactor.



(a) Power balance (mechanical, thermal, and electrical)



(b) Reactor temperature control



(c) Shaft speed control

Figure 9: Simulation results scenario 2, bypass control with fixed reactor output

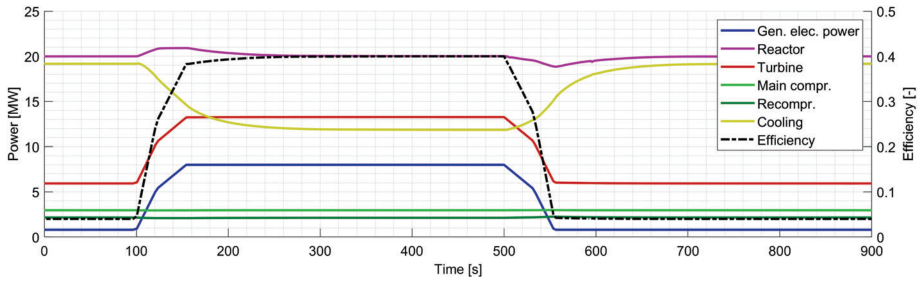
5.3 Dynamics of a nuclear vessel

5.3.1 Impact of the dump cooler

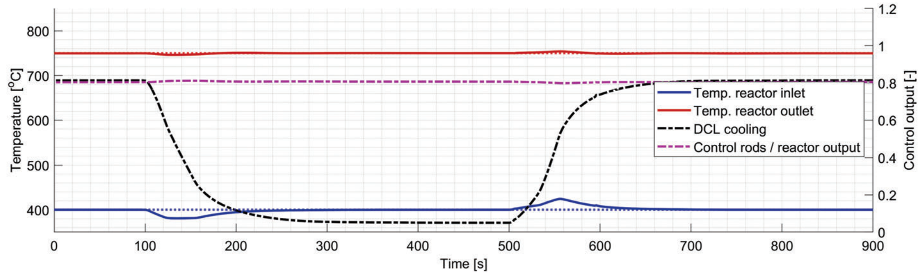
Scenario 2 shows that the power transient of the diesel engine cannot be achieved without exceeding safe temperature values within the reactor. Still, it seems possible to achieve the desired power transients and therefore a preliminary design solution has been implemented to limit the temperature increase within the reactor. A dump cooler has been added to the system to control the inlet temperature of the reactor. Furthermore, the control rods will be used to control the temperature outlet of the reactor, ensuring that the temperatures, and thus power output, of the reactor stays stable. To test the dynamic limits of this system, the simulation results belonging to a fast power transient ramp are presented in Figure 10.

This scenario gives promising results as not only the ramp rate of a diesel engine, but also the fast power transient of a gas turbine can be achieved with the nuclear power plant installation. The bypass control, in combination with the turbine, achieves the required power dynamics while the dump cooler prevents large temperature swings and ensures a stable reactor temperature at the inlet. Due to this relative stable inlet temperature at 400°C, the control rods of the reactor are capable to maintain the outlet temperature of the reactor stable around 750°C, resulting in no violation of the temperature limits. However, as can be seen in Figure 10a, the dump cooler must waste a lot of heat, resulting is low cycle efficiencies during part load, which is the result of constant reactor operation.

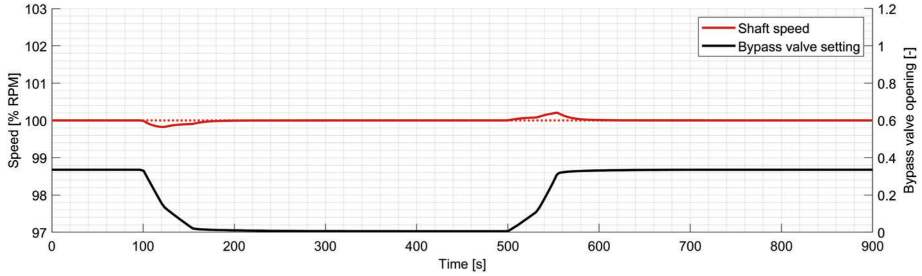
Within Figure 10a a small decrease in power dynamics can be observed near operating at full cycle power. This is however not a limitation of the nuclear power plant, but the result of dynamic limitations due to the performance of the vessel. To give insight into these limitations, scenario 3 has been performed an additional time, but now comparing ship performance between a slow and fast transient.



(a) Power balance (mechanical, thermal, and electrical)



(b) Reactor temperature control



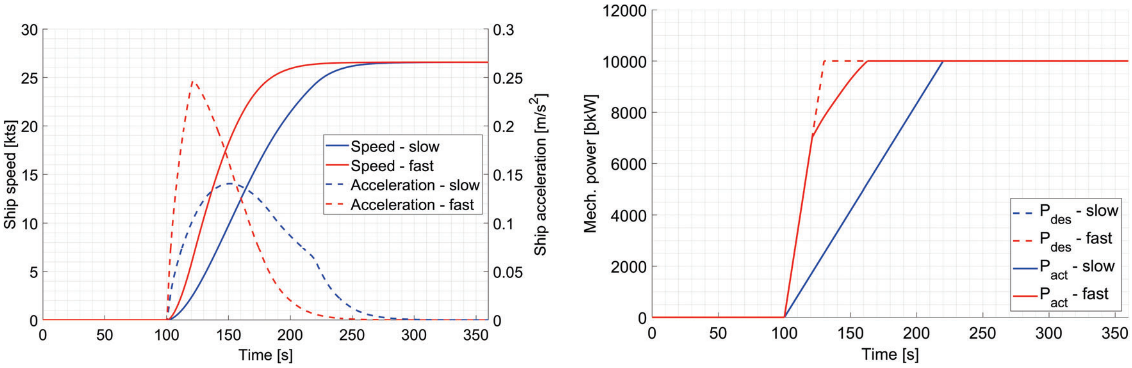
(c) Shaft speed control

Figure 10: Simulation results scenario 3, bypass control with dump cooler

5.3.2 Impact of ship performance

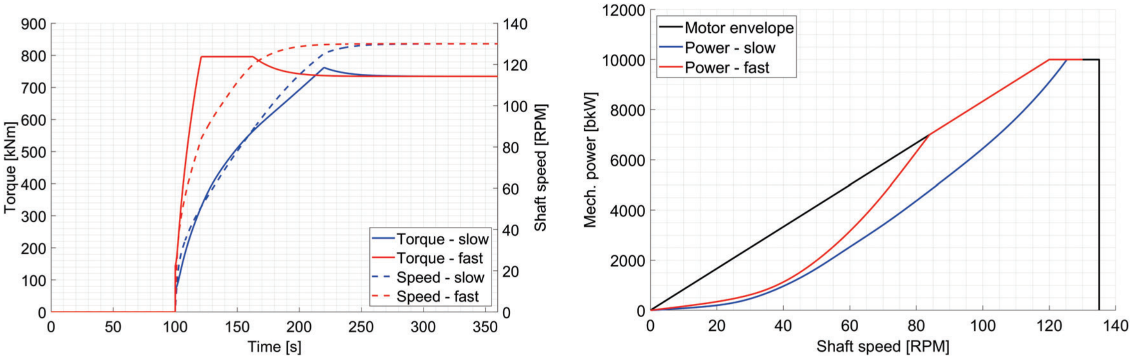
To explain the small decrease in dynamics near full cycle power, the power rate of the diesel engine and the gas turbine will be implemented on the cycle as designed in scenario 3. The results of this comparison on ship performance level are presented in Figure 11. Here, the speed of the ship reaches 95% of its maximum speed in 85 and 125 seconds for the fast and slow power transient respectively. The acceleration also differs, as the acceleration reaches 0.24 $\frac{m}{s^2}$ at 20 seconds during the fast transient, while the slow transient reaches a maximum acceleration of 0.14 $\frac{m}{s^2}$ after 50 seconds.

Looking at Figure 11d, the performance of the electric motor is also presented. During the slower transient, the shaft speed increases gradually and therefore does not reach the limits of the motor before it reaches full mechanical power. The fast transient however, accelerates the shaft faster and therefore the transient limits of the electric motor are reached. This translates itself in Figure 11c to a motor torque that flattens for a certain time period, limiting the power dynamics of the whole vessel. After operating for around 30 seconds with at a flatten torque level, the motor passes its nominal point and enters constant power operation.



(a) Ship speed and acceleration

(b) Demanded and actual power



(c) Electric motor torque and shaft speed

(d) Limit envelope of the electric motor

Figure 11: Ship performance simulation results, comparing slow and fast power ramps

6 Conclusions and further research

This paper investigates a very high temperature reactor (VHTR) in combination with a supercritical carbon dioxide (sCO_2) power conversion cycle for implementation on a naval vessel. By presenting a novel dynamic power plant model of a nuclear reactor, its power conversion cycle and the ship propulsion systems, different ship manoeuvres could be investigated. Power transients of conventional prime movers, the diesel engine and gas turbine, were compared with the designed nuclear power plant to indicate the dynamic possibilities of nuclear power generation.

Using reactor control, even in combination with bypass control, to achieve the power transient of a naval vessel was deemed unsuccessful. If the reactor operates at part load, and the power demand increases, the system is limited by the dynamics of the reactor, and can not provide the required power transient. However, by using the reactor as a constant power load, and achieving the power dynamics with solely bypass control, realises that fast power transient up to gas turbine level can be achieved. This requires however implementation of additional systems on a design level, like the proposed dump cooler, to ensure reactor temperatures are maintained within a safe region. Furthermore, the dynamic performance of the nuclear power plant was not deemed the limiting factor during ship transients, but the limitation occurs in the operating envelope of the electric motor.

The proposed bypass power control results in significantly low cycle efficiencies during part load. If the captain of the vessel is certain a fast power increase is not necessary, then the power production of the reactors could be minimized, lowering the amount of waste heat and thus improving cycle efficiency. However, this is currently not deemed an acceptable choice if there is uncertainty about a possible power transient, as then the transient of the reactor will limit the power transient of the whole vessel. As a result, there is a trade-off between a (relative) high efficiency at part load and the possibility of high power dynamics from the system.

The results of this paper indicate that there are still improvement possibilities regarding the design of a naval nuclear power plant. The balance between efficiency and dynamics will be critical to achieve economically viable and publicly supported nuclear vessels, which can still operate in high combat environments that require fast power dynamics. A nuclear power plant, generally viewed as a more slow and constant power source, is however capable to achieve the power transients of current naval vessels, and is therefore still deemed a feasible and attractive solution for the decarbonization of the maritime sector.

7 Recommendations

This paper focuses on the dynamic possibilities of a nuclear reactor, specifically the VHTR, in combination with an indirect sCO_2 recompression cycle, for naval applications. The authors believe this reactor and power conversion cycle combination is a promising concept option for nuclear power generation, but other philosophies could change the type of reactor or power conversion cycle. This could impact the dynamic behaviour of the nuclear power plant. The main points of this paper should however be valid, as the authors do not see the possibility of improving the dynamics of the components in such a way that results would differ significantly. Still, further research should indicate the maximum dynamic performance of different systems within the cycle, which are especially unknown for a nuclear reactor designed with a focus on dynamic performance.

Furthermore, the models created are focused on implementing existing design technologies for accuracy. Although a preliminary design study, based on scaling assumptions, has been performed on the nuclear reactor, its power conversion cycle and the vessel, a full design study was not performed due to a lack of time. A thorough design study could give additional insights towards the dynamic behaviour of the power plant and is therefore recommended. This is however only beneficial if certain aspects like the type of vessel and the type of reactor are selected, as otherwise the differences between different cycle configurations is too significant.

The paper presents a dump cooler as a solution for the increase in reactor temperature during part load. This is however a preliminary design solution and results in an increase in the amount of heat wasted to the seawater. Further studies could therefore produce other design solutions or control strategies to increase the overall cycle performance, especially during part load, while maintaining the possibility of high power dynamics. The implementation of inventory control is a very promising option in this regard, as this presents a solution for dynamic power control with higher cycle efficiencies. A variable split ratio could also improve part load efficiency. In addition, thermal and electrical energy storage should be carefully investigated to ensure waste energy is minimized. Thermal energy storage could be realized by inserting a molten salt loop between the reactor and the secondary cycle, creating a buffer against large load transients in the secondary cycle and allowing the reactor more time to respond to load changes. Electrical energy storage will introduce the possibility of peak shaving, ensuring that large load transients caused by propulsion, DEW, pulse loads, or otherwise, are not directly transferred to the nuclear power generator units.

Finally, the authors tried to the best of their knowledge to indicate, and propose solutions, for safety issues during power transients of the system. They are however not specialised within material compositions or safety evaluations of nuclear systems, and a full safety evaluation of the different cycle components during the power transients should be performed by experts. This could indicate if other safety issues are present during the dynamic power transient and if changes to system design are required.

Declaration of competing interest

The authors declare that there is no conflict of interest that could have influenced the work reported in this paper. Furthermore, the authors of this paper would like to note that the views and beliefs presented within this paper are solely their views and beliefs, and do not necessarily reflect the views and beliefs of Damen Naval and/or the Royal Netherlands Navy.

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Nomenclature

Symbols

β	Delayed neutron fraction	$[-]$
ΔH	Height difference	$[m]$
$\dot{m}$	Mass flow	$[\frac{kg}{s}]$
η	Efficiency	$[-]$
γ	Specific heat ratio	$[-]$
Λ	Prompt neutron generation lifetime	$[s]$
λ	Effective decay constant	$[s^{-1}]$
ω	Shaft speed	$[\frac{rad}{s}]$
π	Pressure ratio	$[-]$
ρ	Density	$[\frac{kg}{m^3}]$
ρ	Reactivity	$[\$/pcm]$
A	The heat transfer area	$[m^2]$
C	Specific heat capacity	$[\frac{J}{kgK}]$
c	Concentration of a delayed neutron group	$[-]$
C_v	Valve coefficient	$[-]$
C_Q	Propeller torque coefficient	$[-]$
C_T	Propeller thrust coefficient	$[-]$
D	Propeller diameter	$[m]$
d_H	Hydraulic diameter	$[m]$
f	Friction factor	$[-]$
f_{map}	Performance map function	$[-]$
f_{open}	Valve opening	$[-]$
g	Acceleration due to gravity	$[\frac{m}{s^2}]$
h	Enthalpy	$[\frac{kJ}{kg}]$
h	Heat transfer coefficient	$[\frac{W}{m^2K}]$
I	Inertia	$[kgm^2]$
k	Thermal conductivity	$[\frac{W}{mK}]$
k_p	Number of propellers	$[-]$
L	Length	$[m]$
M	Mass	$[kg]$
M	Torque	$[Nm]$
N	Shaft speed	$[RPM]$
n	Neutron population	$[-]$
P	Power	$[W]$
p	Pressure	$[Pa]$ or $[bar]$
Q	Heat	$[J]$
R	Resistance	$[N]$
s	Entropy	$[\frac{kJ}{kgK}]$
T	Temperature	$[^oC]$
T	Thrust	$[N]$
t	Thrust deduction factor	$[-]$
t	Time	$[s]$
t_e	Equivalent thickness	$[m]$
U	Overall heat transfer coefficient	$[\frac{W}{m^2K}]$
u	Speed	$[\frac{m}{s}]$
v	Ship speed	$[knots]$
v_a	Advance speed	$[m/s]$
w	Wake factor	$[-]$
Nu	Nusselt number	$[-]$

Abbreviations

B	Blower
CL	Cooler
DCL	Dump cooler
DEW	Direct energy weapons
DOF	Degrees of freedom
EM	Electric motor
FPP	Fixed pitch propeller
G	Generator
HEU	High enriched uranium
HTR	High temperature recuperator
IHX	Intermediate heat exchanger
LEU	Low enriched uranium
LTR	Low temperature recuperator
MC	Main compressor
P	Pump
P/D	Pitch over diameter ratio
PWR	Pressurised water reactor
R	Reactor
RC	Recompressor
RPV	Reactor pressure vessel
sCO_2	Supercritical carbon dioxide
T	Turbine
TAC	Turbine-Alternator-Compressor
TRISO	Tri-structural isotropic
TRL	Technology readiness level
TTD	Terminal temperature difference
U-235	Uranium 235
UO_2	Uraniumdioxide
V	Valve
VFD	Variable frequency drive
VHTR	Very high temperature reactor

Subscripts

c	cold side
corr	corrected
h	hot side
hotel	hotel and ship service (loads)
i	inlet
isen	isentropic
j	index counter
lim	limit(ed) value
n	node
o	outlet
prop	propeller
set	setpoint
ship	ship-related property
trans	transformer
w	wall

References

Alsawy, T., Mohammed, R.H., Mesalhy, O., Elsayed, M.L., 2024. Dynamic performance of supercritical co2 brayton cycle and its relationship to the correction of turbomachinery performance maps: A comparative analysis. Applied Thermal Engineering 242, 122364.

Atkinson, S., 2018. Design variances and optimisation of the U-Battery. Ph.D. thesis. University of Sheffield.

Atkinson, S., Abram, T.J., Litskevich, D., Merk, B., 2019a. Small modular high temperature reactor optimisation – part 1: A comparison between beryllium oxide and nuclear graphite in a small scale high temperature reactor. Progress in Nuclear Energy 111, 223–232.

Atkinson, S., Aoki, T., 2024. The development of a fuel lifecycle reactivity control strategy for a generic micro high temperature reactor. Nuclear Engineering and Technology 56, 785–792.

Atkinson, S., Aoki, T., Litskevich, D., Merk, B., Xing, Y., 2021. Part 3: Evaluating a small modular high temperature reactor design during control rod withdrawal and a depressurised loss of coolant accidents. Progress in Nuclear Energy 134, 103689.

Atkinson, S., Litskevich, D., Merk, B., 2019b. Small modular high temperature reactor optimisation part 2: Reactivity control for prismatic core high temperature small modular reactor, including fixed burnable poisons, spectrum hardening and control rods. Progress in Nuclear Energy 111, 233–242.

Bian, X., Wang, X., Wang, R., Cai, J., Tian, H., Shu, G., Lin, Z., Yu, X., Shi, L., 2022. A comprehensive evaluation of the effect of different control valves on the dynamic performance of a recompression supercritical co2 brayton cycle. Energy 248, 123630.

Brun, K., Friedman, P., Dennis, R., 2017. Fundamentals and Applications of Supercritical Carbon Dioxide (SCO2) Based Power Cycles. Woodhead Publishing.

Carstens, N.A., 2007. Control Strategies for Supercritical Carbon Dioxide Power Conversion Systems. Ph.D. thesis. Massachusetts Institute of Technology.

Dang, J., Van den Boom, H., Ligtelijn, J.T., 2013. The wageningen c-and d-series propellers, in: 12th International Conference on Fast Sea Transportation FAST, Citeseer.

Deng, T., Li, X., Wang, Q., Ma, T., 2019. Dynamic modelling and transient characteristics of supercritical co2 recompression brayton cycle. Energy 180, 292–302.

Ding, M., Kloosterman, J.L., Kooijman, T., Linssen, R., Abram, T., Marsden, B., Wickham, T., 2011. Design of a U-Battery. `https://www.janleenkloosterman.nl/reports/ubattery_final_201111.pdf`. Accessed on: 21-03-24.

Dostal, V., 2004. A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors. Ph.D. thesis. Massachusetts Institute of Technology.

Duderstadt, J.J., Hamilton, L.J., 1976. Nuclear reactor analysis.

Dutch maritime sector, 2023. No guts, no Hollands Glorie! `https://www.rijksoverheid.nl/documenten/rapporten/2023/10/26/sectoragenda-mmi`. Accessed on: 21-03-24.

Freire, L.O., de Andrade, D.A., 2015. Historic survey on nuclear merchant ships. Nuclear Engineering and Design 293.

Furlong, A.J., Ge, H., Hughes, R.W., Macchi, A., Haelssig, J.B., 2024. Dynamic modelling of cross-flow printed circuit heat exchangers for multistage reactor intercooling. Applied Thermal Engineering 239, 122010.

Geertsma, R.D., 2019. Autonomous Control for Adaptive Ships with Hybrid Propulsion and Power Generation. Ph.D. thesis. Delft University of Technology.

Gen IV International forum, 2014. Technology roadmap update for generation iv nuclear energy systems. `https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf`. Accessed on: 21-03-24.

Henryk Anglart, 2011. Nuclear Reactor Dynamics and Stability.

IAEA, 2022. Advances in Small Modular Reactor Technology Developments. `https://aris.iaea.org/sites/Publications.html`. Accessed on: 21-03-24.

IAEA, 2023. Advanced Reactors Information System(ARIS). `https://aris.iaea.org/sites/overview.html`. Accessed on: 21-03-24.

Jiang, Y., Liese, E., Zitney, S.E., Bhattacharyya, D., 2018. Design and dynamic modeling of printed circuit heat exchangers for supercritical carbon dioxide brayton power cycles. Applied Energy 231, 1019–1032.

Marchionni, M., Chai, L., Bianchi, G., Tassou, S.A., 2019. Numerical modelling and transient analysis of a printed circuit heat exchanger used as recuperator for supercritical co2 heat to power conversion systems. Applied Thermal Engineering 161, 114190.

Michael A. Pope, 2006. Thermal hydraulic design of a 2400 MWth direct supercritical CO2 cooled fast reactor. Ph.D. thesis. Massachusetts Institute of Technology.

Ming, Y., Liu, K., Zhao, F., Fang, H., Tan, S., Tian, R., 2022. Dynamic modeling and validation of the 5 MW small modular supercritical CO2 Brayton-Cycle reactor system. Energy Conversion and Management 253.

Ming, Y., Tian, R., Zhao, F., Luo, C., Tan, S., 2023. Control strategies and transient characteristics of a 5mwth small modular supercritical co2 brayton-cycle reactor system. Applied Thermal Engineering 235, 121302.

NRG, 2023. Small Modular Reactors 2023. `https://open.overheid.nl/documenten/ronl-7222d09bf81cec92c1c0b31f40133cf6fc7a6cea/pdf`. Accessed on: 21-03-24.

Oh, B.S., Lee, J.I., Kim, S.G., Cho, S.K., Yu, H., 2016. Transient analyses of s-co2 cooled kaist micro modular reactor with gamma+ code. The 11th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety Gyeongju .

Olander, D., 2009. Nuclear fuels – present and future. Journal of Nuclear Materials 389, 1–22.

Olumayegun, O., Wang, M., 2019. Dynamic modelling and control of supercritical co2 power cycle using waste heat from industrial processes. Fuel 249, 89–102.

Olumayegun, O., Wang, M., Kelsall, G., 2017. Thermodynamic analysis and preliminary design of closed brayton cycle using nitrogen as working fluid and coupled to small modular sodium-cooled fast reactor (sm-sfr). Applied Energy 191, 436–453.

Pham, H.S., Alpy, N., Ferrasse, J.H., Boutin, O., Tothill, M., Quenaut, J., Gastaldi, O., Cadiou, T., Saez, M., 2016. An approach for establishing the performance maps of the sc-co2 compressor: Development and qualification by means of cfd simulations. International Journal of Heat and Fluid Flow 61, 379–394.

Royal Dutch Navy, 2023. Sail Plan Vooruit! `https://open.overheid.nl/documenten/a45bdebd-7143-4a61-91f3-ebb357bf5d05/file`. Accessed on: 21-03-24.

Seatemperature.org, 2024. World Sea Temperatures. `https://www.seatemperature.org/`. Accessed on: 26-06-24.

Steigerwald, B., Weibezahn, J., Slowik, M., von Hirschhausen, C., 2023. Uncertainties in estimating production costs of future nuclear technologies: A model-based analysis of small modular reactors. Energy 281, 128204.

U.S. Department of Energy, 2024. Fuel Properties Comparison. `https://afdc.energy.gov/fuels/properties`. Accessed on: 21-03-24.

U.S. Department of the Navy and Department of Energy, 2015. The united states naval nuclear propulsion program. `https://shorturl.at/VWQU6`. Accessed on: 21-03-24.

Wang, X., Wang, R., Bian, X., Cai, J., Tian, H., Shu, G., Li, X., Qin, Z., 2021. Review of dynamic performance and control strategy of supercritical co2 brayton cycle. Energy and AI 5, 100078.

Wien, T.H., 2024. Nuclear Propulsion for Naval Vessels; investigating the dynamic behaviour of a nuclear powered super critical carbon dioxide power cycle. MSc. thesis. Delft University of Technology.

World nuclear association, 2023. World Nuclear Performance Report 2023. `https://www.world-nuclear.org/world-nuclear-performance-report.aspx`. Accessed on: 21-03-24.

Wu, P., Ma, Y., Gao, C., Liu, W., Shan, J., Huang, Y., Wang, J., Zhang, D., Ran, X., 2020. A review of research and development of supercritical carbon dioxide brayton cycle technology in nuclear engineering applications. Nuclear Engineering and Design 368, 110767.

van Zalk, J., Behrens, P., 2018. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the u.s. Energy Policy 123, 83–91.

Zohuri, B., 2020. Generation iv nuclear reactors. Nuclear Reactor Technology Development and Utilization , 213–246.

Shocking Permanent Magnet Motors for Naval Applications

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Synopsis

Electric motors form the basis of most modern Naval vessels' and submarine propulsion systems. Naval platforms require cost effective, power dense, highly efficient, resilient, low noise and reliable propulsion solutions. Permanent magnet motors (PMM) offer higher power density, higher efficiency, and lower noise than conventional induction motors. The permanent magnets require special consideration under temperature and shock load conditions and require analysis, design and validation to inform their suitability for the desired application. Permanent magnet motors are not a new technology and have been widely adopted in numerous applications and have a high technology readiness level. This paper looks at the simulation and tests carried out on a PMM to validate the magnets' shock capability to meet typical Naval underwater shock requirements. PMM topologies will be presented, surface and embedded, noting specifically embedded magnets are inserted into the rotor laminations and bonded with epoxy resin to hold them in position. Finite element analysis was carried out on the embedded permanent magnet motor and the motor geometry has been optimised to improve the shock capability of the magnets. Magnets were tested at various shock levels using a vertical drop test machine and their magnetic properties were checked after each test to confirm they can withstand the shock requirements while remaining magnetised. Additionally, a rotor segment was manufactured and tested on a shock table to validate the shock withstand capability of the magnets and the lamination. This paper will summarise the shock design and validation results for the permanent magnet motor investigated.

Keywords: Permanent magnet motor; Naval; Shock

1 Introduction

Internal design work was conducted to explore future naval motor technology which investigated different types of motor topology at three ratings. This included a compact induction motor (CIM) and three permanent magnet motors: one with surface mounted permanent magnets (SPM) one with embedded permanent magnets and one with interior permanent magnets (IPM). A surface mounted permanent magnet motor has magnets attached to the external surface of a solid rotor. Both embedded permanent magnets and interior permanent magnets have magnets embedded within a laminated rotor; embedded permanent magnet motors have magnets embedded at the surface of the rotor and will look visually very similar to a surface mounted permanent magnet motor; interior permanent magnet motors have magnets embedded within the rotor surface ensuring a cylindrical rotor is created.

The study found permanent magnet motors are more power dense, more efficient, and produce lower noise and vibration than conventional induction motors. This paper further investigates permanent magnet motor technology (specifically EPMM and IPMM) regarding temperature and shock load conditions to determine their suitability for naval applications using finite element analysis. Additionally, magnets were tested at various shock levels using a rotor segment manufactured and tested on a shock table to validate the shock withstand capability of the magnets and the lamination. This paper will summarise the shock design and validation results for the permanent magnet motor.

Authors' Biographies

Dennis Mathai MEng Lead Mechanical Engineer for GE Vernova's Power Conversion business, UK. His work includes designing rotating machines for naval applications.

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2 Permanent Magnet Drop Test

The primary purpose of the drop test was to investigate permanent magnet acceleration-induced demagnetisation of small N40UH and N45H permanent magnet samples. Review of the literature found that the demagnetising effects of direct impact acceleration on permanent magnets was well understood, however, these effects have not been fully investigated for acceleration only with no direct impact. Nor had it been investigated in combination with high temperature, which on its own was known to cause irreversible demagnetisation in permanent magnets. Therefore, a drop test was conducted at various impact-free accelerations and temperatures with the goal to extrapolate the results and provide benchmark data to enable motor designers to predict demagnetisation for given shock and temperature criteria.

A typical shock input profile in the form of acceleration and velocity for a large motor is shown in Figure 1. The primary goal of the test is to achieve the first acceleration pulse i.e., a_m, and T_1 corresponding to maximum displacement.

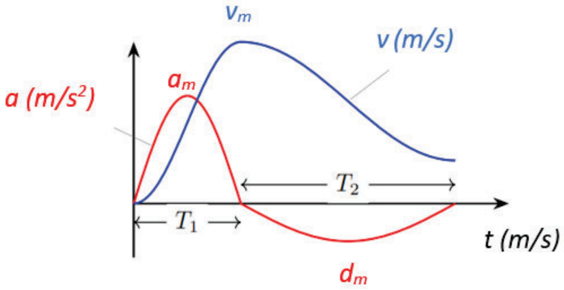
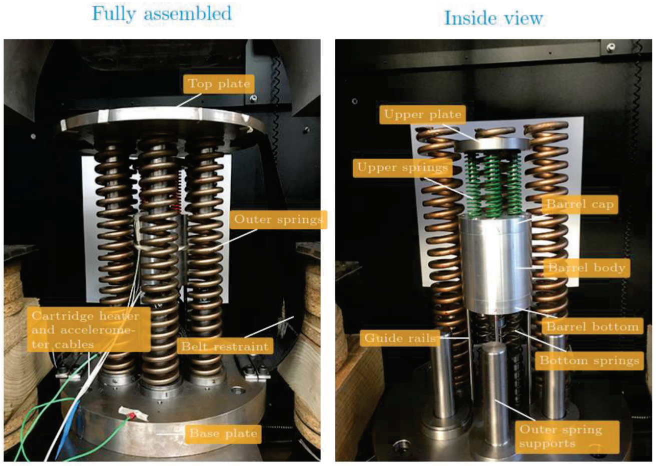


Figure 1: Typical Shock Input Profile for a Motor

Classical or commercial high-strain rate experimental systems, including the Very High Strain-rate testing system and the Split Hopkinson Pressure Bar system were investigated as possible solutions for supplying the required shock input. It was found however, that neither were able to produce the acceleration and/or displacement required and so a drop test was chosen.

Drop tests produce acceleration through direct impact; to produce an impact-free acceleration, a custom rig was created. It consists of a top and bottom plate connected by six outer springs, a “barrel” connected by four upper springs to an upper plate and three bottom springs connected to the base plate as can be seen in Fig. 2. The barrel houses the magnet samples and cartridge heater with additional space to accommodate up to eight copper disks to vary the load and therefore acceleration.


Fully assembled

Inside view

Figure 2: Fully Assembled and Internal View of Drop Test Rig

When released, the striker of the drop tester imparts its potential to the rig’s top plate which is connected to the heavy-duty outer springs. These compress and allow the top plate to contact the upper plate, transferring the remaining energy to the upper springs thereby accelerating the barrel.

The tests were carried out at four different temperatures, ranging from ambient temperature to maximum magnet operating temperature. This was achieved using a small but high–density cartridge heater inserted in the barrel. To vary the output, up to eight weighted copper disks were inserted into the barrel. With this, a good range of acceleration was produced, which includes the target peak acceleration. Figure 3 shows the acceleration profiles produced with varying mass. For Figures 3, 4 and 5, absolute values have not been shown due to security/commercial sensitivity.

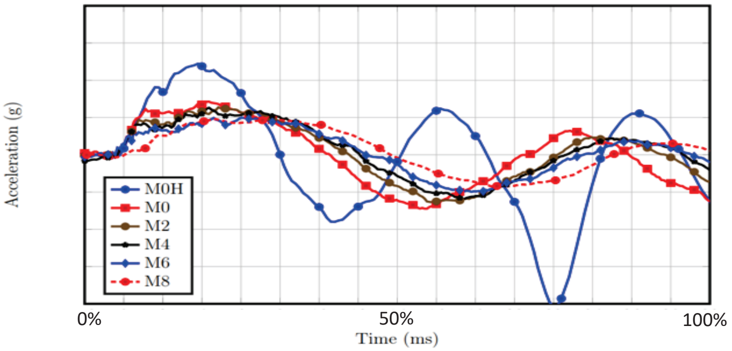


Figure 3: Acceleration Profiles Produced by the Drop Test Rig with Varying Mass

The rig could not achieve the target pulse width of 22 ms, only reaching 50%. However, the peak velocity and displacement are comparable, as shown in Figures 4 & 5, therefore, the acceleration tests largely represent the shock input in terms of acceleration, particularly the first pulse.

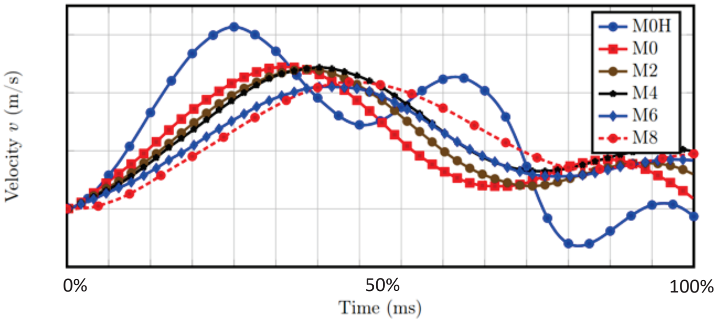


Figure 4: Velocity Profiles Produced by the Drop Test Rig with Varying Mass

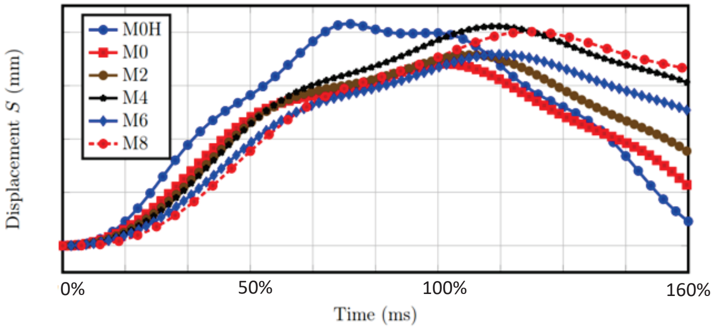


Figure 5: Displacement Profiles Produced by the Drop Test Rig with Varying Mass

Measurements were carried out after the drop tests using an Oxford Vibrating Sample Magnetometer to determine their residual magnetic field strength. It should be noted that only irreversible demagnetisation ct1ould be measured as reversible demagnetisation would require in-situ measurements which were infeasible if not impossible with the current rig design.

The N45H samples were found to exhibit up to 30% demagnetisation at the highest temperature which is three times higher than the maximum operating temperature of the magnet. In contrast with the temperature effect, there is no significant demagnetisation due to acceleration. In comparison, the N40UH samples exhibit only slight (< 5%) demagnetisation, owing to its superior performance at higher temperatures. Again, the demagnetisation caused by acceleration is insignificant. Figures 6 and 7 show the magnetic samples' demagnetisation as a function of temperature and acceleration. Once again due to security/commercial sensitivity, absolute values have not been shown for Figures 6 and 7.

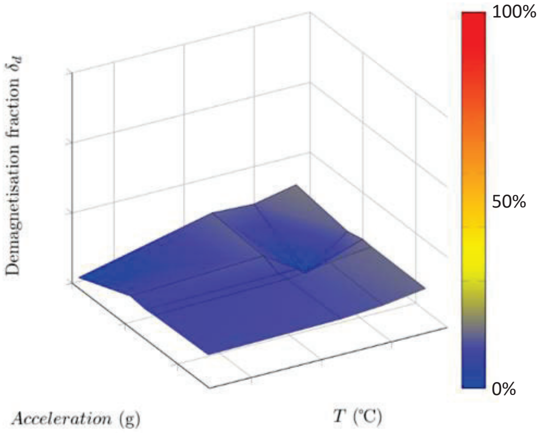


Figure 6: Demagnetisation as a function of temperature and acceleration for N40UH

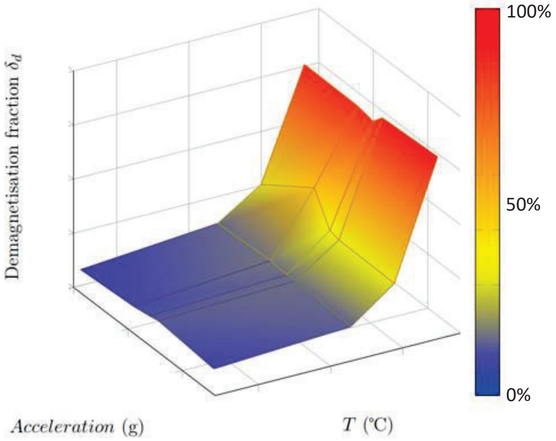


Figure 7: Demagnetisation as a function of temperature and acceleration for N45H

3 Finite Element Analysis of Permanent Magnet Motor

A Finite Element analysis of the permanent magnet motor rotor was completed to determine, via analysis, the ability of the rotor assembly to withstand normal operational and 'rare event' transient loads. The finite element model was used to predict the peak stresses, for both the interior permanent magnet motor and embedded permanent magnet motor rotor designs.

As the assembled rotor core consists of hundreds of thin magnetic steel laminations, compressed via through-bolts, it was modelled in 2D via a Plane Stress analysis. A circumferential span of the rotor, including one pole pair, was modelled; symmetry constraints were applied to the nodes on the circumferentially cut planes. The magnets were bonded, via contact elements, to the top surface of the rotor lamination slot; this is a conservative modelling approach as this ensures the body loads, due to rotational velocity and shock, are transmitted to the thinnest parts of the rotor structure. The laminated rotor is shrunk-fit to discrete arms welded to the shaft; contact elements were used to simulate the shrink-fit. Figure 8 shows the meshed model for the interior permanent magnet motor rotor section.

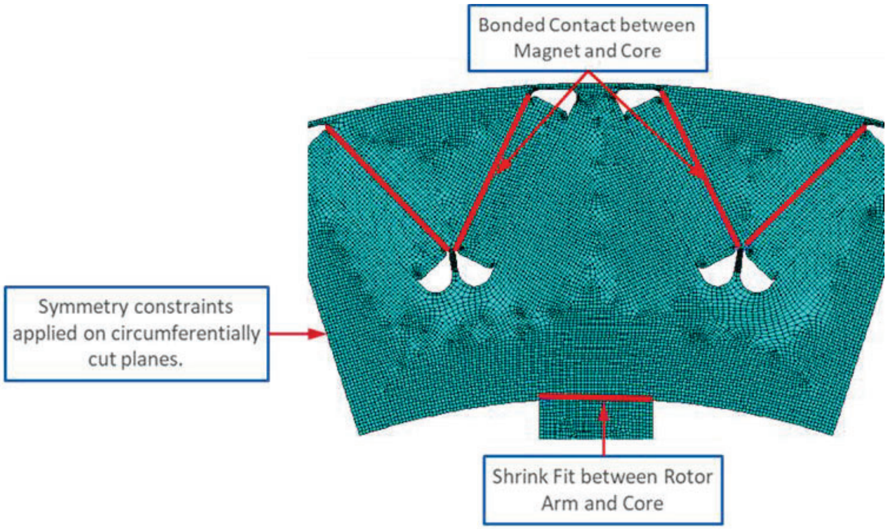


Figure 1: Finite element model of IPMM rotor showing applied boundary conditions.

The effects of operational and transient loads on the rotor were analysed over four Load Steps:

- Load Step 1: Solve for effects of Shrink Fit. A suitable fit is required to ensure float-off doesn't occur due to inertial loads. The interference fit will generate stresses at the contacting interface, which will distribute radially over the rotor.
- Load Step 2: Solve for effects of Overspeed; this is usually 20% above the maximum operating speed.
- Load Step 3: Maintain Overspeed and solve for Shock Acceleration. Although shock load occurring at overspeed is unlikely, this is a conservative assumption and ensures a suitable shrink fit is chosen that covers all scenarios.
- Load Step 4: Solve for effects of Operational Thermal loads.

The Load Steps were applied in the sequence that would produce the greatest cumulative loading on the rotor. From Figure 9 and 10, the maximum predicted von Mises stress on the interior permanent magnet motor rotor occurred during load step 3 and is localised at the bottom of the slot. This is predominantly due to shrink-fit loads; there is no significant change in predicted stress once the other operational loads are applied. The peak von Mises stress on the magnet, due to shock load, is concentrated at a corner; the predicted stress is within acceptable material limits.

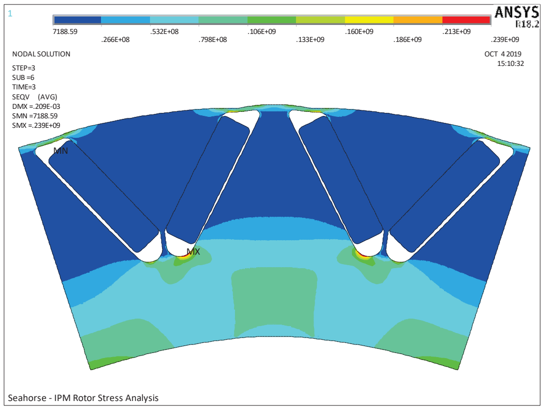


Figure 2: Ansys plot showing predicted von Mises stress at Load Step 3 for the IPMM rotor assembly.

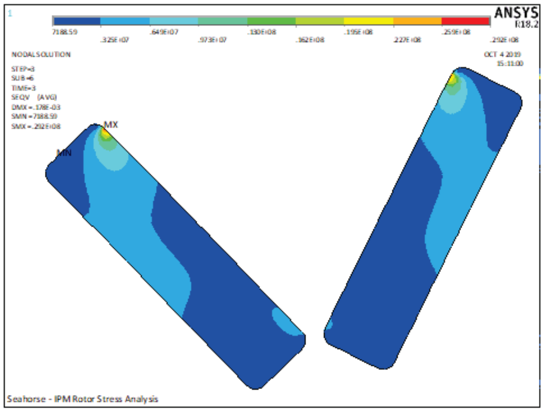


Figure 3: Ansys plot showing predicted von Mises stress at Load Step 3 for the magnet

From Figure 11 and 12 the maximum predicted von Mises stress on the embedded permanent magnet motor rotor occurred during load step 3 and is localised at the bottom rotor and is due to shrink-fit loads; there is marginal change in predicted stress once the other operational loads are applied. The peak von Mises stress on the magnet, due to shock load, is concentrated at a corner; the predicted stress is within acceptable material limits.

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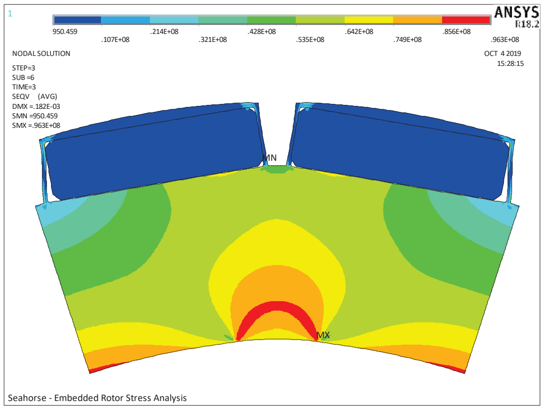

Figure 4: Ansys plots showing predicted von Mises stress at Load Step 3 for the EPMM rotor assembly.

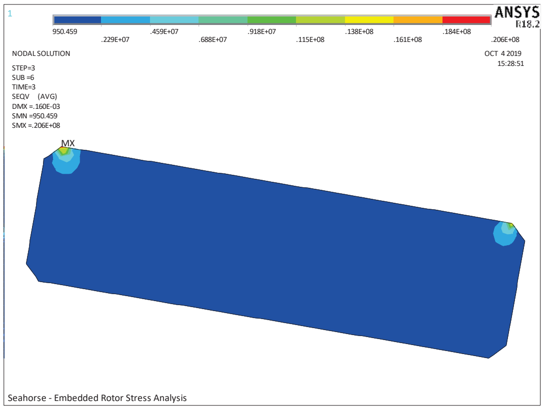

Figure 5: Ansys plot showing predicted von Mises stress at Load Step 3 for the magnet.

4 Shock Test of an Interior Permanent Magnet Rotor

The Power Conversion business designed several interior permanent magnet motors which must withstand a radial shock. As part of the design validation process, a section of the rotor was tested to determine its shock withstand capability. The rotor section consisted of a stack of approximately 1000 laminations, with magnets inserted within discrete slots in the laminated core-pack. The core-pack was compressed between two stainless steel plates; the core compression was maintained via through studs. The test sample consisted of a single pole pair section of the laminated rotor stack, with un-magnetised magnets running the full length of the pole slots; an epoxy resin is used to fill the air gaps between the magnets and the slot. The test was not intended to determine whether shock loads would demagnetise the magnets, therefore only un-magnetised magnet blocks were used for these tests. The assembled rotor section is shown in Figure 13.

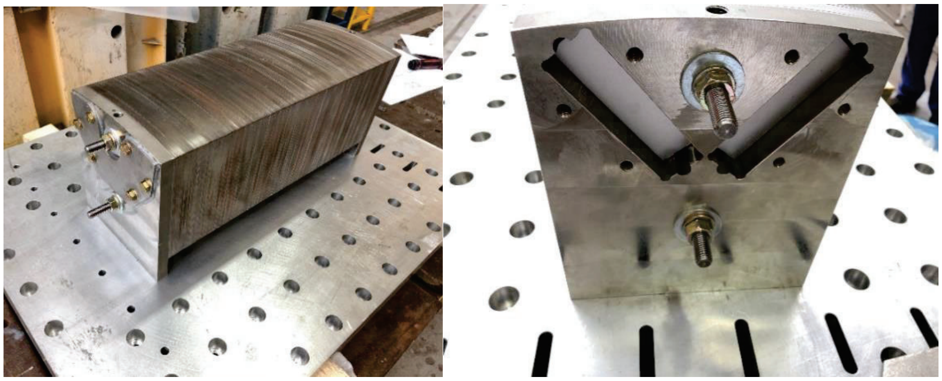

Figure 6: Assembled test sample of the IPMM rotor section

The assembled rotor section was attached to an Electromagnetic Shaker System in its vertical orientation. A control accelerometer was attached as close as practically possible to the specimen's mounting point and a monitor accelerometer was attached on top of the specimen to measure the dynamic response. The test setup is shown in Figure 14.

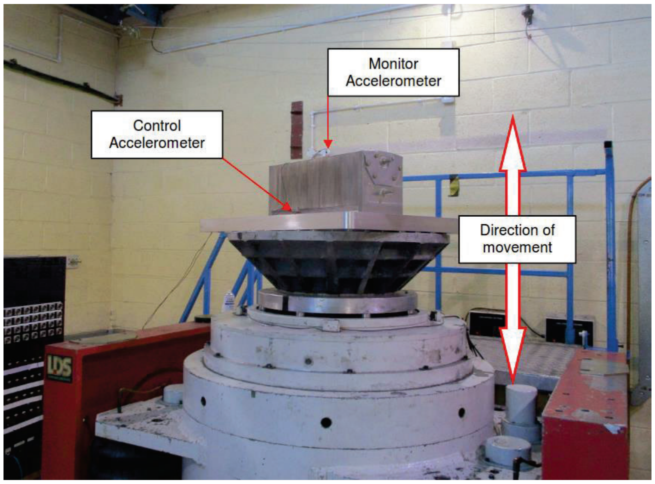

Figure 7: Shock test configuration for test sample.

The test specimen was exposed to a vertical shock acceleration in the positive and negative directions. Figures 15 & 16 show the recorded shock traces, measured on the test specimen. Absolute values are not shown due to security/commercial sensitivity. It must be noted however that both vertical shock accelerations were applied over the same time interval.

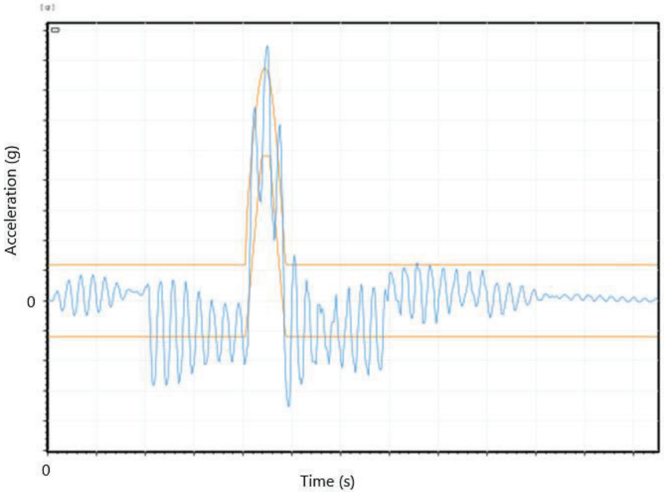

Figure 8: Recorded shock traces showing magnitude and duration of acceleration applied in the vertically positive directions.

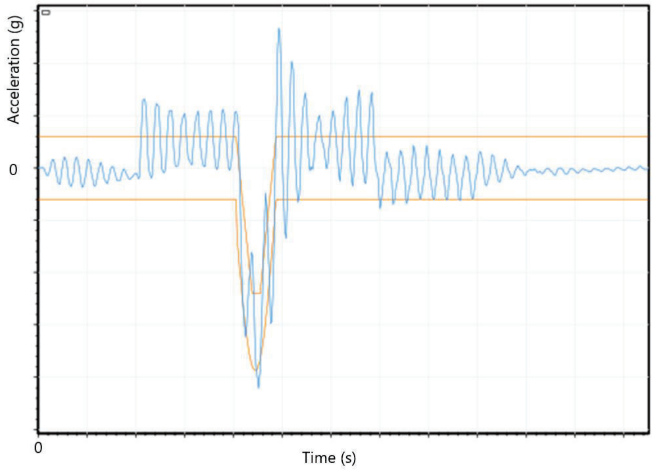

Figure 9: Recorded shock traces showing magnitude and duration of acceleration applied in the vertically negative directions.

Testing was done in accordance with Mil-Std 901D {MIL-S-901D, 1989}; the acceptance criteria was for a Grade A Item. The test acceptance criteria were that:

- The magnets must be intact and must show no signs of damage, such as cracks, which may propagate over time.
- The rotor endplates and core laminations must show no sign of serious damage which will affect its long-term performance.

Inspection of the magnets required a complete strip down of the assembly. Figure 17 shows the stripped-down rotor section: the end plates and compression studs have been removed and laminations have been stripped away exposing the magnets. The magnets, laminations and compression plates showed no signs of damage.

Figure 10: Post test strip-down of test sample: no sign of damage was found on the magnets and rotor components.

5 Conclusion

A drop test rig was designed and built to produce an impact-free acceleration. It was able to accommodate up to eight copper disks to vary the load and thus, acceleration.

The drop tests were performed on two grades of magnets, N45H and N40UH at increasing no-impact accelerations and temperatures to determine their effect on residual magnetisation. It found there is up to 30% and 5% demagnetisation due to exposure to high temperatures in the N45H and N40UH samples respectively whilst the demagnetisation associated with acceleration was insignificant in both sets.

A finite element model was used to predict the peak stresses for an interior permanent magnet motor and embedded permanent magnet motor rotor design. It found lower von Mises stresses occurred in an interior permanent magnet motor and so an IPMM rotor section was created and vertically shock tested in the positive and negative directions. Inspection of the magnets, laminations and compression plates showed no signs of damage, therefore confirming their shock withstand capabilities.

Acknowledgements

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References

MIL-S-901D, military specification: shock tests. H.I. (high-impact) shipboard machinery, equipment, and systems, requirements for (17-mar-1989) [s/s by MIL-DTL-901E].

Bibliography

Jun Liu (2017) ‘Optimised Electric System Architecture’ The University of Warwick

Necessity is the Digital Mother of Invention

Developing an IoT-style digital engine in a low-connectivity environment

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Synopsis

This paper explores the challenges and solutions in developing an Internet of Things (IoT)-style digital engine replica in a low-connectivity environment, specifically within the Royal Navy (RN). It underscores the inherent limitations of continuous connectivity in naval operations, where communication links can be disrupted or intentionally severed. Whilst alternative solutions to this problem exist, utilising data management platforms such as the Palantir Foundry Software Programme allows an increase in the dataset by capturing data not from one digital twin but from multiple, a strategy termed the 'digital mother'. By leveraging the collective data from multiple engines, the dataset's fidelity can be significantly enhanced, nearing the desired level of accuracy with no requirement for additional hardware. Using a lean start up methodology, the paper outlines the fundamental hypothesis and value proposition of the digital mother before demonstrating a methodical approach to building a Minimum Viable Product. Finally, it highlights the unique approach of empowering the end-user to create their own agile digital tools tailored to their specific needs. With training in data engineering, this approach ensures the solutions are not only technically robust but also intuitively designed to meet the demands of front-line RN engineers. The outcome aligns with the 'Lean, Green, Mean' approach. In terms of Lean principles, leveraging an organic workforce asset reduces development costs. In addition, the product enhances the quality of decision-making and streamlines maintenance schedules, providing savings in both costs and maintainer resource. From a Green perspective, using predictive analytics to manage inventory and contractor support facilitates a reduction in the engine's environmental footprint. As for the Mean aspect, employing intelligent maintenance increases availability, maximising resource so the RN can continue to fight and win.

Keywords: Digital replica; Data; Internet of Things; Engine Digital Twin

1. Introduction: The lemon

In 1601 Captain James Lancaster commanded the first East India Company deployment to the Far East. During this trip he performed an experimental study of the effects of citrus fruits on scurvy by providing one of his four ships with a daily dose of lemon juice. By the time the fleet had rounded the Cape of Good Hope, 110 of 278 sailors had died of scurvy on the other three ships. Everyone survived on the ship given lemon juice (Bowen et al., 2012). Lancaster was knighted on his return, and on presenting his report to the Admiralty, his findings of citrus fruits being an effective deterrent to scurvy were only embodied in doctrine in 1795 (Tröhler, 2003).

Whilst demonstrating a staggering 194-year adoption rate of new technologies (Syed, 2015), this anecdote also highlights how the unique operating environment of the Navy forced the requirement of a novel approach to a problem, and the generation of a unique solution. In that instance, the problem was the Royal Navy (RN) taking men into a new frontier where they were dying *en masse* from an unknown illness. That forced the novel approach of experimentation, by a willing amateur, and the generation of a unique solution in providing citrus fruit as an effective antiscorbutic. It also highlights that Captain Lancaster was the end-user, not a health consultant. He intuitively understood the environment that the problem was born from, after all, he was at risk of dying from scurvy himself. He also had the motivation in achieving the desired outcome – not dying of scurvy. Therefore, there was no better person to produce a solution than someone who understood the problem innately and had a vested interest in its success.

With the advance of science, we now know that Vitamin C deficiency is the cause of Scurvy (Szent-Györgyi, 1932), but the humble lemon was the 17th Century RN's best endeavour to get the required result. A solution that could be iteratively improved through empirical testing. A trained physician may have raised an eyebrow at the simplicity of Captain Lancaster's approach, but the key context is that this work was not done by trained physicians. This work was done by RN sailors. The customer was the consultant, creating the tools that they needed.

Author's Biography

Lt Cdr Liam Talbot is a RN Marine Engineer and IMarEST CEng. Educated in Physics & Mathematics, with post-graduate studies in Engineering & Management. Deployed globally, maintaining Ship's Mechanical & Electrical systems. Shore assignments include Personnel & Training, Navy HQ, Integrated Logistics Support, before developing an interest in data engineering where he recently started to navigate the realms of SQL, JavaScript and Python, making up for any natural talent with a boundless enthusiasm for technology.

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2. Problem – Internet of Things in a high latency environment

423 years after the first East India deployment, and the latest problem for the RN would be unrecognisable to Sir James. It is the Navy taking an engine into a low-connectivity environment when an Internet of Things (IoT)-style datalink, and real-time digital replica, would be beneficial (Rijsdijk et al., 2020). Bandwidth limitations, outdated and fragmented IT architecture, and intermittent connectivity during military operations impede the real-time transmission of data from engine sensors. In addition, integrating this data with supplementary information such as inventory and maintenance schedules is essential to paint a complete picture. Currently, the RN relies on standalone systems, with periodic replication shoreside, to ensure vessel safety and efficiency even in the absence of continuous data exchange with shore-based infrastructure. Although an element of resolution can be found in Edge Computing technologies (Morariu et al., 2021), this inherent limitation precludes the RN from achieving a true IoT-style digital replica.

2.1. Fundamental hypothesis

From this identified problem, the four steps of the Customer Development Model (Blank, 2003) are used to develop a potential product strategy:

1. Customer Discovery - Assuming low-fidelity datasets lead to inefficient and ineffective through-life support, the Equipment Authority (EA) would benefit from an IoT-style digital replica.
2. Customer Validation – Implementing a Minimum Viable Product initiates a Build-Measure-Learn loop (Ries, 2011), enabling the validation of the perceived value of a digital replica.
3. Customer Creation – Expanding to additional users of the equipment, and scaling this model to other equipment grows the customer base.
4. Company Building – Transitioning to Business as Usual, and ‘crossing the chasm’ (Moore, 2014) from early adopters to an established customer base.

The efficacy of using the end-user to develop this product is that the first two steps are innate. If the end-user is building the product, then they already understand their problem and what they need to fix it. This expediency allows a fundamental product hypothesis (Ries, 2011) to be generated quickly:

‘The implementation of an IoT-style digital engine replica enhances decision-making quality, optimises maintenance scheduling and inventory management, increases availability and yields savings in maintainer resources, costs, and environmental footprint.’

3. Solution – The Internet of Lemons

The RN recently undertook a large-scale expansion into comprehensive data management platforms through the implementation of the Palantir Foundry Software Programme. Foundry serves as a versatile software development environment with robust back-end capabilities, allowing for the integration of data streams from diverse sources. Datasets that were once isolated on different systems are now accessible within the same software programme, enabling relational links to be investigated and trend analysis performed. The true strength of Foundry, however, lies in its Low-Code/No-Code development framework (Richardson, 2014), meaning users can create their own workflows and applications to manage their data with minimal or no coding skills. In addition, the keen amateur can delve deeper and by learning the basics of programming languages such as Python, JavaScript, and Subject Query Language (SQL), can extend beyond the in-built functionality and start to code their own custom functions. A software engineer may raise an eyebrow at the simplicity of these applications, but the key context is that this work is not being done by software engineers its being done by RN sailors. Just as Sir James was best placed to pursue his scurvy problem, the 21st Century RN engineer is best placed to pursue their low-connectivity problem.

3.1. Engine and its data

Concurrent to developments in data engineering, the Type-45 Destroyer Propulsion Improvement Plan (PIP) and Type-23 Frigate Power Generation Machinery Control and Surveillance Update (PGMU) develop at pace, with the ships’ existing diesel generators being replaced with the Rolls Royce (RR) MTU4000 Series. The confluence of Foundry alongside the introduction of the MTU4000, the relatively small equipment pool size making this a manageable task, and their increasing numbers and importance to the RN, make the MTU4000 an ideal candidate for digital replication on Foundry.

Previous endeavours by other navies and industry partners have also encountered the challenge of low connectivity in the pursuit of digital replication of an engine. The Royal Netherlands Navy (RNLN) attributes data-pipeline ‘*air gaps*’, where human action is required to manually move data between networks, to ‘*limited bandwidth available, the classification and security of data and a fragmented IT architecture.*’ (Tiddens et al., 2020). Rather than treat this as a blocker, the RNLN method is to build a semi-automatic data-pipeline, and leave its enhancement for future projects, thus continuing the process of learning-by-doing (Van der Kerkhof, 2020). In addition, Babcock uncovered the same issue and proposed a solution of rigorous testing, from factory and field tests, to derive a bespoke life-model for an individual engine (Edge, 2022).

Rather than investing additional resources in further attempts to retrieve real-time data from a single engine – a challenging endeavour for the reasons outlined - this paper proposes an alternative approach. The solution of data superposition (see figure 1) expands the dataset to include all engines within the same class. By overlaying, or superposing, data from multiple engines into the Foundry data lake, any air-gaps or inconsistencies are addressed. This enhances the overall accuracy and fidelity of the dataset, particularly as the number of engines increases.

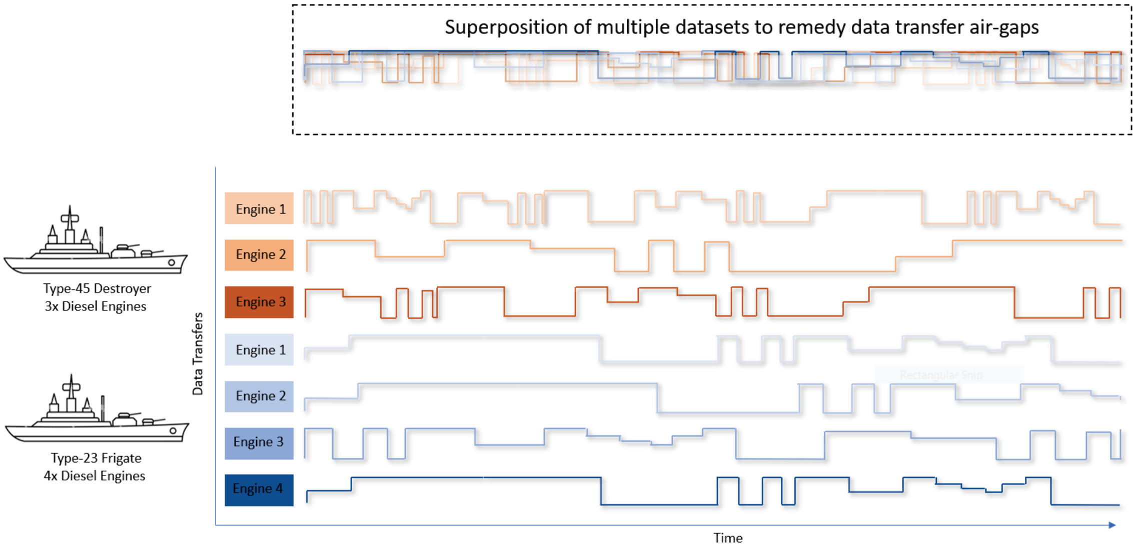


Figure 1: Data superposition highlighting periods of low information density, remedied by increasing the collection of data across multiple engines.

3.2. Value Proposition

Given the scope of this endeavour, initiating the project with a well-defined value proposition (Moore, 2014) serves as a compass, clarifying the purpose of the digital replica, and aligning actions with the fundamental product hypothesis.

‘Value proposition – For Equipment Authorities (EAs) who schedule predictive maintenance and stores for defective components, the product is a low latency digital replica that combats the low-connectivity problem by superposing information from multiple engines when data is available. Unlike alternative solutions, the product is developed by the end-user for the end-user and will not require additional hardware to implement.’

4. Method – What do you call a group of digital twins?

The initial phase of the digital replication process is known as the digital mother – a shared data lake formed from the seven disparate digital twins whose data is collated, examined, and crucially, shared between themselves (see figure 2).

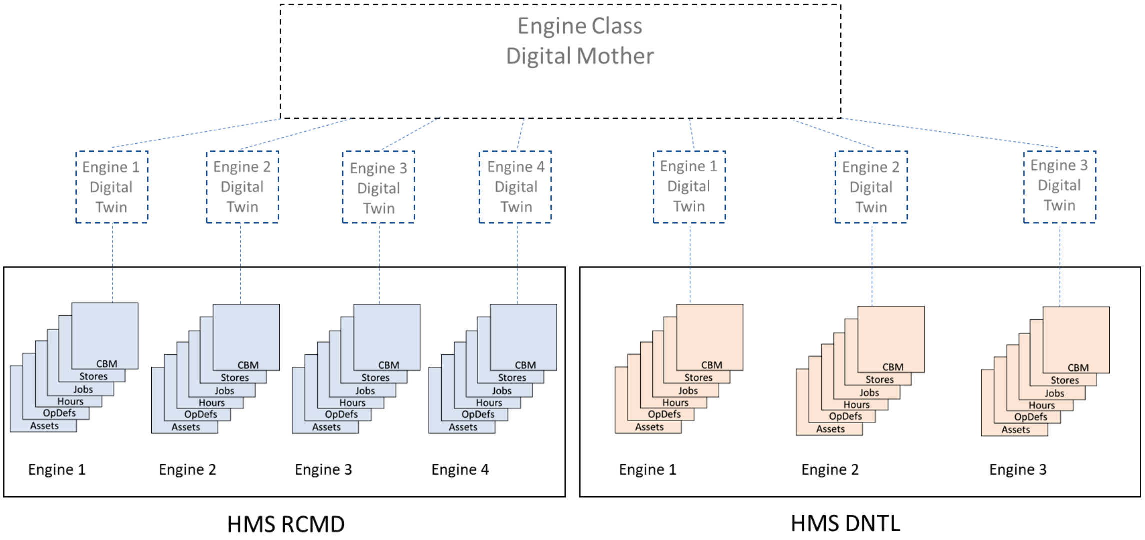


Figure 2: Concept diagram of the first iteration of the Digital Mother which uses Palantir Foundry to collate the superposed data from multiple engines of the same class.

To transform the digital mother from an idea into a product the concept of a Minimum Viable Product is utilised (Ries, 2011), with the high-level system diagram in figure 2 delineated and segmented into major steps, each crafted to validate the fundamental hypothesis detailed in para 2.1:

- Step 1: a repository of relational data from which insights can be generated.
- Step 2: a system of rule-based alerting triggered by set parameters.
- Step 3: utilise machine learning and automation to predict events and resultant actions.

Initiating Step 1 starts the process of learning as quickly as possible. Employing these steps as a handrail, the feedback generated at each stage informs and refines subsequent iterations within a Build-Measure-Learn loop (Ries, 2011). The objective being not to conclude the learning process but to start it, with the systems functionality continuously enhanced – alongside acquiring the skillset to organically develop it. In addition to addressing product design and technical questions, the Minimum Viable Product serves as a constant litmus test for the fundamental product hypothesis, and whether any iterative change will move the concept closer to achieving it.

4.1. Agile development

A key concept is that the digital mother is developed by the user. With training in Foundry, the RN is equipped to build a digital mother with unique flexibility, unrestricted by the constraints of traditional development models characterised by cumbersome bureaucracy and excessive form-filling. Previously reliant on third-parties, RN engineers now possess the autonomy to iteratively refine this digital tool in response to evolving user needs without being beholden to outside partners. Traditionally, a basic change of feature would require a request sent to an outsourced partner, receipt of an estimate, feasibility studies and creation of a change plan along with the back and forth of amends and responses. The organic RN developer can affect a change almost instantly, limited only by an ever-growing skillset to enact them. This simplicity and locality expedite the creation of a digital replica (Kim, 2019). In addition to delivering value both faster and cheaper, this method turbocharges the Build-Measure-Learn loop. Therefore, once the learning journey is commenced, this agility results in rapid iterations where Objects and features are added and withdrawn to suit the required user experience - '*It is much easier to be agile when you are small and light*' (Seagrave, 2023).

4.2. *Digital Mother*

The concept of the digital mother revolves around a system health dashboard, where each engine's condition is monitored using several key data inputs, or Objects, as defined in Foundry's terminology. These Objects are created by developing new data pipelines, and their properties and interconnections are visually represented on the dashboard. The system includes write-back functionalities and rule-based alerts, which notify users when certain thresholds are crossed, signalling potential engine distress (see figure 3).

The initial digital model was developed using Foundry's Workshop Module, a drag-and-drop development space that simplifies the creation of complex data workflows without the requirement for extensive coding. The dashboard's homepage provides an overview of the current engine health, highlighting key parameters such as defect health scores and average engine hours conditionally formatted to draw attention to any areas of risk. The dashboard's built-in filter functionality allows users to maintain a comprehensive view of all engines or focus on specific engines of interest (see figure 4).

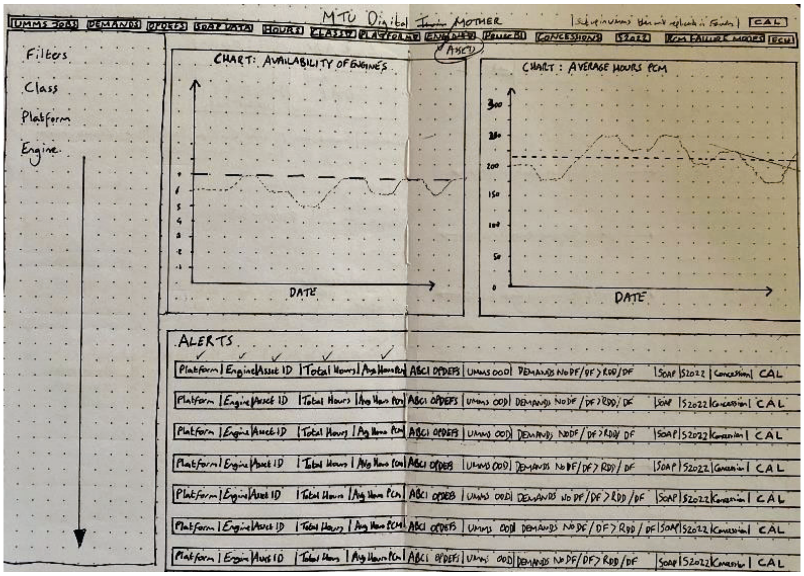
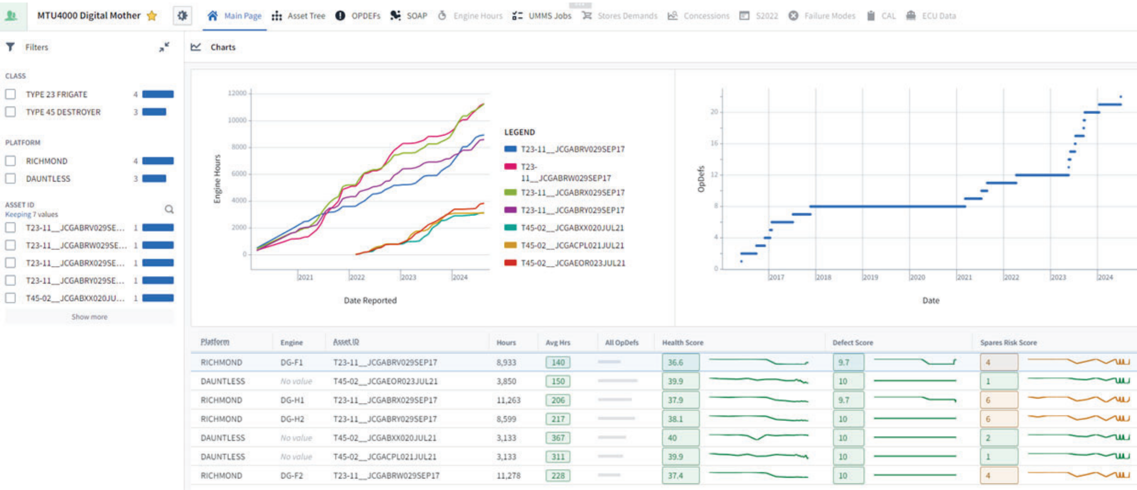


Figure 3: Concept of the Digital Mother Homepage centring on a health dashboard with high-level metrics.



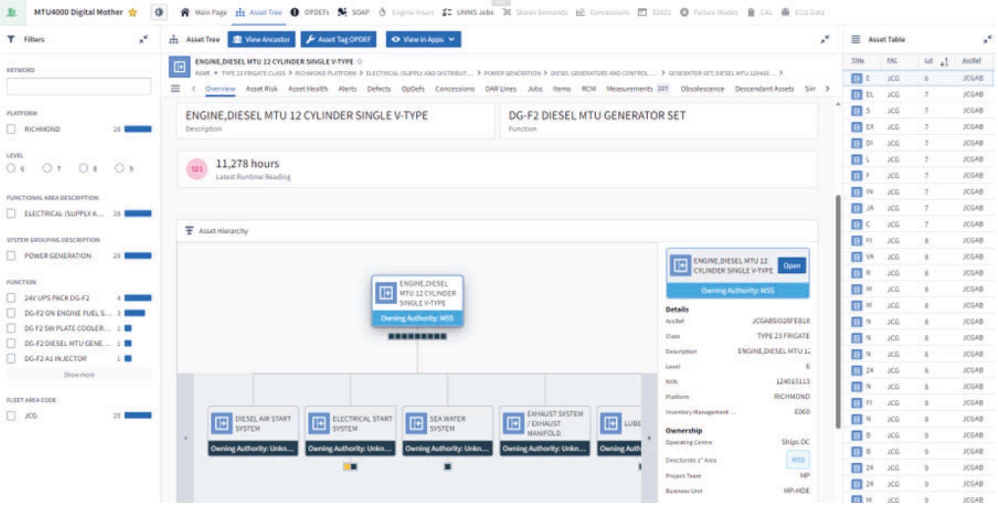
Platform	Engine	Asset ID	Hours	Avg Hrs	All OpDefs	Health Score	Defect Score	Spares Risk Score
RICHMOND	DG-F1	T23-11__JCGABRV029SEP17	8,933	140		36.6	9.7	4
DAUNTLESS	No value	T45-02__JCGAEOR023JUL21	3,850	150		39.9	10	1
RICHMOND	DG-H1	T23-11__JCGABRX029SEP17	11,263	206		37.9	9.7	6
RICHMOND	DG-H2	T23-11__JCGABRY029SEP17	8,599	217		38.1	10	6
DAUNTLESS	No value	T45-02__JCGABXX020JUL21	3,133	367		40	10	2
DAUNTLESS	No value	T45-02__JCGACPL021JUL21	3,133	311		39.9	10	1
RICHMOND	DG-F2	T23-11__JCGABRW029SEP17	11,278	228		37.4	10	4

Figure 4: The actual Digital Mother Homepage created with Foundry's Workshop Module, a Low-Code/No-Code drag-and-drop developer space that makes it simple to create Graphical User Interfaces.

The Objects that form the basis for the first iteration are: Assets, Defects, Oil Analysis, Engine Hours, Maintenance Tasks, and Stores. Although these Objects are interconnected within the data lake, they are organised into separate pages, each contributing uniquely to the overall health assessment. This subdivision not only enhances the manageability of the project but also improves the user experience by making the interface more intuitive and easier to navigate.

4.3. *Assets and Operational Defects*

The creation of a holistic view of the engines necessitates a thorough understanding of their subordinate components or Assets. The Asset Object, serving as a digital representation of the engine's physical components, is the backbone of the digital mother. Through this page, users can efficiently navigate the asset tree of engine sub-components, accessing a wealth of information attached to each component. Additionally, users can tag defects against sub-components, enabling further predictive insights, and export selected objects to other Foundry apps for more in-depth analysis.



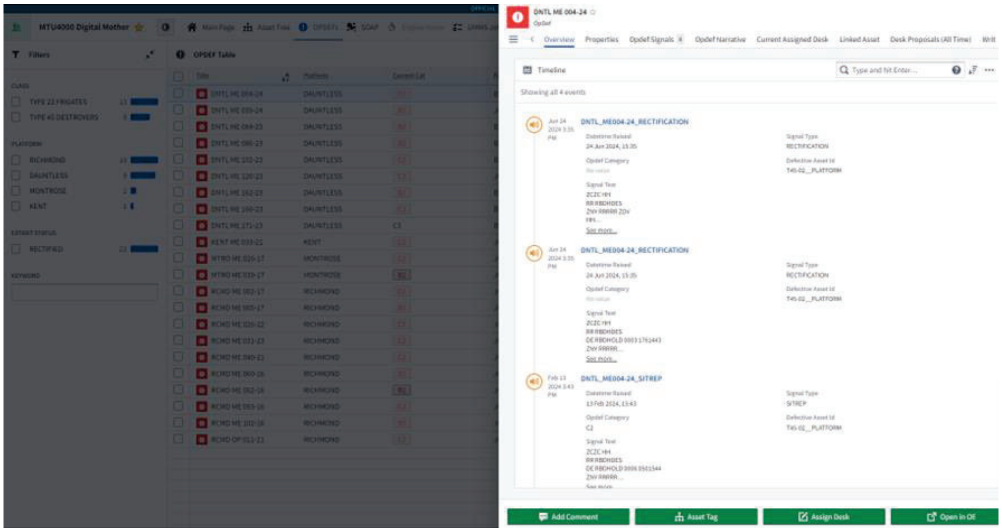
ENGINE,DIESEL MTU 12 CYLINDER SINGLE V-TYPE
Description: ENGINE,DIESEL MTU 12 CYLINDER SINGLE V-TYPE
Function: DG-F2 DIESEL MTU GENERATOR SET
Latest Runtime Reading: 11,278 hours

Details
AccRef: JCGABSI028FEB18
Class: TYPE 23 FRIGATE
Description: ENGINE,DIESEL MTU 1…
Level: 6
NIIN: 124015113
Platform: RICHMOND
Inventory Management …: E060

Ownership
Operating Centre: Ships OC
Project Team: MP
Business Unit: MP-MDE

Figure 5: User Interface of the Asset page enabling the management of the engine's asset hierarchy.

A defect that impacts the operational effectiveness of the ship is known as an Operational Defect (OpDef). Establishing a link between the OpDef and Asset Objects facilitates not only the identification of underperforming components but also enables users to analyse causal factors and emerging trends. Furthermore, connecting the OpDef and Maintenance Objects allows for examination of potential correlations between overdue maintenance tasks and defects, while linking it to the Stores Object streamlines supply chain management and facilitates data-driven decisions regarding stock levels based on historical defects. Additionally, this page offers functionalities for data-writebacks, such as appending comments to OpDefs, reassigning to a different Asset, or transferring to another department for action.



DNTL_ME004-24_RECTIFICATION
Signal Type: RECTIFICATION
Defective Asset Id: T45-02__PLATFORM

DNTL_ME004-24_RECTIFICATION
Signal Type: RECTIFICATION
Defective Asset Id: T45-02__PLATFORM

DNTL_ME004-24_SITREP
Datetime Raised: 13 Feb 2024, 15:43
Opdef Category: C2
Signal Type: SITREP
Defective Asset Id: T45-02__PLATFORM

Figure 6: User Interface of engine defects including write-back functions for comments, linking defects to assets, and assigning to specific Equipment Authority desks.

4.4. *Spectrometric Oil Analysis*

One of the Condition Based Monitoring (CBM) tests performed on the engine is spectrometric oil analysis. Upon receipt of test results, this valuable information is automatically ingested into the RN's data lake through a sophisticated data pipeline engineered using Foundry's Pipeline Builder. This pipeline automates the entire data processing workflow, joining disparate lab results, cleaning them of unwanted or spurious data by validating them against a preset schema, and pivoting the tables into a useful format. The processed data transforms into a Spectrometirc Oil Analysis Programme (SOAP) Object, which regularly updates with new sample test results.

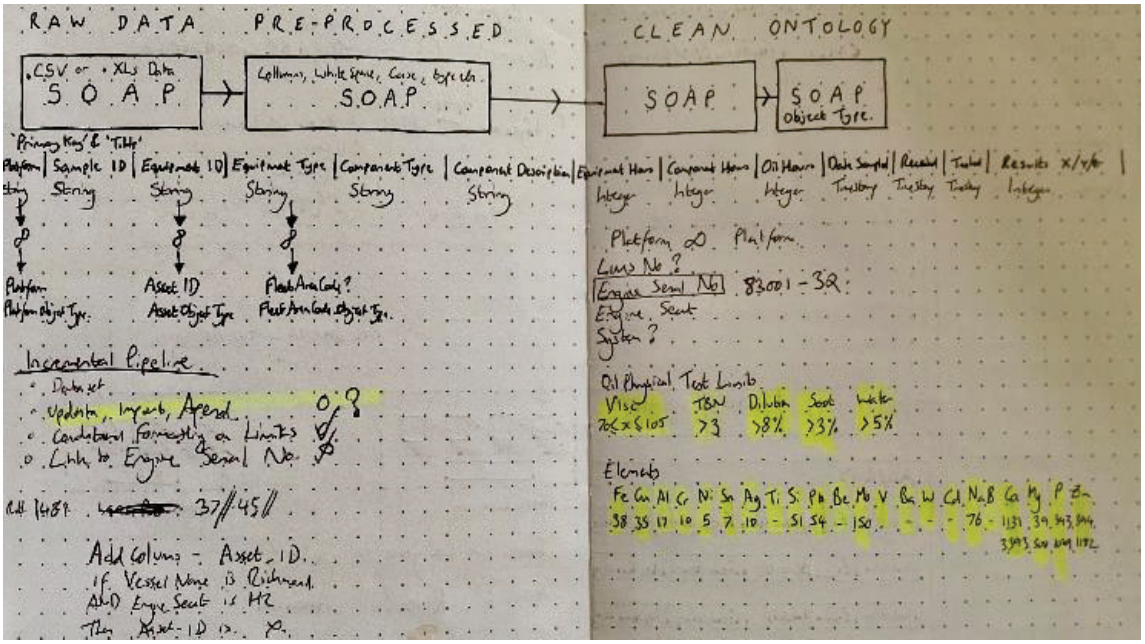


Figure 7: Concept sketch of the data-pipeline used to ingest Spectrometric Oil Analysis Programme (SOAP) data with steps for pre-processing, cleaning, and the assignment of a Foreign Key to enable relational links into other datasets such as Assets and Platforms.

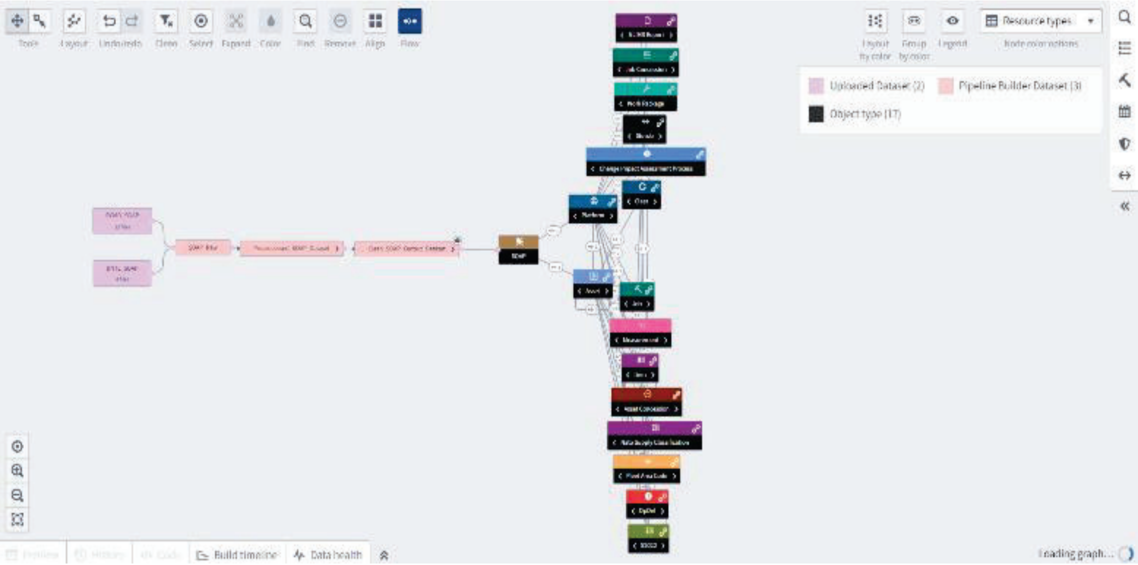


Figure 8: Foundry Pipeline Builder enables the concept sketch to be transformed into an automated data pipeline, where laboratory results of oil analysis are turned into usable Objects in the digital mother. It uses relational links to Asset and Platform to facilitate trend analysis with a variety of other objects.

To ensure seamless integration and relational links within the data lake, the pipeline uses Subject Query Language (SQL) to assign Foreign Keys, connecting the SOAP Object to specific Asset and Platform Objects. This creates a relational link from the SOAP Object into the broader complex web of interconnected objects, as depicted in figure 8, enabling efficient data exploration and analysis. This connectivity facilitates the use of Foundry's Quiver module (see figure 9) which allows the user to visualise SOAP results in a graph format, establish trendlines, and set up tripwires for automatic alerts in case of contaminant threshold breaches. Additionally, linking SOAP results to other pertinent Objects, such as Operational Defects (OpDefs), supports pattern recognition and predictive analytics. This enhances the capability to anticipate and mitigate potential engine failures.

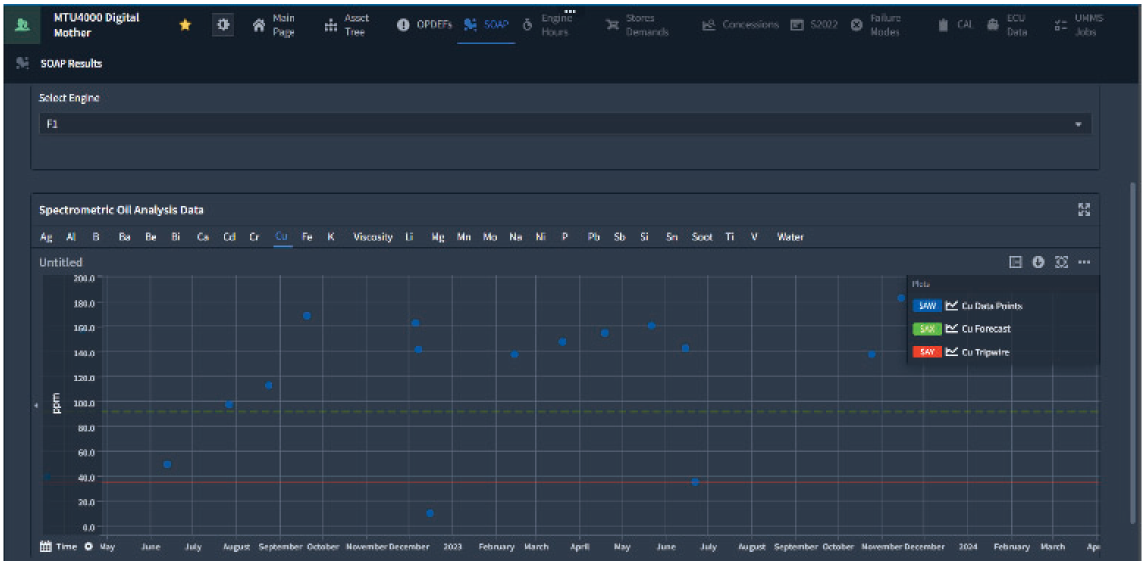


Figure 9: A chart of the oil sample data displayed on the digital mother SOAP page via the Foundry Quiver Module. This provides visual representation of twenty-eight contaminant tests against each engine to enable trend analysis, pattern recognition and automated alerts to the user if thresholds are breached.

The integration of SOAP data with Asset data within the same software platform presents an excellent opportunity to harness advanced machine learning techniques for predictive analytics. This capability represents Step 3 of the Minimum Viable Product outlined in Chapter 4 and is currently under development. The structured nature of this data is well-suited for supervised machine learning, particularly through the development of a regression algorithm that models the relationship between contaminant levels and the 'time-until-failure' of critical components, such as fuel injectors. By partitioning the dataset into training and testing subsets, the model can be trained using supervised learning techniques on the training data and evaluated on the testing data using metrics like Root Mean Square Error. To build and train these models, cloud computing services, such as Microsoft Azure's Automated Machine Learning feature, are being leveraged to identify the optimal regression algorithm and fine-tune its hyperparameters. Once the model is trained, it can be applied to predict future Asset failures based on oil analysis lab results processed through the pipeline depicted in Figure 8.

Currently, the automated alert system is triggered when oil samples exceed predefined thresholds. However, in future iterations, these oil sample results are expected to also generate 'time-until-failure' predictions for assets that are particularly sensitive to oil contaminants, thereby enhancing intelligent supply chain decisions. The advantage of the data superposition method defined in Chapter 3.1 means that the machine learning model used to achieve this will be trained on a comprehensive dataset encompassing numerous engines, thus enhancing the accuracy of its predictions.

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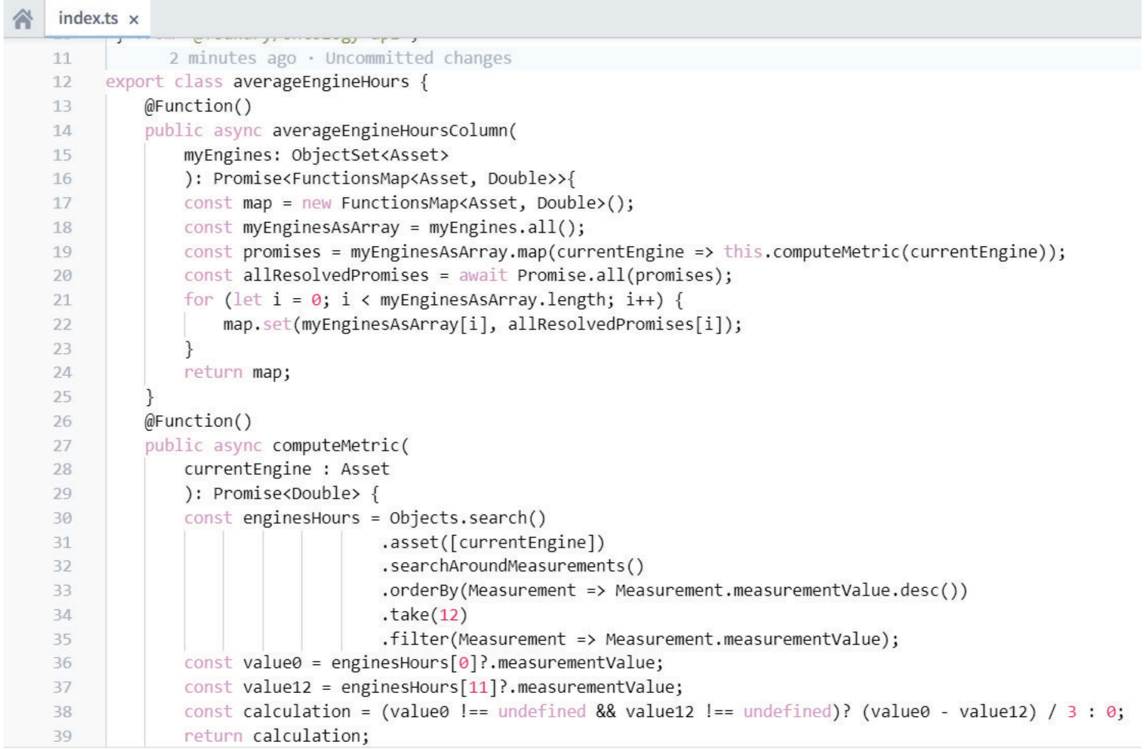
4.5. Engine Hours

The recording of engine hours is a weekly maintenance task within the Unit's Maintenance Management System (UMMS) (MoD, 2020), with the data periodically replicated shoreside and subsequently pipelined into the data lake. This is useful as it allows for the linkage of engine hours (Measurement Object) to an array of other variables. Of particular significance is the ability to discern the operational patterns of these engines. To establish a relational link between the Measurement Object's Asset ID and the corresponding Asset, a simple TypeScript function was coded (see figure 10). This automatically retrieves the latest engine hours, orders them in descending value, then calculates a rolling monthly average based on the preceding three months of UMMS inputs by onboard maintainers.



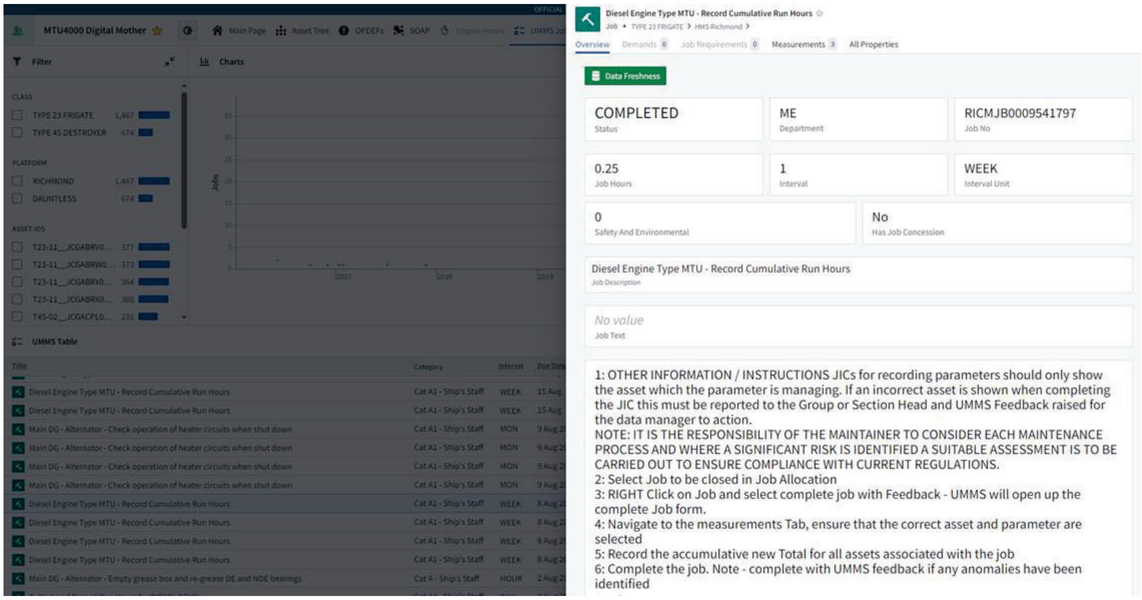
```
    2 minutes ago · Uncommitted changes
export class averageEngineHours {
    @Function()
    public async averageEngineHoursColumn(
        myEngines: ObjectSet<Asset>
        ): Promise<FunctionsMap<Asset, Double>>{
        const map = new FunctionsMap<Asset, Double>();
        const myEnginesAsArray = myEngines.all();
        const promises = myEnginesAsArray.map(currentEngine => this.computeMetric(currentEngine));
        const allResolvedPromises = await Promise.all(promises);
        for (let i = 0; i < myEnginesAsArray.length; i++) {
            map.set(myEnginesAsArray[i], allResolvedPromises[i]);
        }
        return map;
    }
    @Function()
    public async computeMetric(
        currentEngine : Asset
        ): Promise<Double> {
        const enginesHours = Objects.search()
                                  .asset([currentEngine])
                                  .searchAroundMeasurements()
                                  .orderBy(Measurement => Measurement.measurementValue.desc())
                                  .take(12)
                                  .filter(Measurement => Measurement.measurementValue);
        const value0 = enginesHours[0]?.measurementValue;
        const value12 = enginesHours[11]?.measurementValue;
        const calculation = (value0 !== undefined && value12 !== undefined)? (value0 - value12) / 3 : 0;
        return calculation;
```

Figure 10: Foundry's Code Workbook used to create a TypeScript function to automatically retrieve engine hours input by the maintainer at sea, then calculate a rolling monthly average based on the last 12-weeks of data.

Given the absence of historical data for these engines, a statistical framework is used to derive insights from the limited available readings. Assuming a Gaussian distribution, the empirical rule is employed as a convenient alert system. One standard deviation from the mean is acceptable, two standard deviations warrant amber conditional formatting, whilst three standard deviations from the mean prompt an alert to the user, indicating that the average running hours of the engine exceed statistical norms. The emerging trend reveals a heightened level of usage compared to their predecessors, the Paxman Valenta and Wartsila12V200 for Type-23 Frigates and Type-45 Destroyers respectively. So much so that discussions are already taking place on potential changes to major service periods and out of service dates which, due to the increased operation seen, may be earlier than anticipated. Interestingly, Babcock independently came to this same conclusion by monitoring Load Factors (Edge, 2022).

4.6. Maintenance Tasks

The maintenance task, or Job Object, is another pivotal component of the digital picture. Principally, it furnishes invaluable metrics on engine health, affording users the ability to graphically track any maintenance backlog. Integration with the OpDef Object further enables pattern recognition, potentially revealing correlations between defects and neglected maintenance tasks, in addition to prompting the introduction of new tasks as needed, with suggested frequencies derived from historical defect occurrences. As the dataset expands, historical records evolve to drive maintenance decisions based on empirical data rather than time-based or conjectural estimations.



Title	Category	Interval	Due Date
Diesel Engine Type MTU - Record Cumulative Run Hours	Cat A1 - Ship's Staff	WEEK	15 Aug
Diesel Engine Type MTU - Record Cumulative Run Hours	Cat A1 - Ship's Staff	WEEK	15 Aug
Main DG - Alternator - Check operation of heater circuits when shut down	Cat A1 - Ship's Staff	MON	9 Aug 2
Main DG - Alternator - Check operation of heater circuits when shut down	Cat A1 - Ship's Staff	MON	9 Aug 2
Main DG - Alternator - Check operation of heater circuits when shut down	Cat A1 - Ship's Staff	MON	9 Aug 2
Main DG - Alternator - Check operation of heater circuits when shut down	Cat A1 - Ship's Staff	MON	9 Aug 2
Diesel Engine Type MTU - Record Cumulative Run Hours	Cat A1 - Ship's Staff	WEEK	8 Aug 2
Diesel Engine Type MTU - Record Cumulative Run Hours	Cat A1 - Ship's Staff	WEEK	8 Aug 2
Diesel Engine Type MTU - Record Cumulative Run Hours	Cat A1 - Ship's Staff	WEEK	8 Aug 2
Diesel Engine Type MTU - Record Cumulative Run Hours	Cat A1 - Ship's Staff	WEEK	8 Aug 2
Main DG - Alternator - Empty grease box and re-grease DE and NDE bearings	Cat A - Ship's Staff	HOUR	2 Aug 2

Diesel Engine Type MTU - Record Cumulative Run Hours
Job • TYPE 23 FRIGATE › HMS Richmond ›

Status: COMPLETED
Department: ME
Job No: RICMJB0009541797
Job Hours: 0.25
Interval: 1
Interval Unit: WEEK
Safety And Environmental: 0
Has Job Concession: No
Job Description: Diesel Engine Type MTU - Record Cumulative Run Hours
Job Text: No value

1: OTHER INFORMATION / INSTRUCTIONS JICs for recording parameters should only show the asset which the parameter is managing. If an incorrect asset is shown when completing the JIC this must be reported to the Group or Section Head and UMMS Feedback raised for the data manager to action.
NOTE: IT IS THE RESPONSIBILITY OF THE MAINTAINER TO CONSIDER EACH MAINTENANCE PROCESS AND WHERE A SIGNIFICANT RISK IS IDENTIFIED A SUITABLE ASSESSMENT IS TO BE CARRIED OUT TO ENSURE COMPLIANCE WITH CURRENT REGULATIONS.
2: Select Job to be closed in Job Allocation
3: RIGHT Click on Job and select complete job with Feedback - UMMS will open up the complete Job form.
4: Navigate to the measurements Tab, ensure that the correct asset and parameter are selected
5: Record the accumulative new Total for all assets associated with the job
6: Complete the job. Note - complete with UMMS feedback if any anomalies have been identified

Figure 11: User Interface of maintenance task management page including the Job Information Card and completion status alongside relational links into the supply chain if stores are required to complete the task.

The Job Object contains numerous properties, including the Job Information Card and crucial Object links to requisite stores, facilitating a relational pivot into the logistical supply chain data. Consequently, the transition to a data-driven maintenance system inherently translates into efficiencies within the supply chain. Furnished with these datasets, and the relational links between them, provides an opportunity to implement an intelligent maintenance schedule. To a degree, the RN already operates a predictive maintenance schedule based on routine Condition Based Monitoring (CBM) and a Reliability Centred Maintenance (RCM) system informed by manufacturers' input and historical Lessons from Experience. However, the integration of Complex Data technologies enables the construction of this framework from a substantially larger dataset, with scalable pipelines enhancing information latency. The outcome is a higher quality of decision-making and a more efficient maintenance schedule, leading to savings in maintainer time, costs, and environmental impact.

4.7. Stores Items

As the Item Object is already present in the RN Foundry Database, utilising the Asset ID as a primary-key allows a search-around from the engine's assets into stores and demands. This framework, coupled with the information discussed above, affords the opportunity for more accurate predictions of required stores. Such enhancements not only facilitate the deployment of vessels with optimally provisioned storerooms but also enables proactive planning for forthcoming major services. The result of an intelligent maintenance schedule, where the right tasks are conducted at the right time, is a reduction in unnecessary maintenance tasks which were prompted by a low-fidelity dataset. This efficiency will emanate throughout the support enterprise, allowing for timely ordering of stores, arrangement of contractor support and an informed ship's programme based on accurate predictions of engine maintenance requirements.

5. Future development

Whilst developing the first prototype of an engine's digital replica in Palantir Foundry, numerous areas for development were noted.

5.1. Improve the effectiveness and efficiency of the inputs

- Regarding SOAP data, there is potential to automate the ingestion by utilising a webhook system or having the tester send their lab results directly to Foundry. Additionally, this scalable data-pipeline could be expanded to other Condition Based Monitoring data such as cylinder pressures and vibration analysis. This data can be easily sourced from maintainers and integrated into UMMS as part of routine tasks, facilitating automatic feeding into Foundry.

- Engine Control Unit (ECU) data is currently decoded and analysed by RR MTU IT Teams. However, due to the issue of low-connectivity, and lack of Foundry access, this is dependent on downloading and manually sending data. This '*air-gap*' is similar to the one experienced by the RNLN project (Tiddens et al., 2020) and further collaboration is required to seamlessly ingest the ECU data for integration of load profiles and error code history.

5.2. Automate the outputs

- Leveraging machine learning techniques would allow Condition Based Monitoring (CBM) data to be used to produce real-time failure forecasts. The format of the SOAP data ingested by Foundry's Pipeline Builder already lends itself to supervised machine learning via regression algorithms. Once this is initialised, the existing alert system could be further developed to provide 'time-until-failure' predictions for Assets sensitive to contaminants.

- By extending machine learning to the supply chain, an additional degree of automation could be achieved. Potentially, the RN could then have a situation where the engine's digital replica orders its own stores and arranges its own contractor support, to conduct maintenance it predicts it will need on a future given date.

5.3. Royal Navy Engineer Digital Consultancy

Establishing a RN engineer digital consultancy would be a worthwhile investment. This would involve creating a dedicated team of RN engineer data consultants who can swiftly tackle organisational challenges by leveraging Complex Data to inform decision-making. These consultants, drawn from SME-users within the RN, would possess a unique blend of frontline experience and technical proficiency developed through training in SQL, JavaScript, and Python, combined with secondments to organisations like Palantir. Following the lean-startup methodology, the consultancy would prioritise rapid deployment of low-complexity apps to address identified problems. This approach allows for quick iterations based on real user feedback, ensuring that solutions are continually refined and improved. By replicating successful models at pace and scale, the consultancy can overcome the sluggish adoption rates previously seen. A key aspect of the consultancy's approach is its hands-on engagement with end-users. Consultants would parachute into teams, solicit their input, and quickly develop solutions tailored to their needs. Moreover, they would not only deploy these solutions but also provide training to empower teams to utilise and even develop their own digital solutions in the future.

Establishing a RN Digital Engineer consultancy would enable the organisation to harness the power of data effectively, drive innovation, and expedite decision-making. By combining frontline expertise with technical proficiency and a proactive, user-centred approach, the consultancy would represent a significant step forward in modernising and optimising RN digital engineering.

6. Results and Conclusion

The inherent limitations of low-connectivity persist in impeding the realisation of a true IoT-style digital engine replica. However, by aggregating data from all engines within a class, the dataset's fidelity can be significantly enhanced, nearing the desired level of accuracy. Leveraging Foundry as a robust platform for constructing digital models presents a viable solution, particularly given its accessibility to end-users. With minimal training in coding and data engineering, users can advance towards more intelligent and automated systems. In that context, the initial prototype of the engine's digital mother has been broadly successful with the immediate results given below:

- The Asset page is used for scrutinising sub-components and has uncovered disparities between the ships operating these engines. Subsequent data clean-up measures are underway to pay down this technical debt (Cunningham, 1992).
- The OpDef page is used to scrutinise historical defects, ensuring their accurate classification under the correct sub-components to facilitate future predictive analyses.
- The SOAP page is being used to identify potential correlations between CuNi contamination and recent fuel injector failures, aiming to discern any underlying patterns.
- Engine hours serve as a basis for forecasting long-term milestones such as major services and anticipated out-of-service dates.
- Investigation of the Job Object has brought to light numerous discrepancies in the allocation of maintenance tasks across different engines, necessitating further analysis and corrective measures.
- The Item Object and its relational links to defect data, engine hours, and operational usage information, enhances the advisory capability to recommend optimal inventory levels for ship's stores.
- Endeavours to ingest Engine Control Unit data have unearthed various challenges in transnational data transmission to RR MTU, and in providing Foundry access to other industry partners. While interim solutions are viable, collaborative efforts hold promise for enriching the existing Foundry dataset with engine load profiles and error periodicity.

Finally, incorporating RN engineers into the development of these tools is paramount. Drawing on their wealth of lived experience, they possess an intimate understanding of operational challenges and can intuitively envision the most effective solutions. By prioritising investments in expanding their skillset to include coding and data engineering, the continued enhancement of these tools is assured.

As the RN enters its third year of embracing Complex Data, there is reassurance in observing a slight improvement in its 194-year adoption rate. Whilst this problem would be incomprehensible to Sir James Lancaster, the solution method utilised would be very familiar.

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The views expressed in this paper are that of the author and do not necessarily represent the views of the RN.

References

Blank S.G. (2003). The Four Steps to the Epiphany: Successful Strategies for Products that Win. K&S Ranch Publishing Inc.

Bowen H.V., McAleer J., Blythe R.J. (2012). Monsoon Traders: The maritime world of the East India Company. Scala Publishers Ltd for National Maritime Museum, citing Markham C.R. (ed). The Voyages of Sir James Lancaster, Kt, to the East Indies. The Hakluyt Society.

Cunningham H. (1992). The WyCash Portfolio Management System. In Proceedings of the OOPSLA-92 Conference on Object-Oriented Programming Systems, Languages, and Applications. ACM.

Edge W., Fox M. (2022). Delivering the UK MoD's support DEAM. Proceedings of the International Naval Engineering Conference 2022.

Kim, G. (2019). The Unicorn Project. IT Revolution Press.

Ministry of Defence. (2020). Book of Reference (BR) 1313. Hampshire: Navy Publications and Graphics Organisation.

Moore G.A. (2014). Crossing the Chasm: Marketing and Selling High-Tech Products to Mainstream Customers. Harper Business Essentials.

Morariu A-R., Ashraf A., Björkqvist J. (2021). A Systematic Mapping Study on Edge Computing Approaches for Maritime Applications. Proceedings of the 47th Euromicro Conference on Software Engineering and Advanced Applications (SEAA).

Richardson, C., Rymer, J. (2014). New Development Platforms Emerge For Customer-Facing Applications: Firms Choose Low-Code Alternatives For Fast, Continuous, And Test-And-Learn Delivery. Forester Research, Inc.

Ries E. (2011). The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses. Crown Business.

Rijsdijk C., da Silveira N.N.A., Tinga T. (2020). Using ship sensor data to achieve smart maintenance? Proceedings of the International Naval Engineering Conference 2020.

Seagrave S. (2023). Data Bites #38: Getting things done with data in Government [Video]. Institute for Government. https://www.instituteforgovernment.org.uk/ecent/data-bites-38-getting-things-done-data-government. Accessed April 2024. Timestamp (45:08).

Syed M. (2015). Black Box Thinking: Why Some People Never Learn from Their Mistakes - But Some Do. John Murray Publishers.

Szent-Györgyi, A. (1932). Hexuronic Acid as the Antiscorbutic Factor. Journal of Biological Chemistry, 97(1), 39-44.

Tiddens W., Pollmann, B., Curvers D., Teunisse M., Shaneh Saz S., Zegers J. (2022). Smart Maintenance for Modern Naval Ships. Proceedings of the International Naval Engineering Conference 2022.

Tröhler U. (2003). James Lind and scurvy: 1747 to 1795. JLL Bulletin: Commentaries on the history of treatment evaluation (https://www.jameslindlibrary.org/articles/james-lind-and-scurvy-1747-to-1795/)

Van de Kerkhof R. (2020). It's about Time: Managing Implementation Dynamics of Condition-Based Maintenance. CentER, Tilburg University.