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Science and Technology

An Investigation into RAN Ship Structural Life-of-Type Management without Hull Monitoring Systems

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DST-Group-TN-1826

ABSTRACT

A preliminary study was conducted on the considerations, assumptions, and options for managing the structural Life of Type (LOT) of new Royal Australian Navy (RAN) ships without ship Hull Monitoring Systems (HMS). The study used critical thinking, or 'red teaming' techniques, to identify the consequences of not implementing HMS on board RAN ships, as well as to identify LOT management strategies that do not use HMS. The key consequence is that the RAN's ability to manage LOT risks and fleet availability will be impacted. Three alternative LOT management strategies were identified and would lead to a lower level of confidence in the management of RAN ship LOT risks. This is mainly due to the need for accurate data on the ship's operational usage to manage its LOT risks with a high degree of confidence. This data, in combination with emerging technologies such as the Digital Twin, provides opportunities for condition-based maintenance and support for the RAN to be a 'smart owner'. Implementing HMS on board RAN ships will however incur through-life financial and human resource costs and decision-makers will need to trade off these costs with the LOT management and other benefits.

RELEASE LIMITATION

Approved for public release.

UNCLASSIFIED

Produced by

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Telephone: 1300 333 362

May 2019

APPROVED FOR PUBLIC RELEASE.

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Executive Summary

In this report we describe a preliminary study on the considerations, assumptions, and options for managing the structural Life-of-Type (LOT) of new Royal Australian Navy (RAN) ships. The purpose of the study was to identify and investigate the risks and consequences of not implementing a hull monitoring system (HMS) on-board naval ships, to support the RAN to:

- manage the LOT of the fleet
- deliver seaworthy materiel throughout the capability lifecycle
- support the RAN to be a 'smart owner' through the adoption of a Digital Twin approach.

In the study, structured needs assessment and red teaming were employed with a group of Defence Science and Technology (DST) Group researchers. The first stage in the study was a SWOT analysis of implementing HMS on board naval ships. The SWOT analysis identified the key strength of implementing HMS is that it supports the RAN to manage a vessel's LOT risks. The study then explored this strength further by utilising red teaming techniques to minimise the influence of cognitive biases on the investigation. These techniques, which included a data review, structured brainstorming, and key assumptions checking, enabled the identification of approaches to manage the LOT of RAN ships without using a HMS. Three categories of approaches were identified:

1. employ an inspection regime (time- or predictive-based)
2. utilise other data sources (for example, logbooks, hindcast weather data, fatigue damage estimated via simplified or computational approaches)
3. manage LOT uncertainty by implementing alternate vessel management strategies, (e.g. restrict a ship's operations or service life).

The assumptions that underpinned these approaches were then identified and questioned using a key assumptions check. Through this questioning, it was discovered that the three categories of approaches for LOT management without a HMS would lead to sub-optimal through-life management of RAN ship LOT risks. This is mainly due to the need for accurate data on the ships operational usage in order to manage the LOT risks with a high degree of confidence. Ideally, a HMS would be coupled with all three approaches to provide a comprehensive strategy. Implementing HMS on board RAN ships will however incur through-life financial and human resource costs and decision-makers will need to trade off these costs with the LOT management and other benefits. Other opportunities

provided by HMS could include the ability to use the operational data for fleet maintenance and operations planning. This would enable the RAN to optimise fleet usage, maximise fleet availability for operations and support the RAN to be a 'smart owner'.

A final conclusion from the study is that the red teaming approach used to identify underlying weaknesses of the alternative approaches of naval ship LOT management was effective. Further work could utilise the study approach with participants from various Defence stakeholder groups to ensure a broad range of perspectives on the topic are captured.

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Glossary

ABS	American Bureau of Shipping
AD	Aerospace Division
ADF	Australian Defence Force
ADO	Australian Defence Organisation
AMT	Australian Maritime Technologies
ASIMP	Aircraft Structural Integrity Management Plan
ASIP	Aircraft Structural Integrity Program
CBM	Condition Based Maintenance
CLC	Capability Life Cycle
CRS	Cooperative Research Ships
DG	Director General
DST	Defence Science and Technology
DSwMSMAN	Defence Seaworthiness Management System Manual
FIC	Fundamental Input to Capability
HMAS	Her Majesty's Australian Ship
HMS	Hull Monitoring System
LOT	Life-of-Type
MD	Maritime Division
MSAP	Materiel Seaworthiness Assurance Plan
NSP	Naval Shipbuilding Plan
OEM	Original Equipment Manufacturer
OPV	Offshore Patrol Vessel
OSI	Operating and Support Intent

OTS	Off the Shelf
RAN	Royal Australian Navy
SME	Subject Matter Expert
SWOT	Strengths, Weaknesses, Opportunities and Threats
TTCP	The Technical Cooperation Program

1. Introduction

In the design of ships, factors including the construction quality, lifetime loads, and material properties are assumed for the purpose of calculating structural scantlings. For naval applications, there are uncertainties associated with the operation of ships in often harsh seas and changing military requirements. These factors affect the Life of Type (LOT) of the ship [1, 2]. Further, the structural LOT of naval ships is often extended beyond the original design life. The complexity of LOT extension is compounded by the large degree of uncertainty introduced by age-related degradation (corrosion, deformation, and fatigue damage) of the structure.

One approach to obtain a ship's in-service information, required for accurate and through-life LOT analysis and risk management, is implementation of a hull monitoring system (HMS) [3-5]. A HMS is a ship-board system* that can monitor the hull response, sea state, and operational parameters of an aging platform. A recent example of the implementation of a HMS, and subsequent utilisation of the data for structural integrity investigations, was that on the Royal Australian Navy (RAN) Armidale Class Patrol Boat HMAS *Maryborough*.

Through-life monitoring of a naval ship and its operational environment is ideal for managing the risk of the vessel not achieving its service life. It also provides support for the RAN to achieve the seaworthiness outcome† for its ships (RAN seaworthiness management is discussed further in Section 2). However, in general, through-life hull monitoring is resource intensive. Inspection and/or monitoring, and LOT management of a structure is a balance between costs and threats, and performance objectives, and opportunities [3, 8, 9]. Therefore, there is a need to consider the trade-offs with respect to hull monitoring to ensure informed decision-making regarding LOT management of a naval ship.

Recently, the Australian Government has embarked upon an enterprise approach to naval shipbuilding; the Naval Shipbuilding Plan (NSP) [10]. The aims of the approach are to build and sustain naval capabilities, create economic growth, and maximise industry participation. In the NSP, the need for the RAN to have operational flexibility to deal with evolving operational requirements was identified. In addition, the significant acquisition costs of naval ships and budgetary constraints necessitate the effective management of structural LOT of the fleet-in-being to maintain maritime capability [11-13].

* An example or 'reference' HMS may monitor vertical acceleration at forward section of hull, global hull strain at different longitudinal locations, sea-state and wind, and ship position, speed, and course. Sensors are connected to a computer with sufficient capacity to perform the tasks required (for example, signal processing, displaying information on a screen, data storage). This reference HMS is based on recommendations in Det Norske Veritas Rules for Classification of High Speed, Light Craft and Naval Surface Craft [6] to achieve a hull monitoring notation.

† The seaworthiness outcome is the achievement of 'the maximum likelihood of a realised system being able to achieve the specified tasking where the operating and support intent (OSI) is clearly understood and articulated, hazards and risks are eliminated or minimised in context of the OSI and the system is operated as intended' [7, p.18].

The continuous shipbuilding objective is one facet of the NSP. The RAN has adopted a proactive approach to its operationalisation of the NSP and has identified the need to be a 'smart owner' [14]. Being a smart owner requires information to support risk-based decision making, particularly for fleet availability. The Defence Science and Technology (DST) Group conducted a study on managing ship service life risks in relation to HMS and the opportunities that could be missed if HMSs are not implemented on RAN ships. The study employed red teaming techniques to investigate alternate strategies of LOT risk management. Structured workshops were facilitated with participants from DST to understand the problem from different perspectives, and to explore alternative solutions. The overarching aim of the study was to provide evidence-based support to the RAN regarding the consequences of not implementing a HMS during the acquisition of new vessels. A key focus of the study was the consequences for the management of ship LOT risks.

This report commences with a background on approaches used to manage the LOT of assets in related industries. The remainder of the report presents the approach to, and findings from, the study to investigate alternative strategies for LOT risk management of RAN vessels.

2. Background Information on Approaches to LOT Management

In this section, LOT management practices in three industries are briefly considered: military aviation, the offshore industry, and the ship industry.

In military aviation, Aircraft Structural Integrity (ASI) management has been a core part of platform and operational safety for several decades [8]. ASI management is the basis for fleet availability and realisation of the aircraft design life without major unforeseen remediation [15, 16]. For it to be effective, the measurement of the in-service loads and environmental conditions, knowledge of the structural configuration, and maintenance history are required. The overall fatigue management process includes fatigue testing at critical locations, an economic and reliable loads monitoring program on each aircraft to measure cyclic loads, robust damage modelling, and regular operator feedback [8]. For example, when the F-111 entered service in the Royal Australian Airforce (RAAF), it was managed on a safe-life‡ basis. Later, partly because the RAAF became the sole-operator of the F-111, an equivalent damage tolerance philosophy§ was adopted.

Aircraft Structural Integrity Management Plans (ASIMP) are typically used in military aviation, and reflect the level of understanding of fatigue management [18]. An ASIMP is a proactive plan to address Aircraft Structural Integrity Program (ASIP) activities through-life. The ASIP activities are conducted to assure that that structural integrity is maintained at the required level. In the Australian Defence Force (ADF), an ASIMP is established for each aircraft type [15].

The structural integrity assessment of ageing offshore structures for possible life extension has been identified as a growing challenge. Industry codes exist to manage structural integrity, such as ISO 19902:2007 [19] and DNV GL's *Offshore Standards* [20]. The codes require an evaluation of the resistance against fatigue damage. Based on the results of the fatigue analysis, inspection programmes during fabrication and the operational life of the structure are established. Such programmes are considered conservative and expensive, and ways to improve their efficiency are being researched [21, 22].

Implementation of HMS technologies has increased over the last decade. In 2013, Phelps and Morris [1] released a comprehensive review of hull structural monitoring systems for naval ships. Although detailed guidelines for the specification of a HMS for RAN ships is outside of the scope of this report, some general recommendations based on DST's experience with the ACPBs [23] and the review conducted by Phelps and Morris [1] are

‡ Safe life design refers to a conservative approach to fatigue strength estimation, which is based on the calculation of damage accumulation during the structure's design life or comparing the maximum stress range with the constant amplitude limit based on design values. The safe life is the period of time for which a structure is estimated to perform safely with an acceptable probability that failure by fatigue cracking will not occur. Thus, safe life design does not normally depend on in-service inspection [17].

§Damage tolerance is the capacity of a structure to sustain fatigue cracking without structural failure or unserviceability. The design of a structure using the damage tolerance philosophy requires preparation of a prescribed inspection and maintenance programme for detecting and rectifying any fatigue damage. The programme is followed throughout the service life of the structure [17].

provided in Appendix A. It is worth noting some advances since the release of this report, including:

- Fibre optic condition monitoring systems, which offer greater reliability and data quality compared to conventional technology. For example, Light Structures' [24] products enable hull stress monitoring and data for active fatigue management reporting.
- Wireless hull monitoring strategies, which offer relatively quick installation and removal as well as less impact on other shipboard systems. The concept has been demonstrated on a United States Coast Guard Response Boat-Medium [25] and the high-speed littoral combat vessel FSF-1 Sea Fighter [26].
- In addition to the HMS that was installed on HMAS *Glenelg* [27], DST implemented an augmented HMS on HMAS *Maryborough*. Strain, ship motion, acceleration, and operational data was collected. Information on the verification of the sensors, and data processing and analysis methods, have been published and distributed to ADO and industry stakeholders [28-31]. The *Maryborough* HMS operated from May 2015 until December 2016.
- Australian Maritime Technologies (AMT) has gained a capability in implementing HMS on RAN ships. AMT installed a HMS on the ACBP HMAS PIRIE post major structural remediation, to collect hull strain and other associated data over the various sea states that the ACPB vessels would be expected to experience over their approved operational cycles.
- As discussed in the Introduction, through-life hull monitoring is generally resource intensive. Recently, research has been conducted to determine cost-efficient HMS plans that provide crucial information regarding ship performance and optimum maintenance schedules [3, 32].

Some classification societies offer HMS notations when the system complies with the requirements of their respective guides. For instance, both the American Bureau of Shipping [33] and DNV GL [34] specify the requirements regarding the installation, calibration, warning levels, and sensor types and locations for a stress monitoring system to be used as a fatigue monitor.

In the Defence Seaworthiness Management System Manual (DSwMSMAN), one of the functional objectives is 'appropriate structural integrity of physical elements including hull, structures and fittings' [7: p. 191] to be established through monitoring and maintenance. Hull integrity is considered one of several design characteristics that is critical to the function and performance of a maritime mission or support system.

One approach to assure the seaworthiness outcome throughout the CLC may be to link, explicitly, service life modelling and hull monitoring to seaworthiness management. This approach could supplement any classification society survey regime, particularly as design to classification society rules provides the minimum standard for ship structural safety.

3. Study Approach and Results

In this study, critical thinking techniques were used to minimise the likelihood of biases impacting the outcomes and to inject rigour into the process of building a deeper understanding of the issue. These aspects are important because responses can be framed by the responder's perceptual and cognitive biases, which influences their assessment of problems [35]. Cognitive biases in particular can be problematic as they 'refer to a systematic pattern of deviation from the norm or rationality in human judgement, whereby inferences about people and situations may be drawn in an illogical fashion' [36: p. 2].

The critical thinking techniques used include Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, data review, structured brainstorming and a key assumptions check. These techniques are the steps of the study process, which is summarised in Figure 1. The inputs and outputs at each step are also shown in Figure 1.

The techniques and the results are described in the following sections.

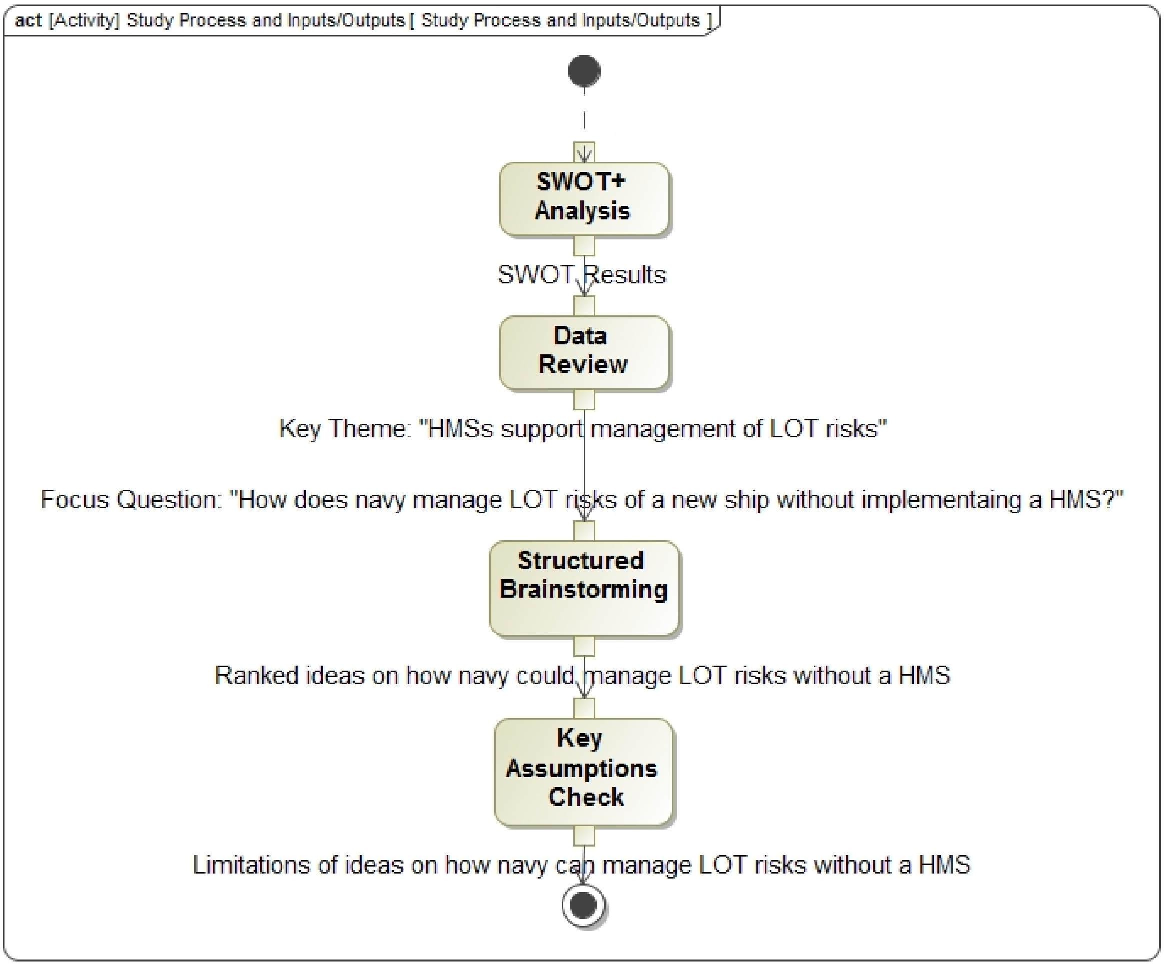

Figure 1. Summary of the study process and inputs and outputs at each step

3.1. SWOT

To begin the investigation, a SWOT analysis on implementing a HMS on a new Navy ship was conducted. SWOT analysis entails identifying the strengths, weaknesses, opportunities, and threats – or SWOT factors as defined in Table 1 – that influence implementation of a program or project. Thus, the analysis is designed to allow a situation to be viewed from four different perspectives. SWOT analysis is especially useful in the early stage of a decision-making process, because it can assist stakeholders to minimise bias and stimulate thinking [37-39].

Table 1. Definition of SWOT factors

Factor	**Definition**
Strength	An internal competence, resource, or attribute that an organisation can utilise to exploit opportunities.
Weakness	An internal deficiency in competence, resourcing, or quality that an organisation requires.
Opportunity	An external possibility for an organisation to pursue to gain benefit.
Threat	An external factor that has the potential to reduce the performance of an organisation.

The steps of the SWOT process were [39, 40]:

1. Decide on the focus of the SWOT analysis to set the boundaries of the discussion. For this analysis, the focus was 'implementing a HMS on a naval ship'.
2. Identify the stakeholders for the analysis. Four people from DST-MD were asked to participate, who have varying levels of knowledge of naval architecture, LOT risks, and hull monitoring.
3. Ask the participants to identify the SWOT factors related to the focus, which are shown in Table 2.
4. Perform a 'fact check' of the SWOT factors, whereby references and examples for some of the factors were found and added to Table 2.

An expansion of the SWOT analysis is 'SWOT+', which involves organising and prioritising the SWOT factors. The SWOT+ process is described in Appendix B. The main findings are discussed in Section 4.

Table 2. SWOT factors for implementing a HMS on a naval ship

	STRENGTHS		WEAKNESSES
S1	Can capture full-scale vessel responses	*W1*	Resource intensive
S2	Can capture actual operational profile	*W2*	Large maintenance overhead e.g. repair/replacement of hardware operating in hot and humid environment
S3	Can estimate fatigue damage	*W3*	Reliant on ship availability
S4	Materiel state implicitly taken into account	*W4*	Need a range of skills to implement and support the system (hardware, electronics, data analysis, project management etc.)
S5	Can be used to baseline any numerical fatigue damage predictions that were performed during design	*W5*	Significant amount of data generated that can be a challenge to manage
S6	Data can be used to validate design calculations e.g. design loads	*W6*	Potentially lacking environmental data (wave, wind, etc.)
S7	Can be used to demonstrate seaworthiness outcome	*W7*	Won't have a full view of the vessel's load history if system isn't installed during build
S8	ADO and Australian industry expertise exists – supports industry as a FIC (Fundamental Input to Capability)	*W8*	Adds to ship weight and power consumption
S9	Can use data to update class rules e.g. ANZAC bilge keels [41], Swedish corvette [42]		
S10	Can lead to through-life costs savings, through managing cost of ownership e.g. F-111 [43]		
S11	Loads are specific to the vessel rather than empirically determined		
S12	Good for novel hullforms		
	OPPORTUNITIES		**THREATS**
O1	Provides data that can be used in collaborations with other navies, governments & research institutions	*T1*	Perception that may have already accumulated sufficient know-how with respect to structural integrity
O2	Data can be used in Condition-Based Maintenance	*T2*	Perception that rules-based** approach is sufficient
O3	Provide operator guidance (e.g. alarms for high-stresses in near real-time)	*T3*	Possible that rules-based approaches have been improved → negates need for a HMS
O4	Can use data to inform subsequent batch vessel design and management (e.g. validate design loads)	*T4*	There are cheaper techniques to manage structural integrity (e.g. maintenance regime)
O5	Use data to optimise usage of fleet and platform transition planning	*T5*	Vulnerable to budget changes throughout vessel lifecycle
O6	Could be used in Digital Twin†† capacity	*T6*	Assumption/belief that Off-the-Shelf = proven design → negates need for HMS
O7	Use data to train operators in platform management	*T7*	Vulnerable to changes in personnel (expertise retires/moves on)
O8	Can support LOT extension analysis		

** Meeting the requirements of a classification society rule set.
†† Digital Twin refers to a digital representation of a physical asset or system.

3.2. Data Review

Following the SWOT analysis, the data collected on the strengths, weaknesses, opportunities and threats could be used to gain a preliminary understanding of the aspects that influence the problem and identify any emerging themes. These insights could also be used to inform the selection of techniques to further analyse the problem.

A qualitative data analysis technique where sections of the data are scrutinised closely and reduced into themes that appear to describe the problem under investigation, called 'open coding' [44], is well suited to this first data review. This is due to the intent of open coding being to 'open up' the inquiry during its initial phases [45]. Any prevalent themes identified from the open coding activity can be used to focus the subsequent investigation.

Open coding of the strengths and weaknesses, identified during the SWOT analysis, was used to ascertain that 16 of these 20 factors were related to the management of LOT risks. This implies the major strength of a HMS is that it supports informed decision making by the operating navy about the ability of vessels to meet their design LOT. Thus, the key benefit of implementing a HMS is the improved ability of the parent navy to manage LOT risks. This finding was used to frame the follow-on activities in the study.

3.3. Structured Brainstorming

Structured brainstorming can be used to elicit ideas from a group of people on a topic of interest. In this instance, the topics of interest are the prominent themes identified from the open coding in the data review of the SWOT analysis.

Brainstorming techniques are widely used and allow a broader range of factors to be considered by the people investigating a problem [35]. These techniques can mitigate the risk of cognitive bias influencing an investigation by collecting ideas on a topic of interest from people from a range of backgrounds and standing within an organisation.

Structured brainstorming is typically performed in focus groups of roughly five to 12 participants and needs to be designed around a clear and specific goal to be effective [39]. There can be disadvantages with brainstorming techniques associated with 'groupthink' and unequal contribution from focus group participants [39]. These disadvantages can however be negated through the use of techniques such as round robin reporting. In this approach, the group members are asked to write down their ideas in response to a specific question, and then each person in the group provides one of their ideas to the group at a time. Each person has a turn at providing one of their ideas related to the question until all ideas have been elicited from the group.

Using the key finding from the data review of the SWOT analysis, 'the parent navy's ability to manage LOT risks of a ship will improve with the implementation of a HMS', the focus question for the structured brainstorming activity was developed as follows:

> 'How does Navy manage LOT risks of a ship **without** implementing a HMS?'

The question was posed to a focus group of five DST SMEs in the field of LOT management of Australian Defence Force (ADF) assets. The 15 ideas below emerged from round robin reporting on approaches that could be used to manage LOT risks on a new naval vessel without a HMS:

1. regular inspection (could be time-based, or predictive-based)
2. age of asset — how old it is
3. modelling and simulation
4. operational usage survey (short-term monitoring) → compare actual usage to design OSI
5. manual reporting (sea state, 'mandraulic'[‡‡], use ship's log)
6. historical data (maintenance data)
7. detailed early modelling combined with external sources of environmental conditions
8. navy equivalent of 'flight hours', that is, use age in mission time rather than age in years, take severity of issues into account (depends on the level of refinement of the information)
9. dispose of the ship after x hours of usage
10. accept uncertainty of usage and of operational profile (simplified HMS e.g. measure acceleration only)
11. regulation, management plan: equivalent of Aircraft Structural Integrity Management Plan (ASIMP), for example, safety by inspection, overarching framework, states of structure will be manage, can be simple of complex, define how much risk you are willing to accept, depends of complexity of program
12. if ship has a HMS, it can be integrated into inspection regime (#1 + #11?)
13. implement a HMS on the first of class rather than fleet wide
14. manage LOT risks by constraining operations
15. operate for less time than the expected LOT.

Following the initial elicitation of ideas, the DST SMEs undertook a facilitated discussion to determine whether the ideas could be grouped into categories. This discussion resulted in the formation of three top-level categories on ideas that Navy could use to manage a new vessel's LOT risks without a HMS. Once this had been completed, the SMEs were asked to rank the three idea categories in terms of their utility for Navy. The resulting three categories and their ranks were:

1. inspection regime - could be time-based or predictive-based (3+3+3+3+2 = 14)
2. other data sources – for example, logbooks, hindcast weather data, and fatigue damage estimated via simplified or computational approaches (2+2+2+2+3 = 11)

[‡‡] 'Mandraulic' is an informal term referring to the involvement of human effort.

3. manage LOT uncertainty by implementing alternate vessel management strategies — for example, restrict the ship's operations or service life (1+1+1+1+1 = 5).

3.4. Key Assumptions Check

A key assumptions check is often performed in critical thinking exercises as a means of managing bias, as well as providing robustness, validity and rigour to the exercise [36]. It provides a questioning framework that can be used to 'red team' ideas [36]. The key assumptions check is designed to identify incorrect assumptions as well as those that have not been clearly stated [38]. According to Kardos and Dexter [36]: p. 31, the key assumptions check:

- helps explain the logic of an argument and expose faulty logic/data
- enhances understanding the key factors of an issue
- stimulates thinking
- helps identify developments that challenge assumptions
- assists preparation for changes that could surprise.

Of key interest for the study at hand is the ability of the key assumption check to explain the logic behind the ideas generated during the structured brainstorming in the previous step, as well as any of their limitations. A key assumption behind an idea is defined as 'any hypothesis or statement that is accepted to be true' [36: p. 31]. Once the key working assumption behind the ideas have been elicited, they can be 'red teamed' using questions such as [36: p. 32]:

- What makes you certain this assumption is correct?
- What circumstances undermine this assumption? When might it be untrue?
- If the assumption proves to be incorrect, how does it impact the idea?

By asking these questions, the answers can be used to build understanding about the limitations of the ideas generated during the structured brainstorming in the previous step of the process.

For each of the three categories of techniques that could be used to manage LOT risks without a HMS, identified by the SMEs during the structured brainstorming, three key assumptions were identified. The assumptions were tested by posing the questions above to the DST SMEs and the responses were captured. Table 3 shows the assumptions and responses to the key assumptions check questions for the 'inspection regime' strategy. Table 4 shows the assumptions and responses to the key assumptions check questions for the 'other data sources' strategy. Table 5 shows the assumptions and responses to the key assumptions check questions for the 'alternate vessel management' strategy.

Table 3. Key Assumptions Check for Using an Inspection Regime to Manage LOT Risks

Underlying assumptions and judgements	**Why am I confident that this assumption is correct?**	**When might it be untrue? (i.e. at what time, under which circumstances)**	**If the assumption proves to be wrong, how would it impact the argument?**
Know where, when and how to look (provided by OEM) → If structure inaccessible, there is no risk (sufficient life)	• OEM designed ship • Confidence in modelling and simulation	• Experience e.g. ACPB • Design and actual usage don't match • When loads are extreme, confidence in OEM's prediction less good • OEM doesn't understand material degradation, how materiel state changes • Usage difference between navy and commercial assets (OEM used to commercial operations of ships)	• Won't meet required LOT • Increased cost of ownership (small repair becomes big repair) • Catastrophic failure
Regime is conservative	• Standard approach, used for other industries across world • Similar fleets exist and are managed similarly • Information shared across operators (user groups)	• Use ship in a different manner to the design intention • As above	• Not conservative • As above
Have comprehensive record	• Navy invest in keeping good records • Other ships/aircraft/assets managed similarly (best practice)	• When Navy doesn't invest in keeping good records	• Won't be able to observe trends, can't predict actual LOT • Unexpected failures, unplanned maintenance • Stuck in fleet mentality, not ship specific

Table 4. Key Assumptions Check for Using Other Data Sources to Manage LOT Risks

Underlying assumptions and judgements	**Why am I confident that this assumption is correct?**	**When might it be untrue? (i.e. at what time, under which circumstances)**	**If the assumption proves to be wrong, how would it impact the argument?**
Able to get correlation between data and life, tracking right parameters	• Have evidence, other ADF assets managed using correct parameters • Physics, first principles	• Don't understand the physics • Models wrong, too simple, - incomplete • Models only good as data that feeds them	• Estimates of uncertainties probably blow out → either have high costs or high risk • Increased cost of ownership • Catastrophic failure
High fidelity + more information = better estimate	• Historical evidence, validation • Getting real-world data, have ability to refine and check model, learn as go, move from design/generic model to real system in real environment • Evidence for decisions (e.g. Collins LOT, design vs. actual no. of cycles)	• Data corrupt or incomplete • Model wrong • Even if capturing all fleet data, won't represent future missions • Not actionable e.g. not able to change op profile • Not using appropriate data (not high value)	• Make poor maintenance and LOT decisions • High cost low value – no value add • (lower impact??) • Overly conservative
Data sources are reliable	• Rely on third party sources	• Incorrect policy and procedure for crew to do right thing • Poor quality	• Under-conservative • Uncertainty grows • Lose faith, don't know • Poor decisions

Table 5. Key Assumptions Check for Using Alternative Vessel Management Strategies to Manage LOT Risks

Underlying assumptions and judgements	Why am I confident that this assumption is correct?	When might it be untrue? (i.e. at what time, under which circumstances)	If the assumption proves to be wrong, how would it impact the argument?
People responsible for sustainment have authority to change LOT strategy	• In One Defence world, supposed to manage across CLC → less stove-piping, capability manager has understanding of issues • Right acquisition decision made • Consistent government decisions	• Change in government • Change in regulatory and/or navy ideology/culture e.g. change of service life without changing maintenance regime • Change in operational requirements	• If maintenance decisions not made with capability owner, blindly following costly regime • Poor LOT decisions
Restrictions to operations/mission are acceptable	• Well understood relationship between seaway loads and maintenance/damage impact	• Change in operational requirements	• If restrictions not acceptable, ships used such that LOT shortened
Rely on external advice (e.g. class society)	• Authority, reason for being • Broad experience • Talk to multiple stakeholders	• When underlying modelling not mature (e.g. extreme loads) • Poor/incompatible ship husbandry • Novel hullforms & materials • Standards are not up-to-date, advanced design tools do not have appropriate class society evidence • Class society inherently conservative, do not want to use new tools • Lack of reachback from Australia to headquarters	• Poor LOT decision • Decisions could be conservative, or optimistic → increase through-life cost of ownership • Operational unavailability • Ship(s) not seaworthy

4. Discussion

As shown in Figure 1, the first step of the study process was the SWOT analysis followed by data review of the results. Open coding of the identified strengths and weaknesses implied that the major strength of a HMS is to enable informed decision making by the operating navy about the ability of a ship to meet the design LOT. This finding was substantiated by the SWOT+ analysis with DST SMEs (described in Appendix B), as the prioritised strengths were '*S6* - data can be used to validate design calculations e.g. design loads' and '*S10* - can lead to through-life costs savings, through managing cost of ownership'.

Following the data review of the SWOT factors, structured brainstorming and a key assumptions check were performed during a facilitated workshop with different DST SMEs. As reported in Sections 3.3 and 3.4, three categories of ideas to manage LOT risks without a HMS were identified. The first column in each of Table 3, 4 and 5 lists the assumptions that underpin these categories. The second column of each of the tables captures the reasons the SMEs made the assumptions. In the third and fourth columns the conditions when the assumptions would be untrue and the resultant impacts, respectively, are identified.

The underlying assumptions for the 'inspection regime' strategy, shown in Table 3, were reliant on the OEM (that is, the ship designer) providing the inspection regime based on their knowledge of the design. This strategy also relies on the operating navy maintaining good records of the inspections to facilitate decisions regarding the LOT. These assumptions would be untrue primarily in cases where the ship is not used as designed, which is a risk when it has been acquired Off the Shelf (OTS) [46][§§], or when thorough records of inspections are not maintained. The latter point is reflected in 'maintenance data failings' being one of the causal factors that contributed to the unavailability of Navy's two Landing Platform ships [47]. If the assumptions are incorrect, the consequences can include increased cost of ownership, reduced operational availability, and premature decommissioning of the ship. These issues have been highlighted in the Rizzo Review [47], by the need for the RAN to charter two Cape Class Patrol Boats to support an intensive program of maintenance for the Armidale Class Patrol Boats (ACPB) [48], and more generally in asset-intensive industries [49]. These consequences highlight the difficulty in managing the LOT risks of a ship using an inspection regime by itself.

Table 4 summarises the results of the key assumptions check for the strategy 'other data sources', such as ship logs, to manage a ship's LOT risks. The 'other data sources' approach would use the data collected from an Integrated Platform Management System (IPMS)[***] or ship's log in combination with simulations to predict a ship's LOT[†††]. The assumptions that

[§§] In 2012, the Senate Foreign Affairs Defence and Trade Committee [46: p. 197] reported that '…while OTS may initially be the preferred option, it may also pose significant risks that involve modifications that may be necessary to meet Australian standards and operational conditions…'.

[***] An Integrated Platform Management System (IPMS) is a distributed control and monitoring system for a ship or submarine's mechanical, electrical and damage control machinery systems. Further information about IPMSs is provided in Appendix C.

[†††] Recently, the Defence Research and Development Canada performed a fatigue assessment of selected locations in the Halifax class frigate to improve understanding of the operating conditions contributing to fatigue damage. Operational area information from ships' logs was combined with representative profiles of ship speed and heading to generate operational profiles [50].

led to the SMEs proposing this approach were largely based on the data being fit-for-purpose and of an appropriate level of fidelity. These assumptions will be untrue if the models used to predict the LOT, as well as the in-service data provided as an input to the models, were incorrect. This has proven to be the case in the authors' experience, where ship log data was not fit-for-purpose for LOT analysis. This is consistent with the incidence of substandard weight reports during the United States Navy Littoral Combat Ship program [51] which can affect LOT calculations, and in the considerable effort required to cleanse historical data for an ANZAC class Condition Based Maintenance tool (CBM) [52].

The SMEs also identified using other 'vessel management' strategies, such as restricting operations and removing the ship from service well before the assumed/estimated LOT during design. This strategy manages the LOT risks as per Table 5. The underlying assumptions were primarily focused on the sustainment manager having the authority to change the LOT management strategy and/or restrict operations, and that the designer's LOT estimate was accurate. If the assumptions are incorrect, use of 'vessel management' strategies for LOT risk management are unlikely to be effective. Ship unavailability, and in turn fleet effectiveness, is likely to arise if the vessels are taken out of service early, or operational restrictions are imposed.

Other observations made by the SMEs during the workshop are as follows:

- The three categories of alternate LOT management strategies may or may not be interrelated. For example, an inspection regime alone will not be optimal for LOT management, as there is a need to correlate any structural degradation with the ship's operational environment. In effect, a ship's damaged or degraded structure is a symptom, whereas the operational environment is the cause.
- There is a cost trade-off associated with each LOT management strategy. This means that each strategy carries a varying degree of financial and human effort overhead over the LOT of a ship.
- All three categories of LOT management strategies placed a heavy reliance on the accuracy of the ship designer's data and calculations, as it provides the baseline for all LOT management activities.

4.1. Opportunities and Key Benefits Provided by HMSs

All three categories of LOT management strategies would benefit from the ship having a HMS installed. This would provide the most accurate operational data required for robust ship LOT analysis and management decisions. A HMS, particularly if coupled with an IPMS (discussed further in Appendix C), can provide the RAN with opportunities to implement new LOT management strategies such CBM, as well as to optimise fleet operations and support the RAN 'smart owner' initiative set out in the NSP [14]. Opportunities to leverage Data Analytics methods in support of fleet maintenance and operations planning, as well as for follow-on ship design optimisation, could also be realised. Furthermore, this would be an effective approach to achieve Seaworthiness outcomes for RAN ships as the data could be used to validate the OSI.

Other opportunities that may be realised through the implementation of HMSs on RAN vessels include the establishment and leveraging of Digital Twins (described further in Appendix D), of ship classes. This approach can be used to simulate the material state of a ship and when coupled with operational data, supports informed LOT analysis and risk management. Furthermore, this approach provides opportunities for training simulators to be developed that assist ship operators to understand the impact of ship operations on the platform life. The data collected from a HMS also provides opportunities for research collaboration with other navies and research organisations such as the Cooperative Research Ships (CRS). These collaborations are undertaken to learn more about maximising the availability of ships and feeding back the lessons learned in-service, to the design of follow-on vessels. Opportunities for industry to support the through-life management of RAN vessels could also be realised.

The key benefits the RAN could realise from implementing HMSs all support the 'smart owner' philosophy. The usage of the fleet can be optimised to maximise availability by managing the operational tempo of individual vessels according to their current LOT condition. Knowledge of the stress profiles a vessel has been exposed to during operations could reduce the cost of ownership as maintenance can be more effectively planned and executed as required. This knowledge also provides the RAN with the ability to more accurately determine withdrawal from service dates of vessels, as well as the remaining fatigue life of a vessel that is retired. Retired vessels with adequate remaining fatigue lives could be gifted or sold to allied navies.

5. Conclusions

This report covered a preliminary study to investigate the consequences of not installing HMS on RAN ships. The key consequence identified was that the RAN's ability to manage its ships' LOT would be impacted. The study then explored this impact further by utilising red teaming techniques to minimise the influence of cognitive biases on the investigation. These techniques enabled identification of approaches to manage the LOT of RAN ships without using a HMS. Three categories of approaches were identified:

1. Inspection regime (could be time-based or predictive-based).
2. Other data sources (for example, logbooks, hindcast weather data, and estimated fatigue damage).
3. Manage LOT uncertainty by implementing alternate vessel management strategies, (for example, restrict the ship's operations or service life).

The assumptions that underpinned these approaches were then identified and questioned using a key assumptions check. From this questioning, it was found that the three categories of approaches for LOT management without a HMS would lead to a lower level of confidence in the management of RAN ship LOT risks. This is mainly due to the need for accurate data on the ships operational usage in order to manage its LOT risks with a high degree of confidence. Ideally, a HMS would be coupled with all of the three approaches to provide a comprehensive LOT management strategy. Implementing HMS on board RAN ships will however incur through-life financial and human resource costs and decision-makers will need to trade off these costs with the LOT management and other benefits. Other benefits could include the ability to use the operational data for fleet maintenance and operations planning.

Finally, it is concluded that the red teaming approach used to identify underlying weaknesses of the alternative approaches of naval ship LOT management was effective. The key assumptions check provided insights into the underlying assumptions of the ideas to manage ship LOT risks without a HMS, as well as identify the limitations of these ideas. Therefore, it is recommended that the approach taken for this preliminary study be implemented with a range of stakeholders from across the Defence enterprise. This would expand on the trade-offs associated with implementing HMS on RAN ships and support decisions on how the RAN manages LOT risks across the fleet.

6. Acknowledgements

The authors would like to acknowledge the following individuals within DST: Andrew Tynan (MD), Daniel Franke (AD), Dylan Dwyer (MD), Geoff Swanton (AD), Mathew Kelson (AD), Seref Aksu (MD), Terry Turner (MD), and Vlado Kekoc (AD).

7. References

1. Phelps, B. and Morris, B. (2013) *Review of Hull Structural Monitoring Systems for Navy Ships*. DSTO-TR-2818, Melbourne, Australia, Defence Science and Technology Organisation.
2. Hess, P., Aksu, S., Blake, J., Boote, D., Caridis, P., Egorov, A., Fjeldstad, A., Hoogeland, M., Murayama, H., Anderson, M. R. and Tammer, M. (2015) Structural Longevity. In: *Proceedings of the 19th International Ship and Offshore Structures Congress*. Cascais, Portugal 211-287.
3. Sabatino, S. and Frangopol, D. (2017) Decision making framework for optimal SHM planning of ship structures considering availability and utility. *Ocean Engineering* **135** 194-206.
4. Nielsen, U., Jensen, J., Pedersen, P. and Ito, Y. (2011) Onboard monitoring of fatigue damage rates in the hull girder. *Marine Structures* **24** 182-206.
5. Stambaugh, K., Drummen, I., Cleary, C., Sheinberg, R. and Kaminski, M. (2014) Structural fatigue life assessment and sustainment implications for a new class of US coast guard cutters. *Transactions - Society of Naval Architects and Marine Engineers* **122** 434-444.
6. (2011) *Rules for Classification of High Speed, Light Craft and Naval Surface Craft*. Høvik, Det Norske Veritas.
7. Department of Defence (2017) *Defence Seaworthiness Management System Manual (DSwMSMAN)*. Canberra, Australia. Australian Government.
8. Molent, L. and Aktepe, B. (2000) Review of fatigue monitoring of agile military aircraft. *Fatigue & Fracture of Engineering Materials & Structures* **23** 767-785.
9. Magoga, T., Aksu, S., Cannon, S., Ojeda, R. and Thomas, G. (2015) The Need for Fatigue Life Prediction Methods Tailored to High-Speed Craft: A Technical Review. In: *Pacific 2015 International Maritime Conference,* Sydney, Australia
10. Department of Defence (2017) *Naval Shipbuilding Plan*. Canberra, Australia, Commonwealth of Australia.
11. Dean, A. W., Reina, J. J. and Bao, H. P. (2008) Identification of Supplementary Metrics to Sustain Fleet Readiness from a Maintenance Perspective. *Naval Engineers Journal* **120** (2) 81-88.
12. Houston, M. and Cannon, S. (2017) Application of Structural Integrity Management Principles Demonstrated in Other Domains to Improve Seaworthiness and Cost of Ownership Outcomes. In: *Pacific 2017 International Maritime Conference,* Sydney, Australia
13. Temple, D. and Collette, M. (2015) Minimizing lifetime structural costs: Optimizing for production and maintenance under service life uncertainty. *Marine Structures* **40** 60-72.
14. Royal Australian Navy (2017) *Navy's Operationalisation of the Naval Shipbuilding Plan*. Canberra. Commonwealth of Australia.
15. Directorate General Technical Airworthiness. (2014) *Airworthiness Design Requirements Manual*. [Accessed 27/1/15]; Canberra, Australian Defence Force Available from: http://www.defence.gov.au/DGTA/Documents/Publications/7001054/eADRM%20web/7117.htm.
16. Military Aviation Authority. (2015) *Structural Integrity Handbook*. [Accessed 14/01/17]; Bristol, United Kingdom, Ministry of Defence. Available

from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/426205/Structural_Integrity_Handbook.pdf.

17. Technical Committee CEN/TC 250 (1999) *Eurocode 9: Design of aluminium structures*. Brussels, Belgium. British Standards.
18. Barter, S. and Molent, L. (2014) Fatigue cracking from a corrosion pit in an aircraft bulkhead. *Engineering Failure Analysis* (39) 155-163.
19. ISO 19902:2007 + Amd 1:2013 (2014) *Petroleum and natural gas industries e fixed steel offshore structures*. International Organization for Standardization.
20. DNV GL (2017) *Offshore Standards*. DNVGL-OS, Oslo, Norway, DNV GL AS.
21. Khedmati, M. R. and Pedram, M. (2014) *A numerical investigation into the effects of slamming impulsive loads on the elastic–plastic response of imperfect stiffened aluminium plates*. In *Thin-Walled Structures*: p. 118-144.
22. Aeran, A., Siriwardane, S. C., Mikkelsen, O. and Langen, I. (2017) A framework to assess structural integrity of ageing offshore jacket structures for life extension. *Marine Structures* **56** 237-259.
23. Magoga, T., Aksu, S., Cannon, S., Ojeda, R. and Thomas, G. (2017) Identification of slam events experienced by a high-speed craft. *Ocean Engineering* **140** 309-421.
24. *Light Structures – Fiber Optic Condition Monitoring Systems for Shipping, Oil & Gas Industries*. (2015) [Accessed 18 May 2018]; Oslo, Norway, Light Structures. Available from: http://www.mapps.l3t.com/integrated-platform-Management-System.html.
25. Johnson, N. R., Lynch, J. P. and Collette, M. D. (2018) Response and fatigue assessment of high speed aluminium hulls using short-term wireless hull monitoring. *Structure and Infrastructure Engineering* **14** (5) 2018/05/04 634-651.
26. Swartz, R. A., Zimmerman, A. T., Lynch, J. P., Rosario, J., Brady, T., Salvino, L. and Law, K. H. (2012) Hybrid wireless hull monitoring system for naval combat vessels. *Structure and Infrastructure Engineering* **8** (7) 621-638.
27. Vincent, P., Gardiner, C., Wilson, A., Ellery, D. and Armstrong, T. (2008) Installation of a sensor network on an RAN Armidale Class Patrol Boat. *Materials Forum* **33** 307-316.
28. Magoga, T., Brincat, M. and Dawes-Lynch, J. (2016) *Verification of Pressure Sensors and Strain Gauges Installed Onboard HMAS Maryborough*. DST-Group-TN-1576, Melbourne, Australia, Defence Science and Technology Group.
29. Kazantzidis, K. and Magoga, T. (2018) *HMAS Maryborough Hull Monitoring System: Data Processing and Analysis Methods - Phase Two*. DST Group-GD-0991, Melbourne, Australia, Defence Science and Technology Group.
30. Dawes-Lynch, J. and Magoga, T. (2017) *HMAS Maryborough Hull Monitoring System: Data Processing and Analysis Methods*. DST Group-GD-0952, Melbourne, Australia, Defence Science and Technology Group.
31. Vincent, P., Wilson, A., Brincat, M. and Yiannakopoulos, G. (2015) Design, installation and repair of hull sensors for the measurement of hull slamming pressure loads on Armidale Class Patrol Boats. In: *International Maritime Conference, Pacific 2015,* Sydney, Australia.
32. Koboević, Ž., Bebić, D. and Kurtela, Ž. (2018) New approach to monitoring hull condition of ships as objective for selecting optimal docking period. *Ships and Offshore Structures* 1-9.
33. (2003) *Guide for Hull Condition Monitoring Systems*. Houston, American Bureau of Shipping.

34. DNV GL (2017) *Rules for Classification: Ships*. DNVGL-RU-SHIP, Oslo, Norway, DNV GL AS.
35. CIA. (2009) *A Tradecraft Primer: Structured Analytic Techniques for Improving Intelligence Analysis*. [Accessed 2018 15/2/2018], US Government. Available from: https://www.cia.gov/library/publications/publications-rss-updates/tradecraft-primer-may-4-2009.html.
36. Kardos, M. and Dexter, P. (2017) *A Simple Handbook for Non-Traditional Red Teaming*. Edinburgh, SA, Defence Science and Technology Group.
37. *The Applied Critical Thinking Handbook* (2015). Ft Leavenworth, United States, University of Foreign Military and Cultural Studies.
38. Hoffman, B. G. (2017) *Red Teaming: Transform Your Business by Thinking Like the Enemy*. London, Little, Brown Book Group.
39. Watkins, R., Meiers, M. W. and Visser, Y. L. (2012) *A Guide to Assessing Needs: Essential Tools for Collecting Information, Making Decisions and Achieving Development Results*. Washington DC, The World Bank.
40. Silberman, M. and Silberman, M. (2005) *ASTD Training and Organizational Development*. United States American Society for Training & Development,.
41. Flockhart, C., Phelps, B. and Cannon, S. (2008) *Fatigue Life Assessment of ANZAC Frigate Bilge Keels*. Melbourne, Australia. Defence Science and Technology Organisation.
42. Rosén, A., Garme, K. and Kuttenkeuler, J. (2007) Full-Scale Design Evaluation of the Visby Class Corvette. In: *International Conference on Fast Sea Transportation, Fast'2007*, Shanghai, China
43. Clarke, G. (2011) Fleet Recovery and Life Extension – Some Lessons Learned. In: *26th Symposium of the International Committee on Aeronautical Fatigue,* Montreal, Canada: 1-3 June 2011
44. Leedy, P. D. and Ormrod, J. E. (2001) *Practical Research: Planning and Design*. 7th ed. Upper Saddle River, N.J., Pearson Prentice Hall.
45. Bazeley, P. (2013) *Qualitative Data Analysis: Practical Strategies*. London, Sage Publications.
46. Senate Foreign Affairs Defence and Trade Committee (2012) *Procurement procedures for Defence capital projects: Final Report*. Canberra, Australia, Commonwealth of Australia.
47. Rizzo, P. (2011) *Plan to Reform Support Ship Repair and Management Practices*. Canberra, Australia, Ministerial and Executive Coordination and Communication Division.
48. Paroz, D. (2015) *Cape Class ships join the Fleet*. In *Navy Daily*. Royal Australian Navy.
49. Hodkiewicz, M. and Ho, M. T. W. (2016) Cleaning historical maintenance work order data for reliability analysis. *Journal of Quality in Maintenance Engineering* **22** (2) 146-163.
50. Thompson, I. (2018) Fatigue damage variation within a class of naval ships. *Ocean Engineering* **165** 123-130.
51. Zimmerman, G. (2012) *The U.S. Navy Littoral Combat Ship: Current Issues and How to Employ it in the Future*. Virginia, United States. United States Marine Corps.
52. Hammond, L., Kelly, P. and Sikorska, J. (2010) Transitioning Towards Condition-Based Maintenance through Enhanced Decision Support Tools. In: *Pacific 2010 International Maritime Conference,* Sydney, Australia
53. *Rules for Classification of High Speed, Light Craft and Naval Surface Craft*. (1996) Høvik, Norway, Det Norske Veritas.

54. Geertsma, R. D., Negenborn, R. R., Visser, K. and Hopman, J. J. (2017) Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Applied Energy* **194** 30-54.
55. Kwon, K., Frangopol, D. and Kim, S. (2012) Fatigue performance assessment and service life prediction of high-speed ship structures based on probabilistic lifetime sea loads. *Structure and Infrastructure Engineering* **9** (2) 102-115.
56. *Integrated Platform Management System*. (2018) [Accessed; Montréal, Canada L3 Mapps. Available from: http://www.mapps.l3t.com/integrated-platform-Management-System.html.
57. *IPMS - Integrated Platform Management System*. (2018) [Accessed; Aalborg, Denmark, Logimatic. Available from: https://www.logimatic.com/automation/maritime-automation/ipms-1.
58. Bøgh, S. (2018) *FW: Please contact me regarding IPMS from Logimatic*. To: Magoga, T., Aalborg, Denmark, 25 May 2018.
59. Zimmerman, P., Gilbert, T. and Salvatore, F. (2017) Digital engineering transformation across the Department of Defense. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology* 1-11.
60. Alam, K. M. and El Saddik, A. (2017) *C2PS: A Digital Twin Architecture Reference Model for the Cloud-based Cyber-Physical Systems*. Vol. PP
61. Lewis, G. (2018) *ABS to pilot bow-to-stern Condition-Based Class for U.S. Navy's MSC.* Houston, United States. American Bureau of Shipping (ABS).
62. Soghomonian, Z., Anindo Bagchi, A., Habiby, S. and Shur, D. (2018) Monitoring Network for Integrated Power Systems. In: *Technology, Systems and Ships 2018,* Washington D.C., United States
63. Kraft, E. M. (2016) The Air Force Digital Thread/Digital Twin - Life Cycle Integration and Use of Computational and Experimental Knowledge. In: *54th AIAA Aerospace Sciences Meeting*. American Institute of Aeronautics and Astronautics
64. Fu, T. (2017) *Navy Platform Digital Twin*. [Accessed 17/12/2018], Office of Naval Research Science & Technology. Available from: http://onlinepubs.trb.org/onlinepubs/mb/2017Spring/fu.pdf.

Appendix A Recommendations for Implementing a HMS on a Naval Ship

Some general recommendations are made based on DST's experience with the ACPBs [23] and a review conducted by Phelps and Morris [1].

- To understand the global wave loading as a hull-girder fatigue indicator, install strain gauges along the length of the vessel. Further, these strain gauges should be located away from bending nodes to ensure that appreciable structural excitation is detected, which can be checked via natural frequency analysis (in general, first and second modes).
- To understand localised fluctuating stresses that induce fatigue damage, install strain gauges in proximity to highly stressed or cracking-prone details. However, care should be taken to ensure that placement of strain gauges is not influenced by stress concentrations. This can be checked via stress analysis.
- The results from monitoring stresses at one location should be able to be related to the structural response at other locations.

Important considerations for the design of a HMS for fatigue monitoring of naval vessels include:

- Ease of access to the structure.
- Weight limitations.
- Potential interference with on-board activities.
- Though-life costs.
- Sampling frequency, and volume and accuracy of the data.

Ultimately, the costs associated with setting-up and maintaining hardware plus analysing large quantities of data, and the complexity of the system, needs to be balanced.

Appendix B SWOT+ Analysis

SWOT+ analysis entails identifying, organising and prioritising the strengths, weaknesses, opportunities, and threats — or SWOT factors as defined in Table 1 (in Section 3.1) — that influence implementation of a program or project. The SWOT+ analysis expands upon the traditional SWOT analysis covered in Section 3.1 by ranking the SWOT factors.

The added value of the '+' in a SWOT analysis is visualisation of the factors within the context, which allows stakeholders to discuss the relationships between the factors: which items to act on, which items to monitor for now, and which items do not need to be actioned.

For the context 'implementing a HMS on a naval ship', a SWOT+ analysis was conducted to gain further insights into the SWOT analysis described in Section 3.1.

The steps of the SWOT+ analysis are as follows:

1. The DST SMEs were asked to individually select the top three SWOT factors per category.
2. The votes were aggregated. For ease of understanding a simplification was made to include only the SWOT factors ranked first and second per category, as shown in Table B1.
3. The SMEs were then asked to define:
    a. The extent that the prioritised strengths and weaknesses are within Defence's (internal) control; that is, to allocate a value between 0 and +3 on the y-axis.
    b. The extent that the prioritised opportunities and threats are within internal control; that is, to allocate a value between 0 and -3 on the y-axis.
    c. The extent that the prioritised strengths and opportunities provide enhancement to LOT management and/or Defence; that is, to allocate a value between 0 and -3 on the x-axis.
    d. The extent that the prioritised weaknesses and threats are liabilities; that is, to allocate a value between 0 and +3 on the x-axis.

The results were plotted in a 'SWOT+ matrix' as presented in Figure B1. In the matrix, the identifiers within the quadrants correspond to the factors in Table B1. There are multiple layers of data interpretation from Figure B1:

- Each quadrant represents a domain of the context 'implementing a HMS on a new naval ship'. For example, the strengths' quadrant (top-right) represents the enhancer-internal control domain.
- The rankings by importance are delineated by colour.
    - Yellow denotes SWOT factors ranked equal second.
    - Red denotes SWOT factors ranked equal first.
- A large circle denotes a SWOT factor allocated the same location by two or more SMEs.

- A factor can have multiple locations. For example, S6 and S10 were ranked equal most important among the strength factors. There are 3 circles each for S6 and S10, which means that 3 SMEs had differing views on the placements of these factors within the enhancer-internal control domain.

The key observations from Figure B1 are as follows:

- In general, the perceptions of the extents that various factors were a liability/enhancer and under internal/external control were disparate amongst the SMEs. For example, although there was agreement that the liability associated with SWOT factor T5 (a HMS is vulnerable to budget changes throughout vessel lifecycle) is relatively minor, there was disagreement regarding the extent that it is under external control.
- There was some consensus on the scoring for T6 (assumption/belief that Off-the-Shelf = proven design → negates the need for HMS).
- The scores of the SWOT factors categorised as opportunities were relatively similar. That is, these factors are clustered in the bottom-right quadrant of Figure 2 whereas the factors in the other three quadrants are spread. Though the prioritised opportunities were viewed as providing a relatively large amount of enhancement to implementing a HMS on a new naval ship, they tended to be associated with a high degree of external control. This does not necessarily mean that these opportunities are out of Navy's control or cannot be changed. Rather, the opportunities exist in the external environment (for example, would more likely be externally funded rather than self-funded, and are conditioned by the actions of external organisations).
- The threat associated with the greatest liability, and under external control, is that meeting the requirements of a classification society rule set is sufficient (T2) with respect to structural integrity[‡‡‡].

[‡‡‡] The RAN's experience with the ACPB brings this perception into doubt: The ACPBs were designed to, and are maintained to comply with, Det Norske Veritas High Speed Light Craft rules [53]. Thus, to ensure that the design life would be met, the allowable stress approach was followed together with good detailed design and fabrication quality. However, serious fleet-wide cracking was discovered in 2012 and, consequently, a major structural remediation program was undertaken.

Table B1. Prioritised SWOT factors for further '+' analysis

Rank	Strengths	Weaknesses	Opportunities	Threats
1	*S6* - Data can be used to validate design calculations e.g. design loads *S10* - Can lead to through-life costs savings, through managing cost of ownership	*W4* - Need a range of skills to implement and support the system	*O4* - Can use data to inform subsequent batch vessel design and management	*T2* - Perception that rules-based approach is sufficient
2	*S1* - Can capture full-scale vessel responses	*W2* - Large maintenance overhead e.g. repair/replacement of hardware operating in hot and humid environment *W6* - Potentially lacking environmental data	*O2* - Data can be used in Condition-Based Maintenance *O3* - Provide operator guidance *O5* - Use data to optimise usage of fleet and platform transition planning	*T4* - There are cheaper techniques to manage structural integrity *T5* - Vulnerable to budget changes throughout vessel lifecycle

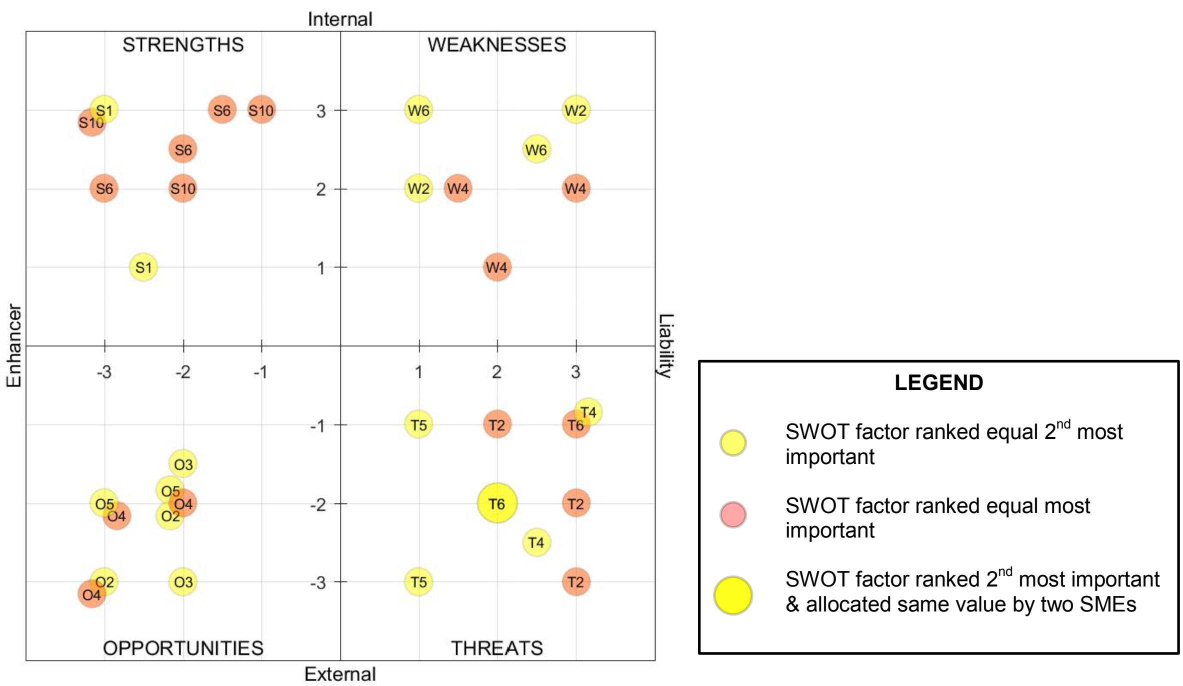

Figure B1. SWOT+ matrix for implementing a HMS on a new naval ship. SWOT factor identifiers correspond to those in Table B1. A small yellow circle denotes a SWOT factor ranked equal second most important; a small red circle denotes a SWOT factor ranked equal most important; a large yellow circle denotes a SWOT factor ranked second most important and allocated the same x-y position by two or more SMEs.

Appendix C Integrated Platform Management System

An Integrated Platform Management System (IPMS) is a distributed control and monitoring system for a ship or submarine's mechanical, electrical and damage control machinery systems.

The purpose of including information about IPMSs in this report is to two-fold:

1. This type of system architecture may be a possible option for hull monitoring synchronised with other shipboard systems that are already part of the IPMS (for example, navigation and propeller shaft speed).
2. A recent trend in both commercial and naval applications is the design of versatile ships. This has led to, for instance, an increase in the variety of hybrid propulsion and power supply architectures [54]. Increasing the sophistication and number of management/control/monitoring 'sub-systems' at the whole-of-ship level may enable links to functional specifications such as transit time, fleet availability, and maintenance. Implementation of an IPMS that includes hull monitoring may be a promising approach to assess and improve platform performance against multiple requirements for future 'smart ships' [54, 55].

A typical warship IPMS includes alarm monitoring, power management, propulsion and propellers, auxiliary machinery, multi-function consoles, built-in diagnostics and training, safety management, condition based monitoring, and logistics support. IPMS technology has been implemented on many surface combatants and submarines, including:

- The Navantia IPMS, on the RAN's Landing Helicopter Docks and Hobart Class guided missile destroyers [42]. Navantia's IPMS enables integration of standard functions like ship control with specialised functions such as maintenance and on-board training by extracting information from the design and construction data to enhance the onboard operational systems.
- The L3 MAPPS IPMS [56], which has been installed on naval vessels of several different navies[§§§]. This IPMS can include a CBM system for machinery plant, to advise maintenance personnel concerning the need for machine maintenance. The CBM system automatically monitors accelerometers and other sensors on critical machinery.
- The Logimatic IPMS [57], which is installed on Danish warships. Logimatic have advised that their system is capable of incorporating real-time data acquisition and monitoring of virtually any kind of equipment where sensors can be installed. Although to date they have not interfaced strain gauges and other hull monitoring hardware to their IPMS, it would be straight-forward to implement. However, they do not have an OTS product for analysing the hull stresses and subsequently generating information for navigational guidance [58].

[§§§] The RAN and Royal New Zealand Navy ANZAC Class frigates have been fitted with the L3 LM2500 Digital Engine Controller.

Appendix D Digital Twin

The Digital Twin refers to a digital representation of a physical asset or system. It is a framework that integrates technical data, software, and knowledge into actionable information, to inform decision makers throughout a system's lifecycle [59]. The Digital Twin should represent all of the functionalities of the physical system [60].

The Digital Twin concept is currently a topic of interest in the research community, including Defence. The requirement for digital engineering concepts has been driven by the need to adapt quickly to changing operational and threat environments, fiscal constraints, and the rapid pace of technology advancement [14, 59]. In addition, sensors and computer networks have become omnipresent; the analysis of acquired data from the physical environment is possible more than ever before [60]. For ship structural management the Digital Twin can facilitate condition-based maintenance, rather than calendar-based hull surveys, to potentially increase a ship's operational availability and flexibility [61] and reduce the through-life cost of ownership.

The volume and type of data, and nature of decisions, vary throughout the lifecycle of the system. Therefore, a wide range of analytical tools need to be available in the Digital Twin for it to be effective [59]. In addition, implementation of the Digital Twin requires 'comprehensive insight into the entire design enterprise' [62, p. 1] to enable the creation and management of precise digital representations of the system. This is an important consideration in the context of OTS acquisition (refer to Section 4).

Recent studies and uses of the Digital Twin concept include:

- The United States Air Force deployment of the Digital Twin concept, via a pilot study and development of an engineering knowledge management system [63].
- Use of the Digital Twin to integrate models and the associated data within a design and developmental framework, to allow stakeholders to appreciate how a complex system can be designed, operated, and modified, before being implemented in the field [62].
- Fusion of measured data and physics-based models of naval vessels, in the form of the United States Navy Digital Twin as illustrated in Figure D1. The aim of this research is to predict the optimum performance, materiel state, and susceptibility of a naval vessel. The anticipated outcome is enhanced resource allocation, logistics planning, and in-situ decision-making [64].
- The American Bureau of Shipping (ABS) is building a Digital Twin for each vessel of the United States Navy's Military Sealift Command. The aim of the Digital Twins is to detect abnormal behaviour, thus acting as an early warning system for problems [61].

DST Group is contributing to research projects that include the Digital Twin as part of CRS and The Technical Cooperation Program (TTCP).

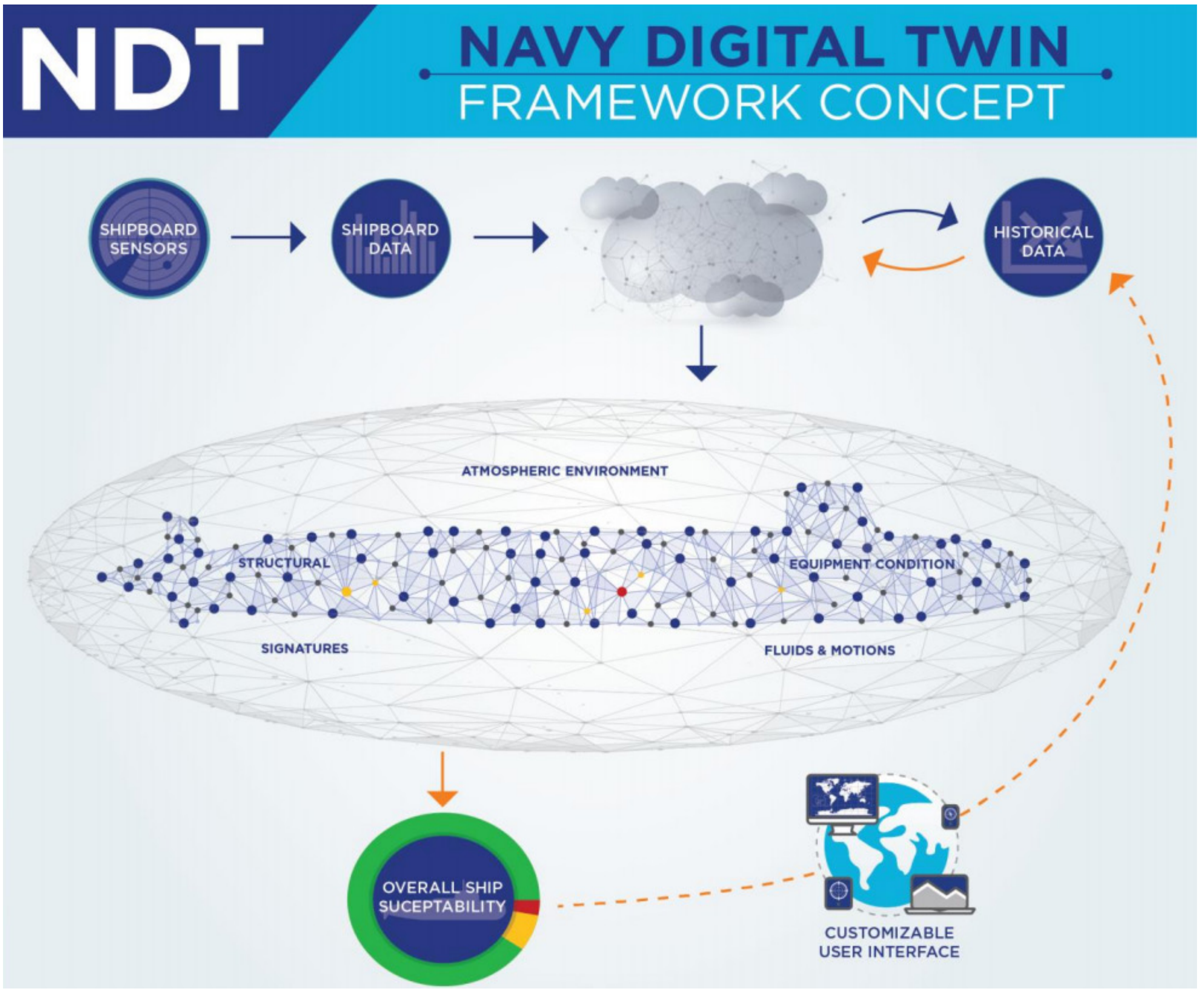

Figure D1. United States Navy Digital Twin framework [64]

DEFENCE SCIENCE AND TECHNOLOGY GROUP DOCUMENT CONTROL DATA			1. DLM/CAVEAT (OF DOCUMENT)
2. TITLE An Investigation into RAN Ship Structural Life-of-Type Management without Hull Monitoring Systems		3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED LIMITED RELEASE USE (U/L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)	
4. AUTHOR(S) Teresa Magoga and Brett A. Morris		5. CORPORATE AUTHOR Defence Science and Technology Group 506 Lorimer Street, Fishermans Bend, Vic. 3207	
6a. DST GROUP NUMBER DST-Group-TN-1826	6b. TYPE OF REPORT Technical Note		7. DOCUMENT DATE June 2019
8.TASK NUMBER NAV 17/566	9.TASK SPONSOR DG Naval Construction Branch		10. RESEARCH DIVISION Maritime Division
11. MSTC Maritime Platform Performance		12. STC Naval Architecture and Platform Systems Analysis	

13. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111

14. DELIBERATE ANNOUNCEMENT

Australian Department of Defence and Defence Force Personnel.

15. CITATION IN OTHER DOCUMENTS

Yes

16. RESEARCH LIBRARY THESAURUS

Ship structures, ship maintenance, monitoring, red teaming

17. ABSTRACT

A preliminary study was conducted on the considerations, assumptions, and options for managing the structural Life-of-Type (LOT) of new Royal Australian Navy (RAN) ships without ship Hull Monitoring Systems (HMS). The study used critical thinking, or 'red teaming' techniques to identify the consequences of not implementing HMS on board RAN ships, as well as to identify LOT management strategies that do not use HMS. The key consequence is that the RAN's ability to manage LOT risks and fleet availability will be impacted. Three alternative LOT management strategies were identified. The study found that the three categories of approaches for LOT management without a HMS would lead to a lower level of confidence in the management of RAN ship LOT risks. This is mainly due to the need for accurate data on the ship's operational usage to manage its LOT risks with a high degree of confidence. This data, in combination with emerging technologies such as the Digital Twin, provides opportunities for condition-based maintenance and support for the RAN to be a 'smart owner'. Implementing HMS on board RAN ships will however incur through-life financial and human resource costs and decision-makers will need to trade off these costs with the LOT management and other benefits.