Information Resources for the Identification of Complex Asset Condition: A Naval Engineering Case Study

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Gary Ford[1*], Chris McMahon[1], Chris Rowley[2]

[1] University of Bristol, UK
[2] Babcock International, UK

[1*]cegnf@bristol.ac.uk

Abstract. This paper describes the research in identifying the key data elements that are indicative of the material state of a naval vessel. Naval vessels are long lived complex artefacts, containing in excess of 100 integrated "hard" systems. The systems may be configured to provide a variety of prescribed capabilities and associated command objective. However, the "hard" systems will not fully integrate or function in a cohesive manner without the interaction of "soft" socio-technical systems (e.g. maintenance teams, operators); the two are interdependent and reliant. The In-Service phase will contribute 70% of the artefact's through-life costs and may comprise an operating period of more than 25 years. The data generated and utilised within each mode will reflect the operational and technical requirements of the numerous stakeholders and the functional state of the vessel.

Keywords: Lifecycle, Maintenance, Naval, Data

1 Introduction

There is extensive interest today in how we may use information technologies to improve our capability to judge the condition of complex engineered assets such as buildings, energy, transportation and infrastructure systems [1,2]. In particular there is interest in exploiting the information collected during the design, manufacture, maintenance and operation of such systems. This paper is concerned with an example of such a complex engineered asset – naval ships – and with exploiting the information collected during their operation and maintenance for identification of their state.

Royal Navy (RN) surface ships and submarines are a compilation of complex systems, i.e. "integrated set of elements, subsystems, or assemblies that accomplish a defined objective" [3]. A warship / submarine will contain in excess of 100 integrated "hard" systems which are linked structurally, mechanically, electrically, hydraulically, pneumatically and electronically [4]. Warfare demands a constant change in offensive and defensive capability, and, in addition to its offensive and defensive capability a warship must also be capable of providing, "humanitarian assistance and disaster relief operations to relieve human suffering" [5] - e.g. the assistance of HMS Daring and HMS Illustrious in the Philippines following Typhoon Haiyan [6,7].

The United Kingdom's Ministry of Defence (MoD) utilise a systems lifecycle model known as CADMID. The 6 CADMID stages are Concept, Assessment, Demonstration, Manufacture, In-Service and Disposal [8]. A high degree of commonality exists between the stages specified in ISO 15288 (Systems and Software Engineering – System Life Cycle Processes) and CADMID (table 1).) During its life a vessel should experience a linear progression through each stage of the lifecycle.

Table 1: ISO 15288 / MoD CADMID Lifecycle

<table>
<tr><td colspan="7">ISO-15288</td></tr>
<tr><td colspan="2">Concept</td><td>Development</td><td>Production</td><td>Utilisation</td><td>Support</td><td>Retirement</td></tr>
<tr><td colspan="2">C</td><td>D</td><td>P</td><td>U</td><td>S</td><td>R</td></tr>
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<tr><td>Concept</td><td>Assessment</td><td>Demonstration</td><td>Manufacture</td><td colspan="2">In-Service</td><td>Disposal</td></tr>
<tr><td colspan="7">MoD - CADMID</td></tr>
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In 2009 a Surface Ship Support Alliance (SSSA) was formed between the MoD, Babcock and BAE Systems, the intention being to "to reduce costs and increase availability" for surface ships. The SSSA introduced a "risk and reward" incentive, linking expenditure and availability, savings to be shared between all members of the alliance. The MoD remains the platform duty holder, with responsibility for the vessel. The formation of a Class Output Management (COM) team as part of the SSSA is intended to provide an industry, rather than a MoD led organisation with respect to planning and execution of maintenance.

Within the CADMID In-Service stage, a naval vessel will cycle through 3 discrete phases (Figure 1), i.e. Tasking, Upkeep and Regeneration.

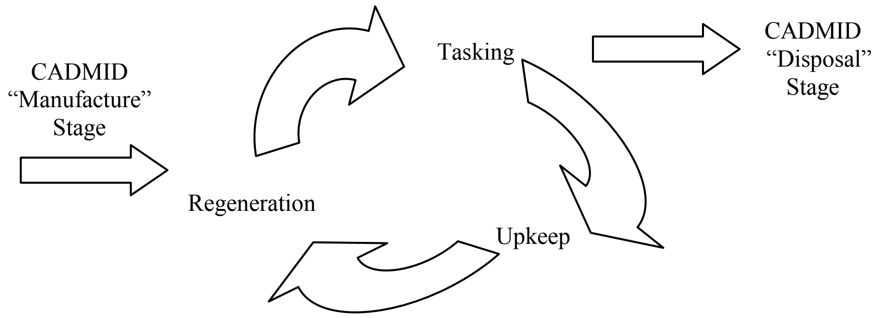

Figure 1: Cyclical phase of naval vessels

Tasking is the phase during which a vessel is under Navy Command Authority and thus available for or undertaking operational tasks. The upkeep phase is when a vessel is subject to major maintenance work, typically including docking periods, Regeneration involves the timely activation, in full or in part, of existing force structures and infrastructure, including the restoration of manning, equipment and stocks to designated levels. The data generated and utilised within each mode will reflect the operational and technical requirements of the numerous stakeholders and the functional state of the vessel, as the examples in Table 2 illustrate. A naval vessel will complete numerous Tasking, Upkeep and Regeneration cycles, e.g. HMS Edinburgh was "In-Service" for 27 years [9].

Table 2: Stakeholder and objective as a consequence of cyclical phase

Phase	Stakeholder	Objective	Information Interaction
Upkeep	Maintenance organisation	Filter hydraulic system to remove particulates	Provide test results
	Ship staff	Observe filtration process	Validate results
Tasking	Maintenance organisation	Liaise with OEM as technical authority	Provide technical advice as requested
	Ship staff	Ensure availability of hydraulic system	Request technical support

In addition to the information available to ascertain the material state of a system varying with the cyclical phase, stakeholder and objective, the validity and life of information will also fluctuate, e.g.

- Engineering logs ~ primarily generated and exploited during Tasking and Regeneration phase
- Pre-Upkeep Maintenance Assessment (PUMA) reports ~ generated during Tasking phase but exploited for Upkeep
- Unit Maintenance Management System (UMMS) ~ generated and exploited throughout all phases.

This paper details an investigation into the key data sources that may be used to determine the material state during each operational phase. The data sources were identified from a series of recorded semi-structured interviews conducted at the interviewees' offices. All interviewees (In-Service stakeholders) were highly experienced MoD, RN, Babcock and system supplier personnel, divided in the key phases as follows:

- Tasking: Fleet Operations Maintenance Officer (FOMO), Ship staff
- Upkeep: COM team, Babcock Project Managers
- Regeneration: Force Generating Authority, Flag Officer Sea Training, Maritime Capability Trials and Assessment
- Support: Defence Equipment and Support (DE&S) Spares, Finance, Chilled Water System Supplier

The "Support" organisations are a component of "In-Service" lifecycle, consequently they were interviewed to assess their "enabling" and "control" influence during the cyclical phase of an RN vessel.

The objective of the interviews was to ascertain the Inputs, Controls, Mechanisms and Outputs within each functional cyclical phase (process), with a view to then exploring (in later research) how engineering experts make a judgement about asset state based on the information sources. In the remaining sections of this paper the key data sources generated at each phase will be explored and then a brief evaluation of their characteristics and their potential as a source of asset condition will be presented.

2 Key Data Within Each Cyclical Phase

This section provides an overview of the processes and key data in each cyclical phase.

Tasking: Initiation of the Tasking phase and hence completion of any previous Regeneration phase is receipt of the "Ready for Ops" signal (see below). An operational vessel, although under the command of Commander Maritime Operations (COMOPS) must also operate as an autonomous safe seaworthy vessel under the direction of the captain. The Marine Engineering Officer (MEO) as department head is accountable for, "the good material order and maximum availability of all equipment and systems within its responsibility, in order to maintain the seagoing and fighting capability of the ship" [10].

Within the Tasking phase, two distinct information pathways detailing and assessing the material state may be seen to exist, i.e.

Internal data that is generated and utilised solely within the vessel. The internal reporting and assessment of the material state will typically comprise multiple "stove pipe" sources, e.g. hand written engineering logs, vibration records, oil sampling, UMMS. The information will be used by the MEO to facilitate the "maximum availability of all equipment and systems", as well as enabling the vessel to fight the *internal* battle, i.e. the preparation, training, management and rectification of action damage and systems failure, in effect enabling the vessel to continue to execute the *external* battle, e.g. engage air / surface / sub-surface combatants.

The internal information sources will typically be objective, e.g. temperature, pressure, vibration, failure, etc. trend analysis being limited to the vessel. Data is invariably current, given the source is contained within the vessel, however, the urgency of assessing the data / information or subsequent action will be dependent upon the "command aim", i.e. the mission objective. Consequently there may be a concentration of focus upon a singular system at the expense of more general analysis or maintenance. System failures that degrade the operational capability of a vessel are reported to naval command as Operational Defects (OpDef's). However, operational constraints may prohibit the vessel from seeking technical support or guidance from FOMO, e.g. submarines on submerged patrol, consequently the vessel is highly dependant upon the accuracy and currency of onboard documentation, configuration management and the knowledge / experience / training of maintainers. Furthermore, a solitary vessel may be unaware of deficiencies / performance issues affecting a system common to a class. Figure 2 illustrates the commonality of maritime systems in RN vessels

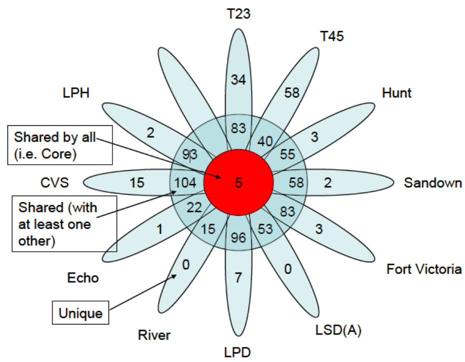

Figure 2: RN Common Maritime Systems [11]

External data generated, analysed and (potentially) aggregated within the vessel before transmission to FOMO for interpretation, execution and provision of assistance. Typically, FOMO will assess OpDef signals and capability reports received from the vessel to assess the material state and subsequent impact upon capability / availability. The data available to FOMO is primarily a latent abstraction of the primary data source potentially containing a mix of objective and subjective data. The FOMO organisation will apply their extensive tacit knowledge to formulate a predominantly subjective assessment of the data and will advise command regarding the material state of vessel and any potential risk to capability in the context of the command aim.

In addition to advising command, a key function of FOMO is to liaise with DE&S "desk officers" for the provision of support and stores. Where stores / equipment are not available from store, FOMO may initiate a 'stores robbery', i.e. the removal of items from other vessels, initially from those within DE&S control, e.g. HMS Duncan – "Early in build, one of our gas turbines was removed for [HMS] Daring after hers was damaged" [12]. If equipment / systems are not available from non-operational vessels, equipment will be taken from operational vessels. The potential impact upon condition assessment is that "new" equipment may have actually encountered considerable usage / load / shock / vibration and a maintenance regime that is possibly unknown to the final user.

Upkeep: The planning and preparation for the Upkeep of a naval vessel starts during the Tasking phase. Initial milestones / stages associated with the instigation and formulation of the work package are detailed in BR8593 [13].

The work package is a composite of numerous maintenance activities contained within UMMS, survey reports including statutory inspections "Lloyds Register class inspections", Work Requisition Forms, OpDefs, etc. The work package will often reflect the impact of operating the vessel in an environment at the limit of its design specification, e.g. high ambient temperatures as experienced in tropical regions. In addition to maintenance activities the work package will include Alterations & Additions, i.e. enhancements to a vessel's capability, life extensions, statutory modifications.

Pre-Upkeep surveys are often undertaken by the maintenance contractor, e.g. Babcock, supported by the Original Equipment Manufacturer (OEM), to provide a detailed material assessment of systems and equipment. The surveys are perceived as a datum with respect to defining the scope of the work package and potential variations. In addition to surveys conducted by the maintenance contractor BR1313 [14] specifies a requirement to undertake various pre-Upkeep inspections, e.g. resulting in PUMA reports.

A considerable number of surveys (structural and system) are undertaken early in the Upkeep phase, these are reviewed in detail at a Hull & Structural Assessment meeting where the initial work package is reviewed and potentially enhanced by means of Variation Orders.

The Upkeep phase will generate a considerable volume of documents including test specifications, Lloyds surveys, etc. however, the Material State Portfolio (MSP) created by the COM is an objective assessment of the vessel's state upon completion.

The document details the work undertaken and the condition of the vessel and is a key data source.

Regeneration: The initiation of the Regeneration process is the receipt of a Force Generation Order (FGO) by the Force Generation Authority (FGA), specifying the required capability of the vessel. The FGO may be perceived as a "User Requirement" with respect to a vessels operational capability. Upon receipt of the FGO a meeting is held with ship staff and the FGA, whereupon deficiencies and areas of concern are identified given the planned objective and the potential impact upon hard and soft systems. Typically the ship will utilise the Manpower, Equipment, Training and Sustainability (METS) construct for reporting

The FGA will formulate the specific regeneration requirements of a vessel including any specialist Military Task Equipment (MTE). MTE, are equipments required for directed military tasks but which do not exist in sufficient numbers to fit to all platforms at all times, consequently, potentially resulting in a lack of familiarity regarding maintenance.

The FGA will subsequently liaise with Flag Officer Sea Training (FOST) to formulate the specific program of regeneration and systems necessitating particular assessment. It is the responsibility of FOST to generate the vessel to the capability specified by the FGA who, "own the regeneration process". The testing and validation of systems will reflect the planned deployment, including physical environment and potential threats, e.g. deployment East of Suez: prioritisation of chilled water cooling systems, davits for boarding.

It should be noted, a vessel may be generated with a specific capability but may subsequently be re-tasked potentially without the requisite capability: Naval Command will subsequently "manage" the associated risk.

In addition to the operational assessment the RN Maritime Capability Trials and Assessment (MCTA) organisation assess mechanical and weapons systems by means of Harbour Acceptance Trials, Sea Acceptance Trials, Ship Performance Assessment's (SPA) and Operational Capability Confidence Check's (OCCC). Detailed objective reports are provided by MCTA to the vessel detailing where standards have been achieved, partially achieved or not achieved.

Completion of Regeneration is marked by a "Final Signal" and a "Ready for Ops" signal that will detail within the METS pillars what is outstanding to generate as specified in the FGO and any associated risks to operational capability when in theatre, e.g. chilled water system. This will raise awareness within FOMO such that any subsequent OpDefs pertaining to highlighted equipment / systems may impact capability.

3 Review

Information: The information sources are diverse, ranging from very detailed objective records of temperature and pressure etc. to latent subjective assessments derived from numerous sources. Stakeholders will attribute characteristics / properties both to their own requirements and the individual data sources. Information characteristics may include:

- Accessibility – location, security, ownership, cost, media
- Process and uncertainty characteristics – fuzziness, randomness, incompleteness [15]
- Granularity – abstraction, aggregation
- Media – paper, digital, standard, propriety
- Validity – range, precision, accuracy
- Volume – growth rate, initial

A review of the information sources identifies a number of key sources that are exploited to ascertain the material state in all phases, i.e.

- OpDef's – defects that impact / reduce the operational capability, updated and interrogated constantly, i.e. identify maintenance / upgrades, performance, operational constraints
- UMMS – the system not only schedules preventive maintenance and will identify outstanding maintenance but is also a repository of persistent defects
- Stores – analysis of material usage provides information regarding persistent defects, i.e. Comprehensive Royal Naval Inventory Systems Project

The information sources identified as key during Tasking are the engineering and condition based maintenance logs. The sources are generated and analysed locally (onboard) and offer a high level of data granularity but provide poor accessibility due to the format, i.e. paper based. The Fuel and Lubrication Consumption (FLUBCON) report provides a record of engine and lubrication usage, analysis will indicate increased usage which may be indicative of increased wear.

During Upkeep the information is primarily objective and detailed, the numerous system and structure survey reports provide considerable detail when aggregated, however, this requires manual processing. Similarly the MSP is a reliable document, however, its creation is a manual process drawing together numerous digital and non-digital data sources, furthermore, it only provides a perspective for a given point in time.

The assessments undertaken by MCTA during Regeneration, i.e. SPA and OCCC are detailed assessments of the material state, which combined with the "Ready for Ops" signal provides a reflective assessment of issues.

Each information source will provide a perspective of the material state to each of the stakeholders, e.g. UMMS provide ship staff information regarding scheduled maintenance as well as a repository for defects. The MEO will be particularly interested in maintenance that is outstanding. The COM may interrogate UMMS to review persistent defects and potential assistance from the OEM.

Artefact Information: The distinctive "concept of operations" and design of naval vessels necessitates and creates a range of data that is not comparable with similar size commercial vessels. Although a number of systems may be similar to commercial vessels, the manner of operation within a naval vessel is not, e.g. "crash stop" a chilled water system to simulate action damage. A number of systems are unique thus minimising the opportunity for comparison. Comparing RN vessels with other naval forces highlights a high degree of similarity with respect to policies, procedures and data collected, e.g. engineering logs, vibration monitoring. The variation being the terminology, e.g. the US Navy refer to an operational defect (OpDef) as a CASREP - Casualty Report.

4 A Proposed Use Of Maintenance Data – "The main thing is, we need to deliver capability" [16]

During Upkeep, substantial preventive and corrective maintenance is undertaken in addition to enhancing a vessels capability, e.g. HMS Ocean's Upkeep (2012-2014) ~ £65 million, 15 months planned duration that will including over 60 upgrades [17, 18].

The Upkeep work package will encompass numerous sources; however, key to developing the work package is an assessment of the material state prior to "Upkeep", i.e. Tasking. Information sources containing data indicative of the material state during Tasking are,

- OpDef's: Contains defects that degrade the operational capability of the vessel, the data is transmitted to a central repository
- SPA: Undertaken by an external authority during Tasking, identifying where standards have not been achieved
- UMMS: Contains details of preventive and corrective maintenance, however, the utilisation of the system is not consistent, furthermore, data is recorded onboard with periodic uploads to a central repository

RN vessels support UK maritime doctrine, i.e. the "ability to project power at sea and from the sea to influence the behaviour of people or the course of events" [5]. Consequently, a defect that degrades "capability" may potentially endanger and negate the *raison d'etre* of the vessel. The OpDef system records all defects that degrade capability and therefore must be perceived as a key information source and indicator of a vessels "capability" material state. The value of the SPA is the assessment is undertaken by an external authority and will identify ME and WE deficiencies necessitating rectification. In this instance UMMS is discounted as a consequence of the latency of the data and the variations in usage and management.

The OpDef system contains structured objective and subjective data which includes information detailing the "loss of operational capability", associated defect(s), the Effect category and associated Repair Indicator, the Operational Repair Plan and the rationale that prevented the defect being cleared [19].

Analysis of operational defects and SPA's across multiple platforms by Upkeep planners will not only reflect the value perceived by FOMO & DE&S but also provide a real time indication of single and re-occurring system defects / deficiencies and their resolution (Figure 3). The information will not only highlight systems of concern and hence the risk of future failure, forewarn of potential future maintenance activities but also identify systems necessitating detailed pre-Upkeep survey. Further analysis of OpDef's, SPA's and Hull & System surveys may highlight deficiencies in the provision of onboard spares and maintenance, thus providing a feedback loop with respect to through-life maintenance.

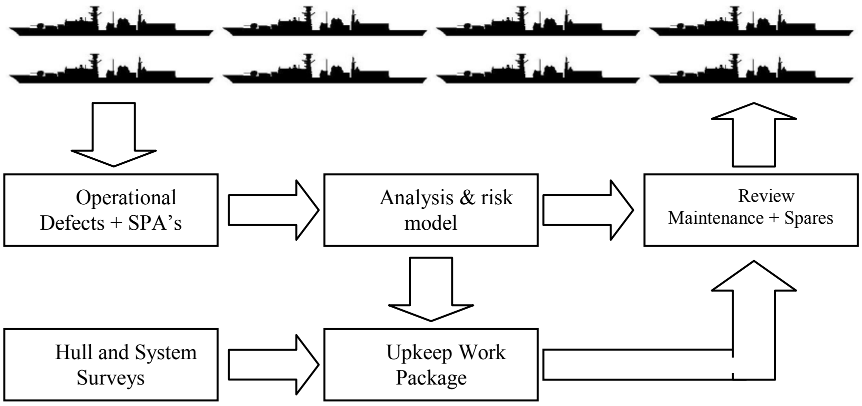

Figure 3: Proposed Use of Maintenance Data

Currently SPA's and OpDef's are analysed in isolation by RN and DE&S staff but not systematically by Upkeep planners, the proposed change would utilise and combine existing data in a manner not currently undertaken. Furthermore, a risk model of potential defects would enable Upkeep planners to plan the availability of resources and purchase spares.

5 Conclusion

A range of issues have been identified as a consequence of this research, i.e.

- The lack of integration of the multifarious data sources is the initial conclusion; however, this reflects the development of dicrete functionality, e.g. UMMS, SPA, OpDefs
- The usage and interpretation of information for purposes it was not intended, e.g. FLUBCON records hours run and lubrication usage, the extrapolation of usage, wear and maintenance was potentially not considered as the report does not record environmental issues that may influence any conclusions.
- The remote operation and potential isolation of RN vessels is an issue not normally encountered in civilian / commercial industry. A Trident submarine with a complement of 135 will undertake a 3 month patrol without contact or re-supply whereas the International Space Station is in constant contact and receives supplies typically each month [20].

The proposed use of maintenance data detailed above is an initial step in improving vessel capability and reducing Upkeep costs by the early assessment of material state.

Further consideration with respect to the development of a "black box" capable of logging and retaining condition data will provide the potential for system prognostics.

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