Digitally Empowering Naval Fleet Support

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Synopsis

Throughout history, the Royal Navy (RN) has invested in technical innovation to gain warfare advantage over its opponents. However, innovation often comes with change to the asset design, its operation and through life support. The most obvious example was during the turn of the 20th century when the RN moved from coal to oil powered propulsion systems, resulting in a major change to the skills of the crew and the support chain.

The demands placed on the RN have continued to grow during the 21st century, with a fleet of highly complex surface ships and submarines that provide the UK conventional and nuclear strike capability. This paper explains how warfare advantage can be further improved by information exploitation that is targeted at the improvement of fleet availability, capability and safety by empowering the operator and its shore-side support organisation.

The projects described in this paper have been developed in collaboration with the RN as part of the Maritime Support Information Exploitation Strategy (known as MarSIX). The paper therefore discusses the information principles used within Babcock's Support Strategy to deliver Navy Command's MarSIX vision.

Keywords: Royal Navy; Digital Transformation; Information Exploitation

Caveat

The views and opinions in this paper are those of the authors and should not to be construed as the official views of the wider maritime enterprise.

1. Introduction to the in-service support challenge

Royal Navy (RN) vessels contain in excess of 100 integrated systems which are linked structurally, mechanically, electrically, hydraulically, pneumatically and electronically. As such, they may be considered to be a complex system of systems, i.e. one in which elements are themselves systems. Typically this can pose large scale interdisciplinary problems with multiple, heterogeneous, distributed systems.

Vessels are designed for specific Concept of Operations (CONOPS), e.g. anti-submarine, air-defence or mine counter measures. Changes in maritime doctrine, technology, tactical and strategic threat may render the original CONOPS invalid, necessitating a review and a change in modus operandi and / or systems. Such change may be further compounded by the longevity of naval platforms, e.g. HMS Portland, which is planned to be in-service for 34 years - almost twice its original planned 18 years - during which time, up to 70% of the total cost of ownership may be expended (Koronios *et al*, 2007). The considerable longevity of naval platforms is not uncommon; the United States navy anticipate a service life from 30 to 50 years (Ayyub *et al*, 1998)

Naval vessels necessitate constant, timely and effective upkeep, not only corrective and preventive maintenance to preserve capability[1], but also upgrades "capable of increased functionality" to obviate challenges with respect to technology, mission, economic and threat (Hobson, 2008; Kelly and Ratchev, 2011).

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[1] Capability – The ability to generate an operational outcome or effect in the context of defence planning Acquisition Operating Framework (AOF, 2016)

Author's Biography

Chris Rowley is the Chief Digital Information Officer. He started his career with the MOD in Naval Platform Design using computer aided design and information technology. Since moving to industry he has specialised in software application development, major IT programme implementation and the applied use of advanced analytics for complex engineering assets.

Gary Ford is a Senior Data Scientist. He has a background in Electrical, Nuclear, Software and Systems Engineering and has broad experience in various domains, including naval, electrical generation, systems analysis design and maintenance.

The provision of equipment and in-service support of naval vessels is within the construct of the Ministry of Defence (MoD) CADMID lifecycle, i.e. concept, assessment, design, manufacture, in-service and disposal. The operational period is known as the in-service stage and comprises three phases, i.e. tasking (undertaking or available for operational assignment), upkeep (deep maintenance activities) and regeneration (typically testing and training in preparation for tasking) (Figure 1).

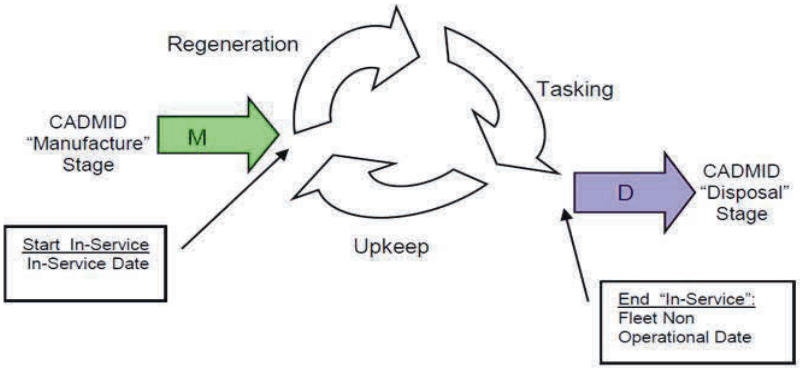

Figure 1: Cyclical In-Service Phase

The RN has worldwide operational commitments, e.g. nuclear submarines provide the UK's "Continuous at Sea Deterrent", NATO commitments, Indian Ocean / Persian Gulf[2], Antarctic Patrol, Mediterranean[3], Atlantic Patrol Tasking (North and South) Fleet Ready Escort and Towed Array Patrol Ship. The large number of commitments and hence vessel / system utilisation is often reflected in a substantial work package formulated prior to and during upkeep. Emergent work, often as a consequence of an unknown material state will increase the duration of upkeep periods. The timely completion of upkeep is essential in returning platforms to tasking; failure to complete when scheduled may result in vessels being extended in theatre in a potentially degraded condition.

This paper considers the work currently being undertaken in transforming the information and knowledge created and utilised in support of the RN, in order to deliver Safe, Capable and Available platforms.

2. An enduring story of RN Transformation

2.1. Transforming the RN in the 21st century

Changes in manpower role, structure and numbers are not new, e.g. the change from coal to oil at the start of the 20th century provided the RN with the opportunity to reduce its manpower requirements:

> "oil fuel settles half our manning difficulties! We should require 50 percent less stokers. Personnel savings were also critical to the Royal Navy, which regarded the shortage of trained sailors as its worst long-term problem." (Marder, 1952)

The change from coal to oil upon the Queen Elizabeth Class warships resulted in a reduction in stokers from 260 to 110 (Brown, 2003), the current HMS Queen Elizabeth has approximately 30 ET[4] to maintain critical systems and propulsion capability. The downward trend in manpower has continued. The standard crew for the new Type 26 (T26) frigate is planned to be 157 (Royal Navy, 2018) whereas the crew of a Type 23 (T23) frigate is 185. The consequence of the change from coal to oil represented a significant technological, operational and stakeholder transformation. The equivalent 21st century revolution may prove to be "Information Exploitation" as part of a digital transformation journey for the RN under the MarSIX strategy (Figure 2).

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[2] Indian Ocean / Persian Gulf – Operation Kipion

[3] Mediterranean – Operation Sophia - EU Naval operation set up to disrupt the business model of migrant smugglers and human traffickers in the Southern Central Mediterranean (EU, 2018)

[4] ET – Royal Navy Engineering Technician

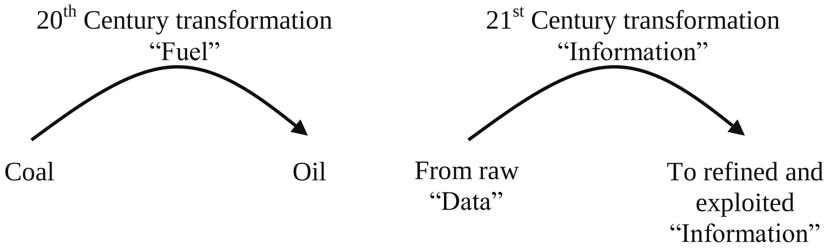

Figure 2: Example of Royal Navy Transformation

The impact upon naval fleet management will be comparable in terms of business benefit e.g.:

- Operational Increased system / platform availability, reduced risk of failure
- Stakeholder Empower the maintainer, enable industry to provide foresight, improve logistic support
- Technology Adoption and development of new technology to change from utilising discrete stovepipe data sources to the integration and exploitation of information and the formation of knowledge and wisdom.

The RN faces a wide range of demands and constraints, including high tempo operational tasking with a limited number of platforms, financial restrictions and reduced manpower. To compensate for these demands, information transformation affords the facility to make informed Decision Making and provides the opportunity for operational advantage and increased optimisation.

2.2. Information is the new naval asset of the fleet

The value of information is generally not financially recognised on a balance sheet (Uckelmann and Bucherer, 2011), furthermore, within a naval domain the potential to financially measure information may not exist. To that end, Moody and Walsh (1999) formulated the Seven Laws of Information (Table 1), whereby the value of information as an asset may be measured without determining the cost / benefit of acquisition, processing, storage etc.

Table 1: Moody and Walsh's Seven Laws of Information

Law number	**Definition**
1	Information is (infinitely) shareable
2	The value of information increases with use
3	Information is perishable
4	The value of information increases with accuracy
5	The value of information increases when combined with other information
6	More is not necessarily better
7	Information is not depletable[5]

Within the naval domain, the validity of each law will vary e.g. information is (infinitely) shareable, may not be applicable or permissible due to security constraints; nonetheless, the laws can provide structure when assessing the value of information.

Law four declares information increases with accuracy, where accuracy is the inverse of error. Within the naval domain there are a vast number of data sources, each with varying information attributes including accuracy, content and usability (Figure 3). The applicability and validity of each attribute will fluctuate, e.g. objective Condition Based Monitoring (CBM) can provide vibration condition data with a high degree of accuracy, versus manual records within UMMS[6] that have variable degrees of maintainer records accuracy. Depending upon how data is combined and the processing undertaken the accuracy of data accuracy can be highly pertinent to decision making.

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[5] Depletable – Information is often created as a result of summarising, analysing different sources. The original information remain and the derived information is added to the existing asset base. (Moody and Walsh, 1999)

[6] UMMS – Unit Maintenance Management System; RN computer-based work management application

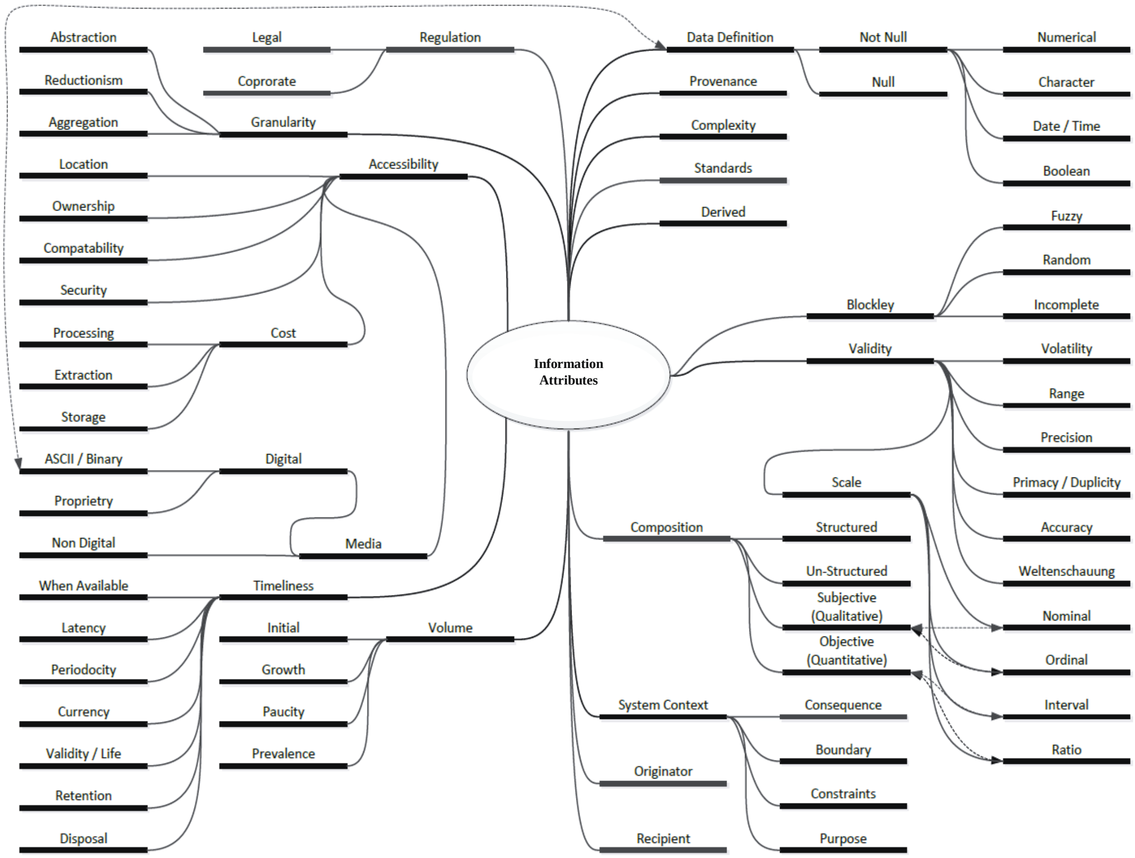

Figure 3: Information attributes (Ford, 2016)

2.3. Start of the transformation

The Maritime Support Information Exploitation (MarSIX, 2017) strategy by Naval Command Headquarters proposes an operating model that is transformative, i.e.

- Mobile technology
- Information exploitation
- Data integration
- Management information

A number of engineering support improvement programmes have involved the implementation of data collection and information exploitation projects as part of the ATHENA warships programme, including:

i.	Mobile technology	The development of a bespoke secure iPad[7] app for the capture of survey data to assist in the formation of a platform material state.
ii.	Connected platform	Application of targeted Internet Of Things (IOT) sensors based on non-intrusive CBM techniques to key equipment within mission critical systems and surrounding environment to collect material state information using novel wireless technology as a data bearer for the Maintainers mobile tablet.
iii.	Analytics (CAPA[8])	Combines diverse internal and external data sources against Key Capability Requirements[9] (KCR) for the platform, delivering a common data translation layer. CAPA is an example of how the Laws of Information can support capability for predetermined operational models.

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[7] iPad – Apple Inc. tablet computer

[8] CAPA – Complex Asset Performance Analytics

[9] KCR – Each class has a set of specific Key Capability Requirements, e.g. situational awareness, survivability and endurance etc.

The CAPA application enables users to visualise and forecast the potential impact of failure / degradation of a critical system or equipment on capability; that is a key enabler within the maritime support enterprise (Figure 4).

Figure 4: CAPA Visualisation

Within an information transformation strategy, each development applies an Agile[10] build on experience approach. To that end, operational data collected as part of the connected platform trial will be integrated into CAPA to provide an additional perspective of actual system usage, the impact upon KCR's and platform support. Within CAPA, each KCR / system association is assessed as being an Effector[11], Enabler[12] or Supporter[13] in order to model the effects on operational capability, availability and safety.

Given the longevity and limited number of available platforms, the potential impact of a change in operational tasking, i.e. contingent tasking or CONOPS may be readily assessed by project planners and logistic / supply support utilising the CAPA functionality and the detailed KCR / system associations.

Technology will often enable data collection and processing however, the "real challenge of 'advanced analytics' in the context of 'big data' is not to process more information, but to create value from trusted information, i.e. to extract and structure re-usable knowledge from data" (Kadiri *et al*, 2016). Creating real value from information requires the ability to dynamically re-configure the query rather than underlying complex data which is often a constraint in existing monolithic vertically structured applications. The variability and flexibility of naval operational tasking must be reflected in a flexible and dynamic information / knowledge management system.

As indicated above, CAPA provides a dynamic proactive capability with real information, i.e. information that is connected by some relations (Nurnberger *et al*, 2009). Within CAPA the relations may be considered to be the dynamic associations between physical systems and KCR's whilst the pseudo real time data, e.g. Operational Defects[14] (OpDef), etc. provides the underlying data / information.

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[10] Agile – generic term used to describe rapid iterative and incremental software development

[11] Effector – System / equipment that performs the function

[12] Enabler – A critical system / equipment without which the Effector could not function

[13] Supporter – A supporting system / equipment that provides an infrastructure function / capability

[14] Operational defect – a defect that degrades or may degrade the operational capability of a vessel

3. Babcock support strategy – "The whole is greater than the sum of its parts" (Aristotle[15])

The support strategy seeks to deliver improved asset and enterprise performance through a framework that integrates Engineering know-how with digital solutions and technology (Figure 5).

Figure 5: Digitally enabled support partner

To enable such digital transformation, business requirements have been categorised into five integrated capability blocks (Figure 6). This new functionality is designed around international standards for Integrated Logistics Support (ILS) and Asset Management in order to integrate and exploit information across the CADMID lifecycle (e.g. from design through to eventual disposal) in a common and repeatable way using the latest digital technologies.

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[15] Aristotle – Greek Philosopher, 384–322 BC

Maintain the Asset

Engineer the Asset

Digital Twin (Digital Asset Management)

Field Support

Connected Asset

Figure 6: Capability blocks

Maintain the Asset:

Director Ships DE&S[16] mission statement, and hence raison d'être for maintenance, is “Putting the Fleet to sea and keeping it there, fit to fight now and in the future”. However, as complex, long lived artefacts naval vessels are “unreliable in the sense that they deteriorate with age and / or usage and ultimately fail” (Murthy and Asgharizadeh, 1999), consequently, vessels require constant preventive and corrective maintenance in addition to upgrades and updating. The capability block will encompass:

i. Risk based maintenance
ii. Dynamic material state assessment
iii. Demand planning
iv. Digital Twin for fleet level maintenance planning and technical authority decision making

Engineer the Asset:

A warship/submarine requires the coordinated application of various design and support activities; “without which the platform and class would lack capability and availability, said a shortage of spare parts for German navy vessels would likely lead to longer repair stays in shipyards” [Hans-Peter] Bertels[17], “funding for spares has reduced across all the Armed Forces. The risk of cannibalisation has increased further … have limited alternative equipment to deploy” (NAO, 2017). The principles of Design for *X*[18] are embedded within Engineering the Asset, hence is a foundation in the design and delivery of a complex asset; this capability block will encompass support of the design through-life:

i. Configured baseline
ii. Supportability planning
iii. Stores and supply modelling
iv. ILS and maintenance modelling

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[16] DE&S – Defence Equipment & Support (https://des.mod.uk)

[17] Hans-Peter Bartels – German Parliamentary Commissioner for the armed forces

[18] Design for *X* – the letter *X* will relate to life-cycle processes and performance, including Design for Supportability (Huang, 1996)

v. Technical information
vi. Integrated support solution
vii. Optimised supply chain

Digital Twin (Digital Asset Management):

A Digital Twin (DT) is a new concept within the naval marine domain: it is a, "virtual representation of a physical object or system across its life-cycle. It uses real-time data and other sources to enable learning, reasoning, and dynamically recalibrating for improved decision making" (IBM, 2018). Information regarding the design and performance of a platform, system or equipment exists within multifarious discrete applications, e.g. Surface Ship Definition Database, OpDef Data Management System, etc. However, there is no record of actual usage, load, environment etc. giving context to OpDefs, spares usage, the provision of real-time data would be a substantive. Consequently, a DT would provide a single cohesive image of the class, platform and systems contained within. The DT capability block will encompass:

i. 3D visualisation model and walk through
ii. Platform level condition based maintenance (prediction)
iii. Digital Twin design baseline versus real time performance
iv. Augmented and virtual reality for the maintainer
v. Augmented and virtual reality for training
vi. Algorithm library for decision support models

Field Support:

Field support is focussed upon enhancing the capability of the maintainer for preventive and corrective maintenance by the application of connected intelligent

- Support – defect definition, maintenance activity, configuration, usage, etc.
- Engineering – provision of design / configuration reference data for 'support' and 'training'
- Training – creation and delivery of intelligent methods and techniques, e.g. video, wiki, images, etc.

The capability block will encompass:

i. Training maintainers
ii. Connected maintainer with in-situ support aids
iii. Connecting the maintainer to real time Equipment performance data
iv. Mobile digital field force (shore side)

Connected Asset:

Vessels are an integrated system of systems; both 'hard' and 'soft' systems. Integration is achieved electrically, mechanically, hydraulically, etc. however, data, information and knowledge is not integrated and is often collated, managed locally and interpreted by soft systems, i.e. personnel. Often the management of information will vary by platform and class; the development of a connected asset will provide the structured, composite base data for the other capability blocks. The Connected Asset capability will encompass:

i. Connected Asset reporting its current material state
ii. Connected maintainer, providing insight to the enterprise
iii. Connected enterprise, providing foresight to the maintainer

The information strategy provides a connected capability set that is far greater than the sum of its parts to deliver the improved Support.

4. Connected Platform

4.1. Condition monitoring: present day

The RN utilises a range of manual and automated CM techniques to monitor and assess the material state of an equipment / system, e.g.

Visual Inspection	applied to pumps, diesels, generators, transformers etc.
Vibration analysis	applied to pumps, diesels, generators, shock / vibration mount etc.
Infra-red thermography	applied to transformers, diesels, electrical systems etc.

The applicability of each technique is detailed in the RN Reliability Centered Maintenance Handbook (RCM, 2007), the current RN CM practice can be labour intensive and localised, i.e. "taking and recording condition based monitoring data at periodic intervals in order to determine the condition of the component being monitored, and then deciding whether the condition of the component is acceptable or not" (Higgs *et al*, 2004).

The consequence of discrete, localised and intermittent recording of data is frequently considered a snapshot of the equipment material state, e.g. vibration: ~ 20msec / month, oil sample: ~ one every 3 months. Material state assessments will often necessitate the application of subjective engineering judgement of marginal, detached stovepipe data lacking a single integrated data repository.

4.2. From Connected Platform to an intelligent naval platform

As intimated, there is a dearth of condition data, lacking integration, and often with high levels of latency. Focussed application of IOT style Condition Monitoring (CM) sensors will allow equipment/system parameters to be remotely and automatically measured, monitored, data fused and analysed (Figure 7), thus providing "exploitable information on time, in the right place and format" (JDP6, 2008).

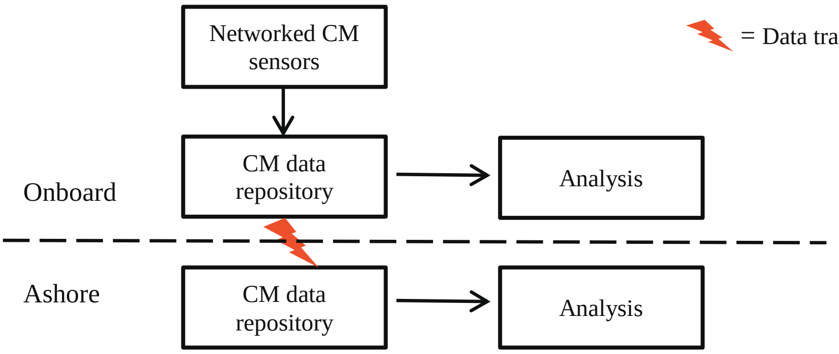


Figure 7: Typical Condition Monitoring system

An intelligent naval platform is a connected asset, encompassing network CM and a 3-dimensional data repository (Figure 8). This forms part of the Connected Asset information capability blocks.

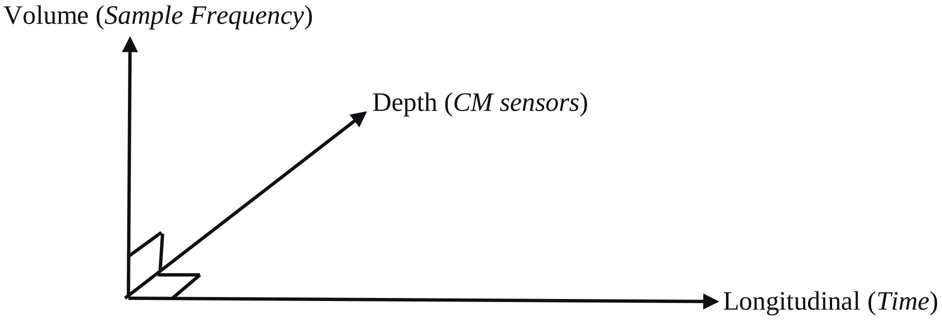


Figure 8: CM data repository

The connected asset is the embodiment of remote/intelligent CM rather than the prevailing localised model with Higgs *et al* (2004) identifying a number of CM systems. In addition to providing a data rich repository, the connected asset would:

- Reduce the number of maintainers to undertake routine data collection activities
- Increase opportunities to apply human senses in assessing the condition of equipment/systems
- Present system managers with real time data
- Enable consistent data collection
- Reduce the cost of data collection as compared with the cost of manual walk-around routines
- Eliminate the requirement for maintainers to be in close proximity to dangerous environments or equipment
- Enable safe data collection in sensitive, dangerous or hazardous areas without risking harm to maintainers

’Connected Platform’ will seek to verify / validate many of the advantages detailed above, e.g. CBM analytics data to the onboard maintainer including trending, diagnostics and visualisation of the equipment/system condition.

However, a connected asset will only constitute part of an intelligent platform; the jigsaw concept was identified by Charles Handy:

> “Information, above all else in life, seems to display the essential features of synergy. The whole is so often more meaningful than the sum of individual parts. An information jigsaw, even though all the pieces are separately available, is nothing until put together.” (Handy, 1999)

An intelligent platform information jigsaw would incorporate not only CM data but a range of other disparate sources (Figure 9), e.g. OpDefs, maintenance records, concessions, design, test data, etc.

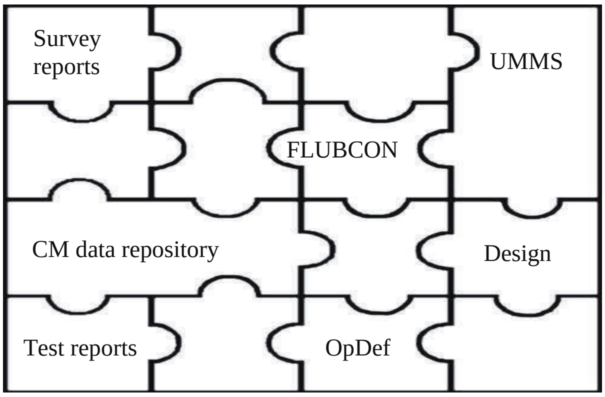


Figure 9: Intelligent platform information jigsaw

Note:
FLUBCON – Fuel lubrication consumption report

The physical manifestation of an intelligent platform information jigsaw would:

i. Satisfy many of the Laws of Information (Moody and Walsh, 1999).

ii. Overcome many of the problems highlighted in the MarSIX strategy, e.g. “I do not have the right technical information to perform the job”, “I do not have ready access to the IT systems that I need” (MarSIX, 2017).

iii. Form part of the delivery of the Information Transformation Strategy.

Naval platform information may be considered to exist in two distinct domains, i.e. onboard / tactical and ashore / strategic (Figure 10). Currently, common information is limited and frequently an abstraction of base data, e.g. OpDefs.

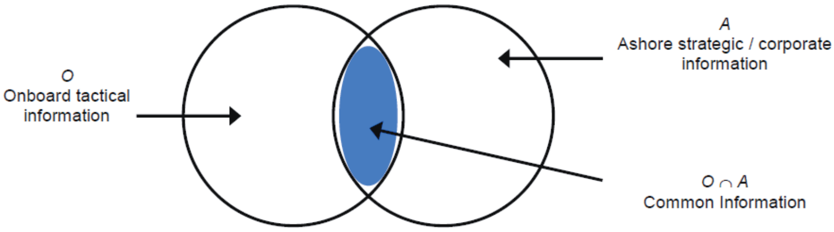
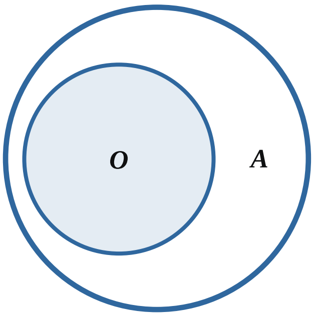


Figure 10: Information domain

Limited common information reflects operational tasking, stovepipe development of applications and constrained communications. Information exploitation and management information - as specified in MarSIX and the information strategy – will necessitate a substantive change in information domains (Figure 11), e.g.



Where:

O is a subset of A ($O \subset A$)

A – Ashore: all data accessible

O – Onboard: a subset of all data

Figure 11: Intelligent frigate information domain

Shore support is frequently constrained by a lack of actual data and the high level of data abstraction, however, the information domain model enables the potential for shore support foresight by the application of advanced objective and subjective data analytics, e.g. enhanced material state awareness, performance analysis and enhanced logistic support.

A function of creating information domains and jigsaws, etc. is to model actual usage / load against design and characteristics of real physical assets, e.g. pumps, motors and diesels, etc. The realisation is a DT capability block as detailed within the Information Strategy.

5. From creating a digital twin to empowering the enterprise

5.1. Digital twin

The IOT and the use of cyber-physical systems are deemed to represent the fourth industrial revolution, i.e. Industry 4.0. This is symbolised by connectivity and integration of real artefacts and software providing the capability of creating a DT. A DT is a, "virtual representation of a physical object or system across its life-cycle. It uses real-time data and other sources to enable learning, reasoning, and dynamically recalibrating for improved decision making" (IBM, 2018).

Within the naval environment, it may not be possible to acquire platform real time data ashore however, given a key objective for CM data is to predict equipment failure, this may not be relevant. The CM system illustrated above (Figure 7) will provide data for a DT that mirrors actual usage within a physical environment thus enabling shore support to model and monitor equipment / systems.

Industry 4.0 includes a range of enabling technologies, e.g. radio-frequency identification, global positioning systems, Bluetooth, Wi-Fi and near field communication. In addition to enabling the functionality for cyber-physical systems, the enabling technologies provide a capability not currently available, e.g. monitor the location and movement of equipment and its configuration by means of Radio Frequency Identification Data (RFID) tag.

5.2. Empowering the enterprise

The naval in-service enterprise encompasses a vast number of stakeholders as part of the Common Support Model construct, e.g. MoD, RN, members of the Surface Ship Support Alliance, extended supply chain (Tier 2 and below); information requirements will relate to functional role and in-service phase. The DT offers a range of potential opportunities, each relevant to a specific stakeholder, e.g.

i. Equipment/system trend analysis / condition monitoring
ii. Comparison of anticipated and actual usage
iii. Comparison of predicted logistic support with actual requirements as a consequence of real usage
iv. More accurately predict actual equipment / system condition prior to upkeep periods

v. As a consequence of a change in CONOPS, operational (contingent) tasking will change the operating profile, load, environment of individual systems etc.
vi. Assess the effect and value of upkeep, maintenance, alteration, addition and configuration
vii. Affect change to the design process for future equipment / systems as a consequence real data
viii. Measure equipment/system degradation and hence predict the P-F point of functional failure[19]

Engineering the Asset will demonstrate maintainability (see “Design for *X” – footnote 18*); the US Army, as part of its maintainability requirement for the Apache helicopter engine, specified it must “disassemble the system using seven hand-tools and within a time frame of thirty minutes” (Herbert, 1999). Improved maintainability positively improves reliability, whereby a maintainer may affect corrective / preventive maintenance more readily and hence return the equipment back to a functional condition (Figure 12).

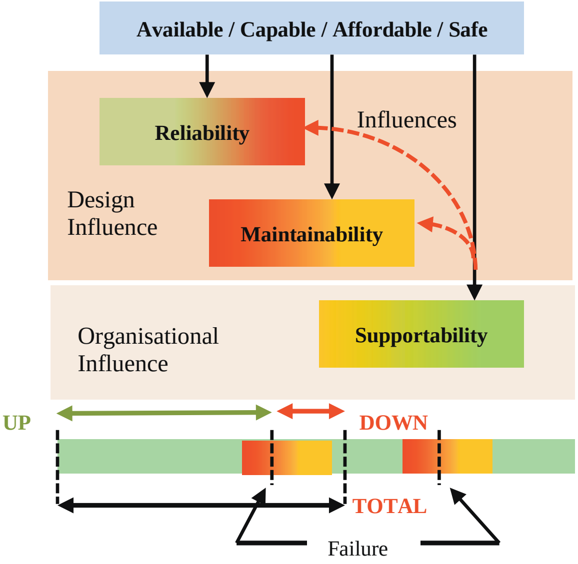


Figure 12: Reliability, maintainability and supportability (ISO 55000)

Stakeholder data visualisation is a facet of empowering the enterprise; whereby large volumes of objective categorised data may readily be displayed and analysed. The Localiti application (Figure 13) enables users to identify hot spots of concern and review the maintenance regime, design, etc.

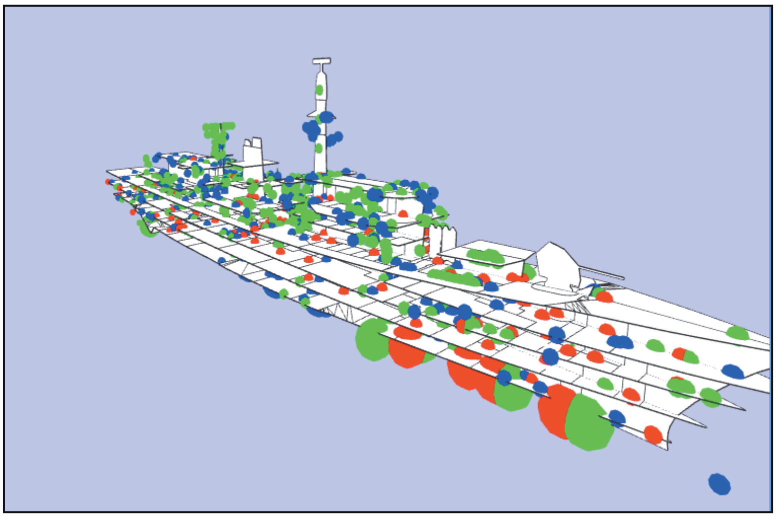


Figure 13: Example of data visualisation within a 3D Model

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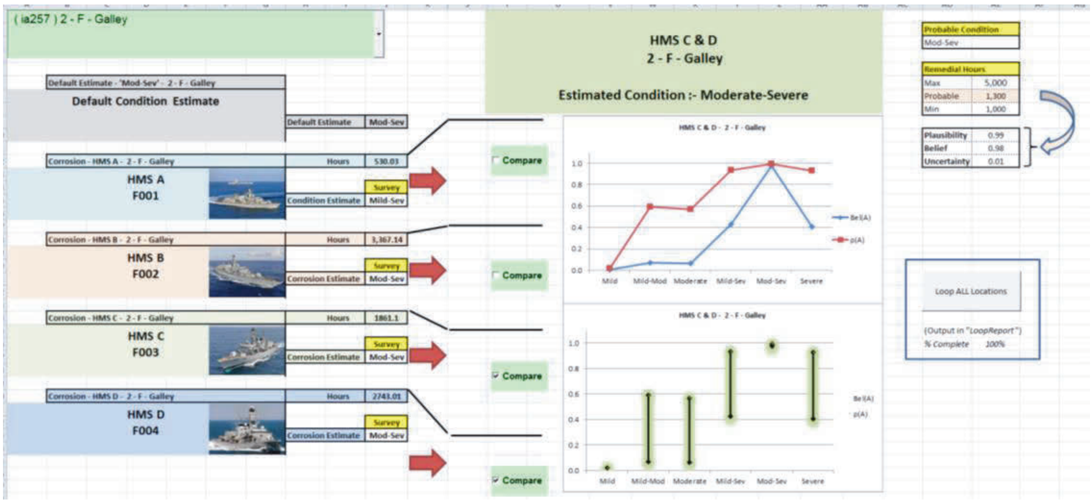
[19] P-F interval curve – detailing condition v operating age (DStan0045, 2010)

Data developed and utilised by Localiti has subsequently been re-used, combined and exploited by the application of Dempster-Shafer probability modelling to predict the most likely structural condition and corrective maintenance of vessels planned for future upkeep periods (Figure 14).



(ia257) 2 - F - Galley

Default Estimate - 'Mod-Sev' - 2 - F - Galley
Default Condition Estimate
Default Estimate: Mod-Sev

Corrosion - HMS A - 2 - F - Galley
HMS A F001
Hours: 530.03
Condition Estimate: Mild-Sev

Corrosion - HMS B - 2 - F - Galley
HMS B F002
Hours: 3,367.14
Corrosion Estimate: Mod-Sev

Corrosion - HMS C - 2 - F - Galley
HMS C F003
Hours: 1861.1
Corrosion Estimate: Mod-Sev

Corrosion - HMS D - 2 - F - Galley
HMS D F004
Hours: 2743.01
Corrosion Estimate: Mod-Sev

HMS C & D
2 - F - Galley
Estimated Condition :- Moderate-Severe

Probable Condition
Mod-Sev

Remedial Hours	
Max	5,000
Probable	1,300
Min	1,000

Plausibility	0.99
Belief	0.98
Uncertainty	0.01

(Output in "LoopReport")
% Complete 100%

Figure 14: Predicting structural condition

The prediction model is an exemplar of:

i. An information transformation capability block – whereby predicting the probable condition will assist to maintain the asset.

ii. The application of multiple laws of information, e.g. information is shareable.

The transformation of the naval information domain has begun.

6. Conclusions

Naval platforms are a complex network of systems, intended to operate in multiple threat environments, requiring constant upkeep: information is therefore a valuable asset and key component in maintaining availability and operational advantage.

The application of the laws of information, ILS engineering principles and asset management standards within a digital twin context provides the required structure and logic to better exploit complex asset information using the latest information technology.

The RN MarSIX strategy outlines the problem and defines the head marks for future information requirements, with the key principles of flexibility and scalability. The support strategy has incorporated MarSIX into a delivery framework that fully defines its five capabilities and associated user / functional requirements. The information principles detailed in this paper, e.g. laws of information, CM and information jigsaw, etc. support each of the capability blocks specified, to provide the required horizontal business and data integration as part of the digital twin approach.

Supporting a digital transformation journey that has comparable impact to the RN's change from coal to oil, Babcock's modular approach delivers early benefits whilst providing a flexible and scalable solution for the RN.

7. Acknowledgements

Dr Gary Ford and his co-researchers at Bath and Bristol University in the field of Knowledge and Information Management for complex Engineering assets.

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9. Glossary of Terms

CADMID	Acronym for MoD Acquisition Lifecycle comprising of 6 discrete stages, i.e. Concept, Assessment, Demonstration, Manufacture, In-Service, Disposal
CAPA	A tailored analytics platform that collects, collates and analyses data from multiple disparate data sources for complex Maritime platforms to assess and predict the risk associated with operational, availability and safety performance.
Condition Based Monitoring	As part of a preventive maintenance regime, i.e. preserve capability, the application of Condition Monitoring will assess and compare the actual condition of an equipment / system with anticipated condition.
Condition Monitoring	Continuous monitoring of equipment / systems to assess condition / usage.
CONOPS	Concept of Operations
DE&S	Defence Equipment & Support: MoD Department responsible for support and maintenance of all MoD equipment.
Dempster-Shafer	Arthur P. Dempster developed the theory of "Upper and Lower Probabilities" (1966), this was extended and refined by Glen Shafer in 1976 to formulate the "Dempster-Shafer Evidential Theory". The advantage of the method being it is not dependent upon single probabilities but the combination of multiple values.
Digital Twin	A virtual representation of a physical object or system across its life-cycle; enabling visualisation and differentiation between the physical and logical artefact with respect to usage, maintenance, etc.
FLUBCON	Fuel and Lubrication Consumption: monthly report
ILS	Integrated Logistics Support: an integrated and iterative process providing through life support of the artefact.
Internet of Things	The Internet of Things is the networking of physical artefacts with embedded electronics, software, sensors, etc. with network connectivity that enable objects to collect and exchange data.
Key Capability Requirement	Functional / operational requirement for a naval platform, e.g. endurance – provide all services and systems to enable a vessel to transit to / from an operational area.
Localiti	Tailored visualisation tool that maps multiple data sources onto a 3D virtual representation of a Naval Platform to assess material state and trends.
MoD	Ministry of Defence (www.mod.uk)

OpDef	Operational Defect: Royal Navy acronym, referring to a defect that degrades / may degrade the operational capability of a vessel.
RFID	Radio Frequency ID: uses radio frequency to uniquely identify tags attached to artefacts for the purposes of asset tracking and management.
RN	Royal Navy (www.royalnavy.mod.uk)
UMMS	Unit Maintenance Management System: Work management system used on RN vessels