# Virtual integration: managing complex warship design through model based engineering

W J Tudor* MEng (Hons) MSc
N Harrison** MEng (Hons)

**BAE Systems Maritime – Submarines, UK*
***BAE Systems Maritime – Naval Ships, UK*
**Corresponding author email: williamjtudor@gmail.com*

## Synopsis

Modern warships have become increasingly complex systems, capable of performing a variety of roles, in demanding environments whilst under the presence of a military threat. As the complexity of warships has increased, so too have the systems and processes established to design and manufacture them. Warship designers have become systems engineers charged with delivering integrated products often within programmes constrained by cost, risk, resource and commercial construct.

For centuries, if not millennia, models have been an essential component of the warship design process providing a contextual reference for what the finished product may look like and how it may perform. Traditionally, these models have focussed on the physical performance attributes of the warship, its hull-form, its length, beam and displacement, its propulsion system and its likely payload; in unison these models provide an early understanding of key characteristics such as range, speed, complement and sea-keeping. However, with the reduction of ships' companies and the proliferation of increasingly complex software-based control systems, coupled with a backdrop of squeezed defence budgets/development timescales, the call upon models to help manage and de-risk such complexity is becoming prevalent.

Across the industrial landscape, model based systems engineering, architectural frameworks and the Systems Modelling Language have become common tools within the systems engineer's arsenal as a means for managing system complexity and mitigating system integration risk. Within the warship design domain, the use of model based systems engineering has been most widely deployed by combat system designers, largely in recognition of the software based nature of these systems. This paper discusses how such approaches are equally applicable to the wider warship design and manufacture process – notably the development of Marine and Platform Systems; it describes the deployment of model based engineering and the Systems Modelling Language to de-risk modern warship design. It presents an overarching modelling framework and corresponding design methodology that can be deployed in concert with the more traditional modelling techniques used in warship design, to more effectively reduce risk and manage whole-ship integration.

Keywords: systems engineering, model based engineering, integration, requirements, de-risking, complex systems, architecture frameworks.

## 1. Introduction

### *1.1 Modern Complex Warships*

Modern warships have evolved to become some of the most complex man-made systems around [1]. From fulfilling a variety of military anti-surface, anti-submarine and anti-air warfare roles, to conducting counter-piracy/counter-narcotics operations or to offering humanitarian/disaster relief overseas – the capability demands placed upon a modern warship are challenging and wide-ranging. If these demands were not difficult enough, a modern warship must also operate independently as a total military system or as part of a task-force, working across a wide-spectrum of climatic conditions and environments whilst simultaneously providing a suitable home for its sailors; perhaps it's inevitable that modern warships have become so complex.

At any single point in a warship's lifecycle the active capability demands are significant enough to drive complexity into the design, however a warship has a life-span that extends into decades not years. Predicting what future capabilities a warship will need to deploy 10, 20 or even 50 years into the future is an incredibly

**Authors' Biographies**

Will Tudor is the Head of Engineering – Function for BAE Systems Maritime – Submarines. Prior to that Will worked for four years as the Systems Integration Technical Authority in BAE Systems Maritime – Naval Ships where he led the deployment of systems engineering in the platform and marine design teams. He has worked in BAE Systems plc for the last eleven years having joined the company on the prestigious Sigma Leadership Development Programme. He has worked across multiple business units and roles within BAE Systems including leading the integration of Radar 997 with the Type 23 Frigates and the replacement of Sonar 2076 on the Astute and Trafalgar Class submarines. Will undertook his undergraduate master's degree in civil engineering at Durham University and completed an MSc in systems engineering management at University College London in 2015.

Neil Harrison is a Technologist in the research department in BAE Systems Maritime – Naval Ships where he is working to seed new engineering approaches in the business, based on the latest technology developments in model based engineering and data science. He's also undertaking a PhD in a related field at The University of Strathclyde in the department for Design Manufacture and Engineering Management (DMEM). He has worked in BAE Systems plc for the last decade in various capacities delivering across systems engineering, engineering management and information management. Neil graduated MEng in Mechanical Engineering from The University of Strathclyde in 2009.

---

difficult task, particularly in the current era of rapid software based technology and military capability evolution, and this drives further complexity and non-deterministic problems into the warship design process.

### *1.2 The Development Challenge*

The complexity of a modern warship's design is arguably matched by the complexity of the warship design process itself [6]. The task of achieving a balanced, functionally and physically integrated design – that meets its existing military needs whilst also accommodating for emerging threats – represents a major challenge for warship designers. They are tasked with designing a ship that is "essentially bespoke for each new class" [7] with the rare disadvantage that a full-scale physical prototype is still prohibitively costly despite the integration risks.

As the complexity of a warship's functional and physical design increases so too does the variety and number of risks that could lead to a failure in systems integration. Typically, programmes respond to this increasing risk picture by growing the size and nature of the design team itself. The design team and the design development process are segregated into individual areas through a 'divide and conquer' approach whilst still endeavouring to achieve a single point of truth for the design baseline. Specialist teams are formed and charged with handling a particular aspect of the design (such as Underwater Radiated Noise) or with accountability for a particular sub-system (such as the Platform Management System) [4]; these teams have an engineering skillset commensurate with the nature of the tasks and risk set that they are charged with resolving.

By its nature, the 'divide and conquer' approach, however necessary, drives complexity into the warship design process. The importance of integrating the design teams becomes as important as integrating the warship – because one doesn't come without the other.

## 2. Model Based Engineering

### *2.1 Model Based Systems Engineering*

Over recent years, the term Model Based Systems Engineering (MBSE) has been used to describe "the formalised application of modelling to support systems engineering," [14]. MBSE is essentially about placing models in a central and leading role the engineering process to drive requirements exploration, specification, design, integration, validation and operation of a system [14].

The benefits of moving to a model based approach are well documented [13,14,16]. Essentially, the principle of MBSE is that the quality of a system specification can be enhanced by capturing information as elements and relationships within a model, rather than unstructured data distributed across documents. Further, a principal outcome of a model based approach is that it enables data-centric systems engineering to be at the core of the design process as opposed to document-centric – this is seen as reducing design risk by removing the issues that documents pose (i.e. difficulty in maintaining consistency, language, configuration etc.) [4].

### *2.2 MBSE in Warship Design*

Warship designers have long used models as a means for mitigating design risk and enabling design cohesion. From scaled down physical mock-ups of the ship to complex mathematical representations of its behaviour; models provide insight into the finished product that would otherwise be gained only through its manufacture and test.

However, the traditional approach to warship design has largely been predicated on a document-based systems engineering methodology [11]. Aside from the physical CAD model, models have been used elsewhere to understand the design and explore functional behaviour/performance characteristics; having undertaken such analysis, the outcomes and the design intent continue to be captured in documents. The problem with this approach is that there are typically many document authors all with their own assumptions, perspectives and style of presenting information [4]. Multiple documents will tend to repeat the same information in different ways or, at worst, be inconsistent or contradictory. A great deal of effort is incumbent on a document-centric design team in passing design documents back and forth, which is not only inefficient but also highly error prone. As stated above, designing a modern warship is taxing enough without compounding the situation with the degeneration of veracity of the data captured in documents.

### *2.3 The Need for Logical Architectures*

To date, there has been mixed uptake of MBSE across the warship design community [9]. Largely, combat system design has been the domain where MBSE has been embraced most fully – which perhaps is to be expected given the predominance of software in combat systems and the fact that MBSE originated from within the software engineering community.

However, outside of combat system design the use of models as the primary representation the system is not so common [6]. Where models have been used, they have largely focussed on exploring the physical performance attributes of the warship through consideration of its hull-form, length, beam, displacement, its propulsion system and its likely payload, and the interplay that these characteristics have on top-level performance outcomes.

Models are used extensively within the early design phases of warship's lifecycle to understand likely performance outturns. Rapid iterations of the parametric design are undertaken [5] with key requirements being plugged into mathematical models to explore the design trade-space and provide a rough estimate of the ship in terms of its initial size and parametric performance, and the effect that these characteristics will have on capabilities such as speed, range, sea-keeping, manoeuvrability and payload [10].

Whilst such models play a critical role in the whole-ship design process during these early lifecycle phases – providing designers with a means of analysing and settling upon key performance outcomes and the overall capabilities of the ship – two challenges remain:

1. First, by focusing predominantly upon the interplay between the physical attributes of the ship and its performance outcomes at the whole-ship level, the process risks placing limitations on the functional/logical design early in the lifecycle and introducing design constraints that could threaten the design team's ability to reach global optima later. Typically, little time is spent on modelling/defining the system's architecture, instead "for ships, the 'general arrangement' is the primary mechanism for…..maintaining overall design cohesion," [9]. Where modelling is undertaken, it tends to focus on the physical attributes of the platform rather than its functions/operations.
2. Second, documents continue to form the basis for mastering resultant design data across the various disciplines and therefore attracting the complications listed above. Where systems are inherently complex in nature, particularly where there is a large software based control component, the challenge of achieving successfully integration whilst trying to manage data through documents is magnified even further [4, 5].

The benefits of well-defined systems architectures have not been fully realised by the design community beyond combat systems [10]. The overall community of naval ship designers doesn't tend to take a holistic system perspective in the decision making process, instead relying upon their domain specific training and experience. Although feasible, this approach does not readily support transparency in decision making, interrupting traceability back to the originating user requirements. Architectural decisions are often made on a technical basis without systematic consideration of how the decision may affect the whole-ship. As a consequence, there is an increased risk of undesirable emergent properties occurring at the integrated platform level some-time after the decisions that led to them, leading to higher and avoidable costs of rework [3, 5, 10].

Considering these challenges, the need for a robust process for developing system architectures to describe a warship's functional, physical and operational breakdown is evident. This is particularly the case given the additional complexity that warship designers now face stemming from; the reduction of ships' companies, the proliferation of increasingly complex software-based control systems and a backdrop of squeezed defence budgets/development timescales. The call upon models to help manage and de-risk such complexity is becoming exigent.

## 3. A Model Based Warship Development Framework

The background outlined above demonstrates readiness for a holistic data-centric model based warship design development framework to capitalise upon the existing use of models whilst augmenting them through an emphasis on functional/logical architectures and transcend traditional document-based design methodologies.

Architectures describe the most important aspects of a system, its components and how they interrelate [12, 18]. Architectural frameworks are used to direct the development of consistent architectural models; they define how system models are developed and structured as well as providing a meta-model that underpins consistency in language/visualisation.

The hypothesis of this paper is that an architectural framework aligned to the warship development lifecycle would reduce the risk of successful whole-ship integration by:

- Enabling a richer exploration of the requirement space and facilitating a full and traceable mapping between the requirements and the design,
- Promoting commonality, coherency and consistency across the design dataset and the design teams,
- Stimulating logical and functional design, that can be assessed for safety, operability, security and other such transversal factors,
- Providing a traceable link between the functional design, the physical design and the expected performance characteristics of the warship,
- Reducing document dependence and enabling automated document generation where unavoidable,
- Reducing the challenges associated with integration testing and evaluation by enabling 'virtual commissioning',

- Providing the basis for a verifiable dataset that can be validated through real-world commissioning and act as a 'digital twin' for the ship in-service,
- Providing enhanced collaboration across organisational boundaries and greater ability to leverage innovation across the supply base.

### *3.1 Overview*

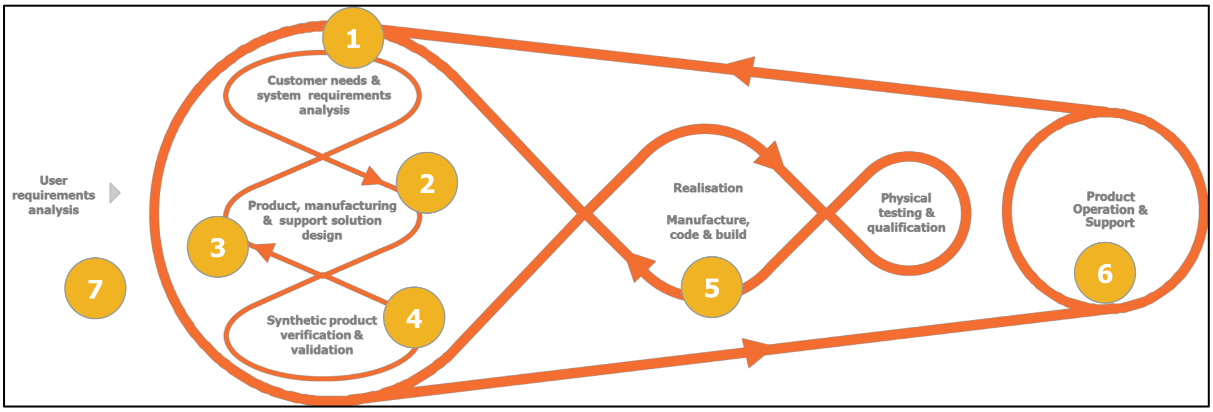


Figure 1: Model Based Development Racetrack

Figure 1 presents a framework, developed in BAE Systems, that depicts the inter-relationship between modelling activities and the product lifecycle; it provides a high-level context for how various modelling types interact and deliver value. The framework has relevance for the development of any complex product, but particular relevance in warship development due to the notable system complexity and the infeasibility of full physical prototyping – the first in a new class of warship is brought to life fully for the first time at sea trials with an operational readiness date often not far behind.

The framework integrates the three most widely utilised ways of describing the warship lifecycle, whilst presenting modelling as the core practice to enable effective delivery:

1. First, it relates to the CADMID lifecycle often used to describe the warship lifecycle [4] (i.e. it demonstrates progression, within a model based environment, between phases of early requirements exploration, concept design/assessment and then manufacture, qualification, acceptance and in-service operation).
2. Second, it also broadly maps onto Forsberg and Mooz's (1992) 'Vee-Model' (i.e. it is characterised by the establishment of requirements, the specification / design of sub-systems, the manufacture of sub-systems followed by overall integration and transition into service) [8].

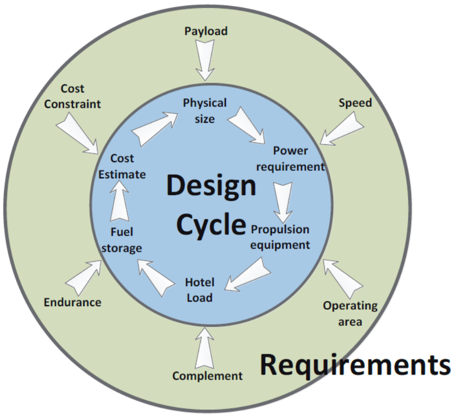
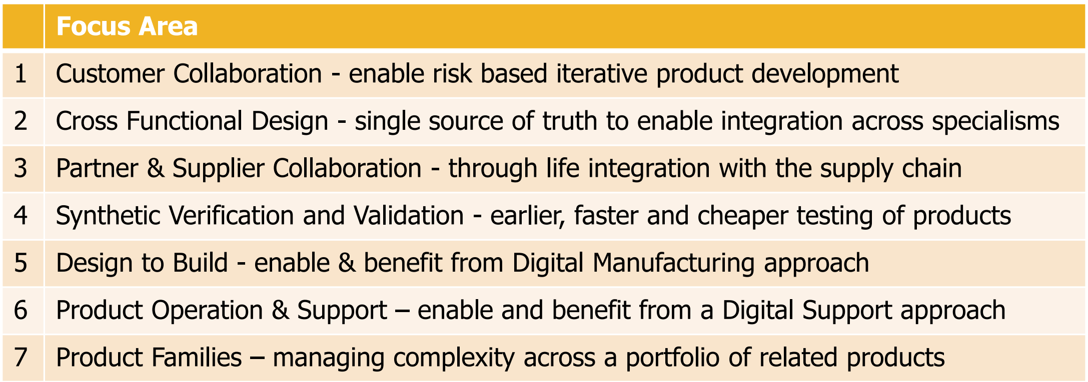


Figure 2: Cyclical Design (reproduced with permission from Edmondson (2018) [20])

3. Finally, it recognises the cyclical nature of warship design, as characterised by Edmondson (2018) [20] as a set of 'circular argument[s]' that depend on one another to satisfy independent requirements (Figure 2). Rapid iteration of the physical and functional models occur in the early lifecycle phases, as the trade-off between requirements and overall design concept is explored. The difference with the framework is signified by the 'race-track' aspect, acknowledging the need to retune/refine the models as the development progresses and creating an expectation for an equitable balance between functional/logical architectures right from the start, and that these be maintained throughout the product lifecycle.



| | Focus Area |
|---|---|
| 1 | Customer Collaboration - enable risk based iterative product development |
| 2 | Cross Functional Design - single source of truth to enable integration across specialisms |
| 3 | Partner & Supplier Collaboration - through life integration with the supply chain |
| 4 | Synthetic Verification and Validation - earlier, faster and cheaper testing of products |
| 5 | Design to Build - enable & benefit from Digital Manufacturing approach |
| 6 | Product Operation & Support – enable and benefit from a Digital Support approach |
| 7 | Product Families – managing complexity across a portfolio of related products |

Figure 3: Modelling Focus Areas

The framework also presents six 'focus areas' (Figure 3) that describe where the benefits from particular model based activities are realised; these are articulated in more detail in sections 3.3 to 3.8.

Before going into further detail on these, it is worth noting that currently no single 'model' or modelling toolset is capable of managing all the design data necessary for a warship's development. Just as documents have different purposes and provide different levels of information, so too do we need models targeted at addressing particular design considerations.

The framework therefore does not seek to present a vision of all aspects of the design being managed within a single model/toolset but rather one that depicts a product development lifecycle that is data and model-centric with a variety of models being interconnected and federated through a common model based approach.

### *3.2 Model Variety & the Systems Modelling Language*

To bring this framework to life, it's worthwhile considering the extent of modelling that can be used within a model based warship development lifecycle; these largely fall within the following categories:

- **Operational Models** – provide the top-level context for whole-ship outcomes/scenarios that the ship would be required to deliver. Examples could be a pictorial representation of whole-ship evolutions (such as Replenishment at Sea or Entering/Leaving Harbour), operational use case diagrams depicting the role of the Operator in delivering evolutions or system-level use cases describing how a system is to be operated. The Operational Models provide context to the whole-ship requirements and the military capability expected of the vessel.
- **Requirements Models** – provide context to how the top-level requirements set is decomposed. Models of the requirements can assist in assessing requirement completeness/consistency and present a framework against which verification and validation can take place.
- **Logical/Functional Models** – provide an understanding of required behaviour of systems/sub-systems to achieve whole-ship outcomes. They relate back to the whole-ship and system-level use cases described within the Operational Models and provide additional context on how functional/dynamic behaviour should be achieved. Examples of functional models using the Systems Modelling Language (SysML) notation described below would be Activity Diagrams, Sequence Diagrams and State Machines.
- **Performance Models** – provide a mathematical expression of the expected behaviour of the warship. Examples could be the parametric models used to understand the impact of hull-form on speed/range, electrical models used to understand Quality of Power Supply (QPS) risks or models of the ship's Radar Cross-Section (RCS). The performance models are key to ensuring that the desired behaviour (articulated functionally) is matched by performance that is within tolerable limits (as expressed through the predicted actual performance of the kit).
- **Structural Models** – describe the warship's systems, their structure and hierarchy (i.e. components of a system) as well as the inter-relationship between systems (i.e. the nature and type of interfaces between sub-systems). Structural models provide an overview of the actual physical decomposition of the warship's systems into equipment and components and can be used therefore to interrogate alignment between function, form and performance.
- **Spatial Models** – these are a 'physical' representation of the ship and its equipment. Examples would be the CAD model, Bill of Materials (BOM), the General Arrangement and manufacturing output data. The spatial model could also be, for example, a 3D scan of the warship 'as built'.

Within BAE Systems Maritime – Naval Ships, the above framework and modelling types have been used to de-risk the design of our Marine and Platform Systems. Table 1 (included in the Annex) shows a representative list of the different models used in this process.

The following six sections expands further on how models can be used in the warship development lifecycle, as a way of fully articulating the utility of the race-track framework.

### *3.3 Customer Collaboration*

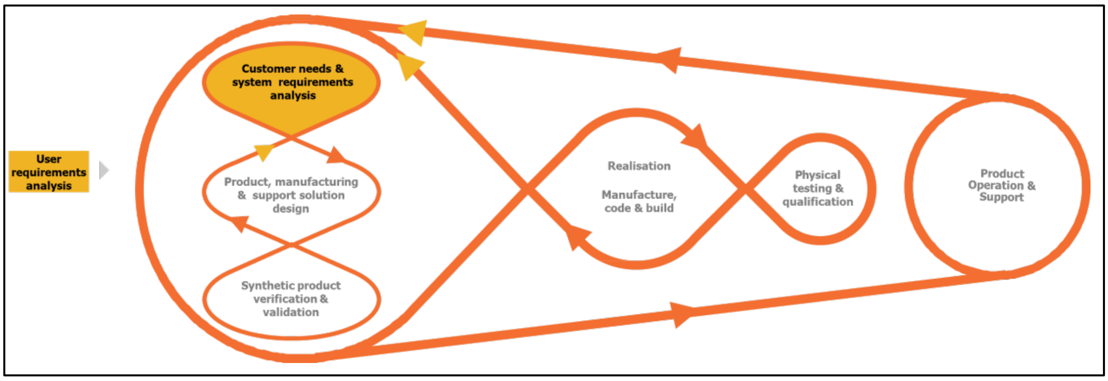
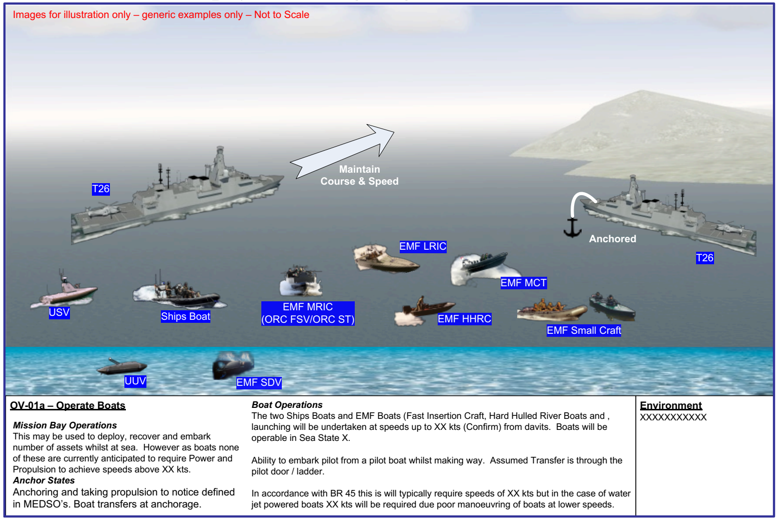


Figure 4: Customer Collaboration

The first phase of development in warship design is associated with establishing a thorough understanding of customer need and whole-ship / system-level requirements.

Through the adoption of a model based approach, customer collaboration and engagement can be enhanced through the exploration of model based designs, end-user centric visualisation, and experimentation augmented with representative operational and engineering data:

- The warship's Concept of Operations (CONOPS) can be explored through pictorial representations (such as in Figure 5) and the development of Whole-ship Use Cases (via SysML use case diagrams), to aid understanding and enrich requirements elicitation,
- The initial whole-ship functional/logical structure of the warship can be understood and captured using SysML activity diagrams to articulate logic and trace functionality back to the CONOPS,
- 'Traditional' modelling techniques can be deployed at this stage to understand the interplay between the General Arrangement, the ship's initial performance characteristics (e.g. range, speed, payload etc.) and the functional architecture. In so doing, greater coherence could be maintained between the operational, functional and physical design right from the outset.



**OV-01a – Operate Boats**

***Mission Bay Operations***
This may be used to deploy, recover and embark number of assets whilst at sea. However as boats none of these are currently anticipated to require Power and Propulsion to achieve speeds above XX kts.

***Anchor States***
Anchoring and taking propulsion to notice defined in MEDSO's. Boat transfers at anchorage.

***Boat Operations***
The two Ships Boats and EMF Boats (Fast Insertion Craft, Hard Hulled River Boats and , launching will be undertaken at speeds up to XX kts (Confirm) from davits. Boats will be operable in Sea State X.

Ability to embark pilot from a pilot boat whilst making way. Assumed Transfer is through the pilot door / ladder.

In accordance with BR 45 this is will typically require speeds of XX kts but in the case of water jet powered boats XX kts will be required due poor manoeuvring of boats at lower speeds.

**Environment**
XXXXXXXXXXX

Figure 5: Example OV-01a Diagram

The development of operational and logical models to expound the requirements set should start prior to a programme's full inception, but should also continue iteratively throughout the development lifecycle and into support and operations.

By capturing such information within a model based approach, the benefits are enhanced traceability (from requirements through to design) and communication (because the data is reproducible/consistent) [16]. Contrast this with a document centric approach where the operational scenarios are either implicit or captured across multiple sources and the original rationale behind the requirements can be easily lost [19].

### *3.4 Cross Functional Collaboration*

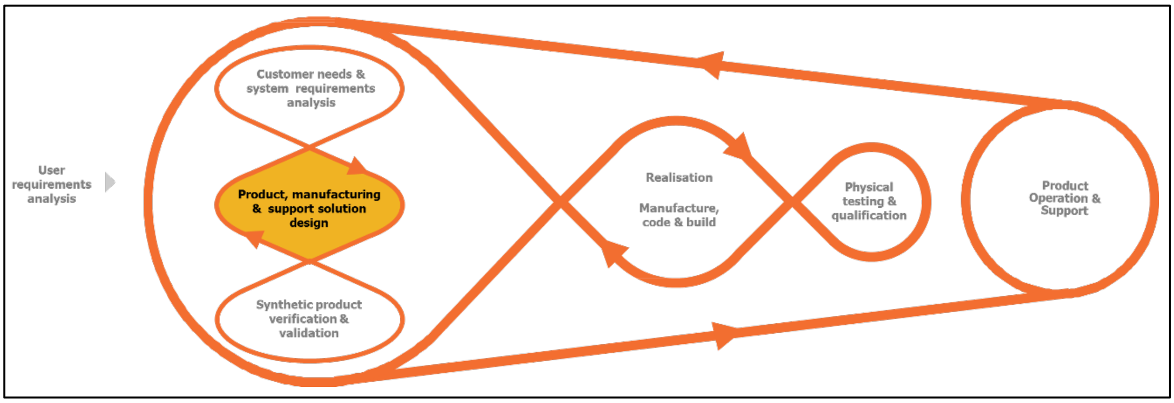


Figure 6: Cross Functional Collaboration

The second focus area concentrates on developing a model based design that is a multi-disciplinary ‘single source of truth’. As discussed, the complexity of modern warship design requires an increasing number of engineering specialisms to work concurrently around an evolving system description. A shared digital representation of the design acts as a single source of truth, removing ambiguity between engineering teams and other functional specialisms. Reviewing a common articulation of the design, using a standard widely understood notation such as SysML, enables a culture of collaboration through the elevation of data, information and knowledge [11, 16, 19].

Synergistic model based design and synthetic verification and validation presents the opportunity to lower the cost and time implications of exploring designs, enabling more novel concepts and innovative ideas to be iterated through design and tested rapidly.

The types of modelling that could be undertaken to develop the product, manufacturing and support design solution include:

- Detailed development of the functional/logical model,
- Settlement on the structural model and the over-arching systems architecture,
- Maturation of the General Arrangement and development of the physical model,
- Further exploration of the warship’s performance characteristics and behaviour as the functional design matures.
- Describing the relationship between the enterprise build and commissioning process / plan and the design, to refine and optimise.

Continuing to keep the customer in the loop throughout means innovation, management of risk and maturing the design are done in concurrence with direct understanding of operational context and user requirement.

### *3.5 Partner & Supplier Collaboration*

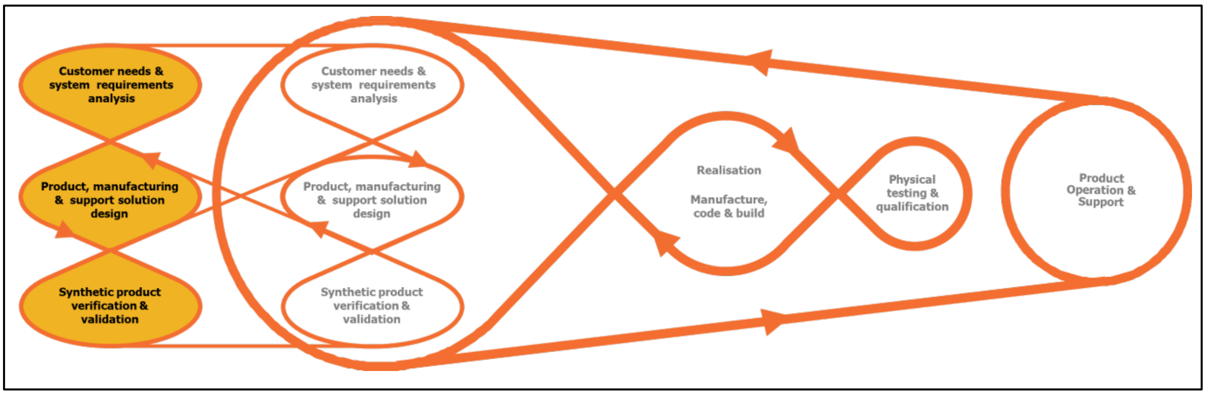


Figure 7: Partner & Supplier Collaboration

A key component of successful warship design is the integration of supplier and government furnished components, equipment and sub-systems. Establishing a model based data architecture that enables this type of enterprise interoperability has the potential to revolutionise the interaction and integration of supply chain partners throughout the product development lifecycle.

Collaboration with the customer can be extended to include key suppliers of systems that underpin or directly deliver critical end-user capability, enabling risk and opportunity to be explored thoroughly and to gain operational insight. Through the establishment of trusted digital interfaces, rapid information exchange would be made possible, enabling incremental delivery/assurance against requirements, specifications and the design of components; this would in turn enable more seamless integration into the product throughout its development.

The same types of modelling as articulated before could be undertaken during these phases of work with the emphasis being on garnering design understanding through collaboration with the supply base to de-risk the overall integration programme and enhance design maturation.

### *3.6 Synthetic Verification & Validation*

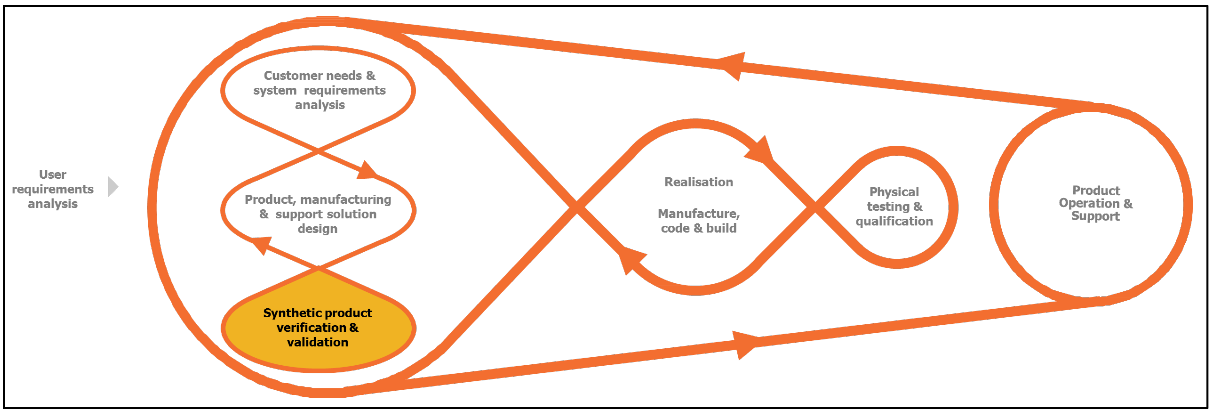


Figure 8: Synthetic Verification & Validation

Having explored the requirements set and established the architecture for the design within the model, recent advances in modelling capability now enable aspects of the warship's design to be tested within the virtual environment – the realisation of a 'virtual commissioning' in effect:

- Mathematical models provide a view on expected performance outcomes; when coupled with 'real-world' data obtained through shore-based testing verification can then take place to provide additional confidence on the design (possibly in real-time cyber-physical hybrid test systems),
- Simulated functional behaviour and the transition of systems between states can be executed through SysML State Machines,
- Exploration of the physical environment can be obtained through 3D visualisation of the CAD model and 'immersive' Operator experiences to give a sense of the look and feel of the finished vessel,
- Testing may range from specific component level testing of physical and functional properties through to integration test to visualisation and experimentation at a system, or integrated capability level, with human operators in the loop,
- Application of statistical computational methods to quantify and propagate sources of uncertainty across multiple models and real-world systems in sets of simulations that explore feasible bounds of performance and expose emergent sub-system interactions or failure modes.

Undertaking synthetic verification and validation (V&V) through a 'virtual commissioning' approach should have the effect of reducing the effort and variability involved in real-world verification and validation, enabling efficiency gains. Of course, physical testing will always be required, but the extent of this could be minimised as confidence in the fidelity and representability of the model increases. Indeed much physical testing will be providing V&V for the synthetic test environments as standalone system development assets. This paradigm could be further extended into the operations and support phase of the lifecycle where Digital Twins will provide continuous through life assurance.

### *3.7 Digital Manufacturing*

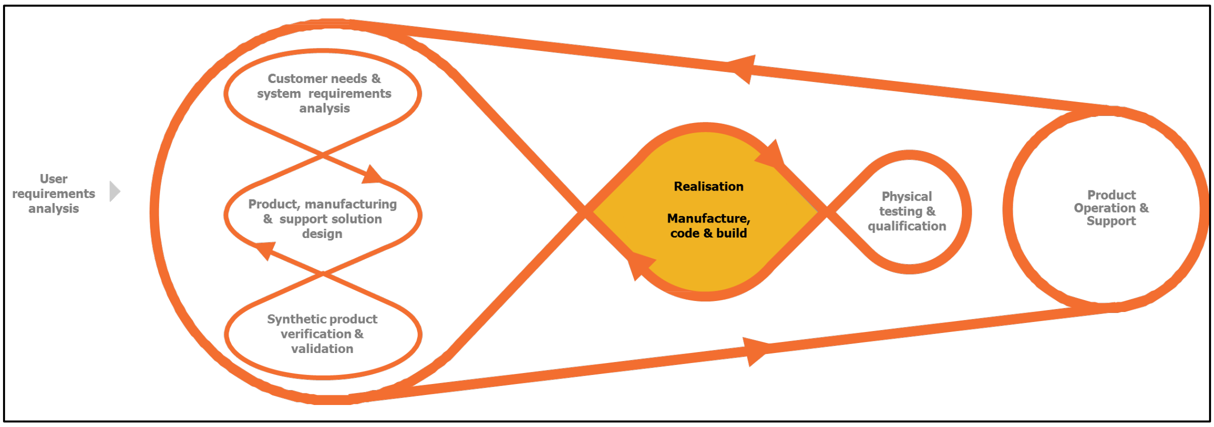


Figure 9: Digital Manufacturing

Digital models enable the transition from design to manufacture to be eased. A digitally enabled shared reality between the upper level of the design process and its final specifications in PLM and CAD prevents drift in coherence between that which is procured/manufactured and that which was anticipated at the point of design/specific in design. Sustaining this level of interlock between representations is further enabled by digitally codifying the processes of producing manufacturing drawings and information into in rule-based direct feeds of master data into build instructions, in some cases even without intermediate human-readable representation such as in the case of Additive Layer Manufacturing.

As Industry 4.0 continues to make advances in digitising and automating the manufacturing environment, enterprises with rationalised and managed digital assets describing both sides of this partnership will be most able to capitalise on the opportunities it presents to get complex and unique systems realised with minimal fuss and waste. This unfolding collapse of the traditional divide between engineering and manufacturing into more connected digital representations with less static manually produced documents frees up the people to focus on reducing the gap between 'as designed' and 'as manufactured' standards.

The ability to create and maintain Digital Twins of all products manufactured helps to enable support and provide feedback to design processes to validate assumptions and provide continuous improvement. This is augmented by a reduced set of physical testing used to validate synthetic testing approaches.

### *3.8 Product Operation & Support*

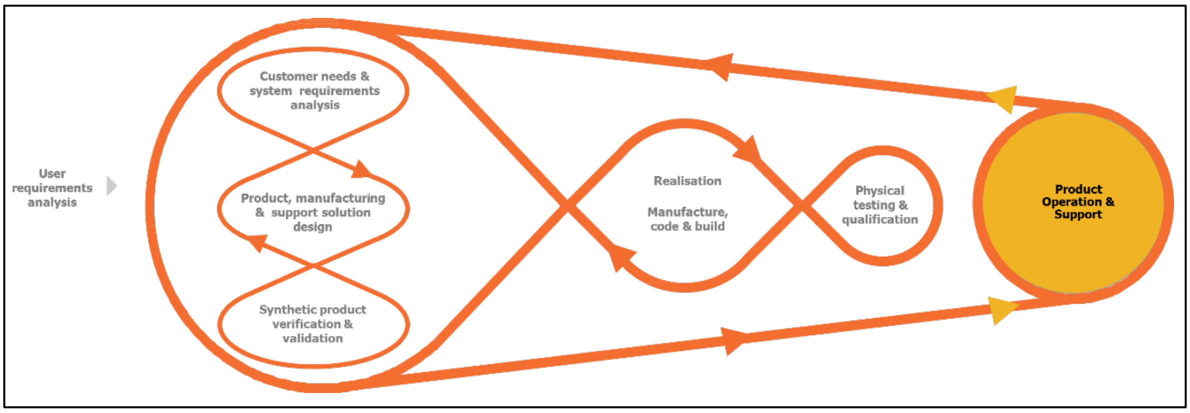


Figure 10: Product Operation & Support

By using modelling right from the outset, Digital Twins can be developed that provide relevant and validated functional, physical and performance information, gathered to in-service teams:

- By having Digital Twins, support engineers can assess opportunities for system optimisation and continuous improvement against a validated virtual reference set. The Digital Twin can be used to analyse 'real-world' information, transmitted from the ship, to assess and improve the quality of system performance. Ultimately this means that decisions can be made on how to optimise existing whole-ship performance and make improvements that align with the operational needs of the ship.
- By gathering whole system operational data and insight through embedded Digital Twins, the design teams have a truly closed feedback loop and are directly connected to the reality, foibles and human nuances of the physical system being operated in service, enabling future designs to deliver capability

in inventive ways that may be outside the customers current paradigm (i.e. we increase our influence and value-add at the very highest level concepts of operation and user requirements).

## 4. Conclusion

The paper has presented a vision for a warship development lifecycle underpinned by Model Based Systems Engineering. Modern warships have additional complexity compared with their counterparts because of the challenging requirements set that they have to fulfil and because of the proliferation of increasingly software based control. In turn, the warship design and development process has become equally complex with multiple specialist teams needing to come together successfully to achieve a balanced, integrated design.

Increasingly complexity drives modularity and re-use across families of related products. Model based engineering, knowledge management and data storage can support this trend enabling design cycles to be reduced and economies of scale across Product Families – the final focus area of the Racetrack.

Undoubtedly there is no silver bullet for resolving such challenges however the framework presented for the application of MBSE brings together various modelling methods, with targeted emphasis at different phases of the lifecycle, in order to manage such complexity.

## ANNEX

| Modelling Category | Type | Purpose |
|---|---|---|
| **Operational Models** | OV-01a (MoDAF) | • Visual representation of operations that the whole-ship will undertake.<br>• Provides a means for exploring the top-level capability requirements for the platform. |
| | Use Case Diagrams (SysML) | • Visual representation of operations that a system needs to undertake and how 'actors' interact with it.<br>• Provides a means for maturing the requirements set and setting the functional context. |
| | Textual Use Cases (SysML) | • Textual description of how a system is used by an Operator. |
| **Requirements Models** | Requirement Decomposition Diagrams | • Provides traceability of key requirements to the design, through to integration test and acceptance.<br>• Provides traceable decomposition of the requirements set to ensure completeness and consistency. |
| | IV-05 (MoDAF) / Activity Diagrams (SysML) | • Demonstrates the means / process map for progressive assurance and acceptance. |
| **Logical/Functional Models** | Activity Diagrams (SysML) | • Diagrams used to describe the system's dynamic behaviour.<br>• Provides the sequencing and logical flow between sub-systems/equipment to depict how functionality is achieved. |
| | Sequence Diagrams (SysML) | • Represents a sequence of messages exchanged between the operator(s) and sub-system(s) in order to achieve an overall function/behaviour. |
| | State Machines (SysML) | • Specification of the sequence of states a system undergoes in response to events combined with its responsive actions. |
| | Functional Failure Analysis | • Emphasis on functional threads that underpin whole-ship safety.<br>• Enables analysis of consequence associated with loss, un-commanded or erroneous operation of sub-systems within the functional chain. |
| **Performance Models** | Hydrodynamic Model (BAEShip) | • Enables analysis of hull-form against a suite of performance parameters. |
| | Propulsion Model (MATLAB) | • Mathematical model used to analyse steady state power requirements, dynamic performance and operating state transitions<br>• Provides progressive assurance that ship can meets its dynamic performance targets. |
| | Power Systems Model (MATLAB/Simulink) | • Steady-state mathematical model used to calculate: load flows, fault levels and arc-flash behaviour.<br>• Time-variant model used to understand: transient performance, harmonic behaviour and micro-second level performance. |
| | Fluid Systems Model (Fluid Flow) | • Mathematical model that enables analysis of fluid flow in Auxiliary systems |
| **Structural Model** | System Inter-Relationship Diagrams (SysML) | • Interface diagram describing sub-system to sub-system relationships.<br>• Captures and validates system and subsystem parts and interfaces – identifying conflicts, gaps, inconsistencies early. |

| Modelling Category | Type | Purpose |
|---|---|---|
| | | • Used to ensure interface definitions appropriately captured. |
| | Parts Relationship Diagrams (SysML) | • Describes system structure and hierarchy (i.e. components of a system). |
| **Physical Model** | 3D CAD Model | • Detailed geometric representation of the physical ship design used for the assessment of physical integration and the delivery of manufacturing outputs. |
| | Integrated Bill of Materials | • Comprehensive list of parts, items, assemblies and other materials required to build the ship. |
| | General Arrangement | • Representation of the overall composition of the ship. |

Table 1: Modelling Types and Notation Used to De-Risk Marine & Platform Systems

## GLOSSARY OF TERMS

| ACRONYM | DEFINITION |
|---|---|
| BOO | Basis of Operation Document |
| CADMID | Concept, Assessment, Design, Manufacture, In-Service, Disposal |
| C&DR | Constraints and Derived Requirements |
| GTR | General Technical Requirements |
| MBE | Model Based Engineering |
| MBSE | Model Based Systems Engineering |
| MODAF | Ministry of Defence Architectural Framework |
| P&P | Power & Propulsion System |
| PMS | Platform Management System |
| PPMS | Power & Propulsion Management System *(a sub-system of the Platform Management System)* |
| OPSTAT | Operability Statement |
| Sparx EA | Sparx Enterprise Architect |
| SysML | Systems Modelling Language |
| TES | Technical Equipment Specification |
| Type 26 | Type 26 Global Combat Ship |
| WSR | Whole Ship Requirement |

## REFERENCES

1. D J Andrews, ‘Simulation and the design building block approach in the design of ships and other complex systems’, *Proceedings: Mathematical, Physical and Engineering Sciences*, Vol. 462, No. 2075, pp.3407-3433, The Royal Society (2006).

2. A R Edmondson, B Twomey, ‘Systems Engineering – The Hard Way’, Proceedings of the International Naval Engineering Conference 2018, IMarEST, (2018).

3. Z Liang, L Yan, J Shang, ‘Collaborative multidisciplinary decision making based on game theory in ship preliminary design’, Journal of Marine Science and Technology, Vol.14, No. 3, pp. 334-344, JASNAOE (2009).

4. C Buck, ‘The use of an Integrated Architecture Framework for the design of the Type 26 Global Combat Ship’, Proceedings of the International Naval Engineering Conference 2012, IMarEST, (2012).

5. P Pearce & M Hause, ‘ISO-15288, OOSEM and model-based submarine design’, Proceedings from the Systems Engineering Test & Evaluation Conference 2012, 6th Asia Pacific Conference On Systems Engineering (2012).

6. I Boyle & A Hird, ‘An Evaluation of the Integrated Architecture Framework’, University of Strathclyde report produced for BAE Systems’ Integrated Product Development Environment project, (2013).

7. D J Andrews, ‘A Comprehensive Methodology for the Design of Ships (and other Complex Systems)’, Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, Vol. 454, pp. 187-211, The Royal Society – London (1998).

8. K Forsberg & H Mooz, ‘The Relationship of Systems Engineering to the Project Cycle’, Engineering Management Journal 4, pp.36-43, Hunstville (1992).

9. J Harvey-Evans, ‘Basic Design Concepts’, U.S. Navy Design Journal 71, pp.671-678, United States Navy (1959).

10. D J Andrews, ‘Integrated Approach to Ship Synthesis’, Royal Institute of Naval Architects 128, pp.73-102, United Kingdom (1986).

11. N A Tepper, ‘Exploring the use of Model Based Systems Engineering (MBSE) to develop System Architectures in Naval Ship Design’, MSc Thesis submitted to Department of Mechanical Engineering Department, Massachusetts Institute of Technology, USA (2010).

12. M R Emes et. al, ‘Interpreting “Systems Architecting”’, INCOSE UK Systems Engineering Volume 15 No.4, pp.369-395, London (2012).

13. J A Estefan, ‘Survey of Model Based Systems Engineering (MBSE) Technologies’, Revision. B, INCOSE MBSE Initiative, Jet Propulsion Laboratory, California Institute of Technology, USA (2008).

14. INCOSE, ‘What is Model-Based Systems Engineering?’, INCOSE UK Leaflet-Z9, International Council of Systems Engineering, London (2015)

15. D Steinbach, D, ‘Guidelines for Model Based Systems Engineering’, from http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&arnumber=6176450, (2015).

16. L Baker et al., ‘Foundational Concepts for Model Driven Systems Design’, INCOSE Model Driven Systems Design Interest Group Paper, International Council on Systems Engineering, London (2009)

17. D Harvey, M Waite, P Logan & T Liddie, ‘Document the Model, Don’t Model the Document’, from http://shoalgroup.com/wp-content/uploads/2015/02/Harvey-et-al-2012-Document-the-Model-Dont-Model-the-Document-SETE-2012.pdf, (2012).

18. S Pilemalm, N Hallberg, M Sparf, & T Niclason, ‘Practical Experiences of Model Based Development: Case Studies from the Swedish Armed Forces’, INCOSE Systems Engineering Vol. 15, Issue 4, pp.407-421, International Council on Systems Engineering, London (2012).

19. W Tudor & C Bach, ‘Designing marine systems in complex warships: an exploration into the deployment of model based systems engineering’, Proceedings from International Naval Engineering Conference, IMarEST, Bristol (2016)

20. A Edmondson & B Twomey, ‘Systems Engineering – The Hard Way’, Proceedings from International Naval Engineering Conference, IMarEST, Glasgow (2018)