Examining User Requirements for a Digital Twin Capability Supporting Naval Platform Management and Operations

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ABSTRACT

The provision of logistics support to, and managing the operations of, military platforms are complex processes. The use of digital engineering technology supporting these processes allows for adaptation to the rapidly changing requirements influenced by (for example) operational environments; technology refresh cycles; and security. The relevancy and fitness-for-purpose of any applied digital engineering technology requires understanding of the end user perspective and decision-making requirements. A recent study performed by The Technical Cooperation Program (TTCP) Digital Twin Community of Interest (CoI) endeavoured to understand operator needs in support of naval platform operations. The study purpose was to identify opportunities benefitting from capabilities afforded by the digital engineering technology known as the Digital Twin; and identify impediments that might hinder the implementation of a Digital Twin for such purposes. The success of the study was evidenced in identifying various applications that may benefit from a Digital Twin capability in support of naval platform management and operations. Presented is the study methodology as a possible user requirements analysis technique for digital engineering technology supporting military platforms. Analysis specific to supporting naval platform operations is examined, with opportunities for: prioritisation of fleet maintenance; ability to improve operational planning based on platform health; and prognostic and predictive health monitoring. The ability to convert these opportunities and impediments into user requirements for digital engineering technologies is also discussed.

1.0 INTRODUCTION

The Technical Cooperation Program (TTCP) science and technology community deemed it imperative to understand the evolving digital engineering technology eco-system. In particular, there was a need to examine the concept known as 'Digital Twin'. Consequently, the TTCP Digital Twin Community of Interest (CoI) was formed. The first task of the CoI was a study to identify the applicability of the Digital Twin in support of naval platform management and operations. The study output was a consensus regarding opportunities that might benefit from the capabilities provided by a Digital Twin. Risks and barriers associated with the implementation of a Digital Twin were also identified. This included data quality and quantity to perform the requisite analysis, the validity of the output, and information security. Operator trust and confidence is key to successful application of a Digital Twin capability. Without this, operators may not include the output in their decision-making, thereby negating the effectiveness, and need for, a Digital Twin.

The study involved interviewing stakeholders (primarily end use operators) who had experience supporting the management and operations of naval platforms. Using the information supplied by the interviewees, it was possible to derive user requirements for a Digital Twin supporting management and operations of naval platforms. However, due to study constraints, these user requirements cannot be considered complete or formal. An in depth analysis is required, using information collected from a larger, more diverse set of interviewees. This would be coupled with analysis of formal documentation detailing relevant processes and information requirements. The outcome would then be a detailed formal specification for digital engineering technology, such as a Digital Twin, capable of: informing decision-making; minimising logistics costs; optimising platform (and system) usage; efficient management of personnel; predicting sparing and platform defects; and efficient, traceable risk management.

This paper presents a proposed requirements analysis technique for a digital engineering technology supporting naval and, more generally, military platforms. Using the identified requirements (from a larger, formal study), a phased approach to developing a Digital Twin capability could be achieved.

2.0 DEFINING DIGITAL TWIN

The concept of a Digital Twin emerged in the early 2000s, with Grieves [1] credited as providing the first definition. However, Grieves referred to the Digital Twin concept as the 'Mirrored Spaces Model' as applied to Product Lifecycle Management (PLM). With the advent of 'Industry 4.0'[1] [2, 3], Digital Twin is becoming a 'go to' solution for PLM. However, there is no commonly accepted definition for the Digital Twin concept. Kritzinger et al. [4] found there was a diverse and incomplete understanding of the Digital Twin. Cimino et al. [5] and VanDerHorn and Mahadevan [6], in their respective literature reviews, claimed: there was no commonly accepted definition for Digital Twin; there was no agreement regarding the features a Digital Twin should possess; and there was no agreement regarding the scope a Digital Twin should encompass. During the TTCP Digital Twin CoI study, an informal definition for the Digital Twin was proposed, defining it as a concept consisting of the following components [7]:

- a real world system of interest;
- one or more digital models representing the real world system;
- sensor data plus fusion logic to join the real world system with the digital models; and
- a decision that will change based on the output from the digital models.

After reviewing the literature [1, 4, 5, 6, 7, 8, 9], Woolley et al. [10] proposed the following Digital Twin definition:

A Digital Twin implements a virtual representation of a physical system by way of integrated multi-physics, multi-scale, probabilistic simulation and models of the as-built physical system utilising the best available sensor updates, fleet history, etc., to interact with and mirror the operation of the corresponding physical system.

Further, Woolley et al. [10] identified that a Digital Twin framework should consist of the following:

- the physical system;
- the virtual system (a digital replica of the physical system); and
- data (relating to the physical and virtual systems, and modelling and processing);
- the connection of data and information linking the physical system to the virtual counterpart;
- services (to support: management and control of the physical system; operation of the virtual counterpart; and connection of data and information for information sharing between the physical system and the virtual counterpart); and
- decision-making (autonomous and/or human-in-the-loop) to effect an outcome and/or output in the physical system.

[1] Also known as 'Industrie 4.0' and 'Fourth Industrial Revolution' (4IR).

The work by Woolley et al. [10] was an extension of the TTCP Digital Twin CoI study, making use of Royal Australian Navy (RAN) information collected during the study.

3.0 STUDY METHODOLOGY

To examine the suitability of Digital Twin in support of naval platform capability management, a study was developed involving semi-structured interviews with navy personnel (service and civilian) experienced in the management and operations of naval platforms. To focus the interviews and workshops, four high-level scenarios were investigated. These scenarios were considered representative of the day-to-day management and operation of naval platforms. Personnel were selected based on their experience relating to a given scenario and their responses were to be in the context of their respective scenario. The purpose of the interviews was to gain understanding of daily operations and decision-making with respect to each scenario; and identify tools and policies that contributed to the decision-making.

Information collected during the interviews enabled the development of 'Journey Maps' [11, 12]. Journey Maps visually depicted the emotional experience of the interview respondents when they considered: the processes required for managing and operating naval platforms; the available data and tools to enable decision-making; and policies that might constrain or further enable their decision-making. Workshops were then convened (one each per scenario) to examine the interview responses in more detail, and identify how a Digital Twin capability may support platform managers and operators in their day-to-day operations.

The following method was applied to achieve the goals of the study:

1. define the scenarios;
2. develop semi-structured interview questions;
3. develop Journey Map templates for each scenario;
4. perform the interviews with relevant operator experts for each scenario;
5. process the information collected during the interviews;
6. populate the Journey Maps for each scenario using processed interview data;
7. preliminary analysis of the Journey Maps;
8. develop workshops. Each workshop followed the same agenda:
    a. present scenario description;
    b. definition of the Digital Twin concept;
    c. Breakout Session 1: Journey Map discussion, validation, and identification of domains suited and not suited to Digital Twin application;
    d. Journey Map Share Out to discuss key points identified during Breakout Session 1;
    e. Breakout Session 2: identification of concept applications supporting the scenario;
    f. cohort discussion of concepts identified during Breakout Session 2;
    g. cohort vote to identify top three concepts (voting criteria: most feasible; and most impactful);
    h. Breakout Session 3: teams identify advantages/disadvantages for their respective concept;
    i. making the case: each team champions the concept to which they were assigned; and
9. cohort vote to identify top two concepts (voting criteria: most feasible; and most impactful);

10. convene the workshops (one for each scenario); and
11. analysis of data collected from the workshops.

The methodology is described and exemplified in the following sections.

4.0 DEFINE THE SCENARIOS

Scenarios should encompass operations of the system to be examined. Define as many scenarios as required to encapsulate the different operating modes of the system. Scenarios should be defined with enough detail to provide context for the interview respondents, thereby ensuring relevant information is obtained during the interviews. For the study, four scenarios, encompassing support of naval platform management and operations, were defined. The scenarios were broadly defined to elicit specific details during workshop discussions with relevant operator experts for specific aspects of each scenario. A summary of the four scenarios follows:

- *Scenario 1: Platform Selection and Readiness* - examine the decision-making relating to the choice and/or readiness of a suitable platform a navy will commit to a six-month task force deployment.
- *Scenario 2: Platform Class Life-of-Type Management* - examine the remaining capability life management process for a fleet of mid-life platforms. The aim: maximise operations; minimise hull maintenance costs; and a phased withdrawal from service.
- *Scenario 3: Underway Management* - examine platform operational guidance while underway via awareness of expected versus actual hull, mechanical and electrical system performance.
- *Scenario 4: Survivability* - inform decision-making during damage control and recoverability of a platform, whilst deployed, after exposure to a damage event, either during peace or wartime conditions. The aim: maximise survivability and mission effectiveness.

5.0 DEVELOP SEMI-STRUCTURED INTERVIEWS

The interview process is to elicit the knowledge of domain experts who provide support and decision-making related to the respective scenarios. The interview process also facilitates understanding of their satisfaction in the ability to provide that support. Satisfaction is measured against decision-making requirements, and the data requirements, policies, and tools to support them in decision-making. Issues impeding their ability to perform their duties, are identified as ‘pain points’. Conversely, processes that work well are identified as ‘gain points’.

For the TTCP Digital Twin CoI study, the interview questions were grouped into five focus areas:

- Demographics: to understand experience and identify the statistical spread of each respondent;
- Role Identification: to understand a respondent’s daily activities relating to the respective scenario, and identify tools and policies available to assist with their duties;
- Goal Identification: to identify the purpose of the role;
- Decision-making: to identify decisions, and time constraints, for goal achievement; and
- Information Requirements: to understand the information needs for informed decision-making.

In ideal circumstances, interviews should be performed with two interviewers: one interviewer leads the discussion, asking questions of the respondent; and the second interviewer acts as note-taker. Interview questions should be open ended, to encourage the domain experts to discuss their answer. Follow-up questions are used to clarify responses and obtain further information. Due to constraints placed on the study (primarily, lack of researchers to perform interviews; and lack of available domain experts) each participating nation in the study performed the interviews according to their available resources. For example, one nation distributed interview questions via electronic mail to respondents for written feedback. Another nation performed interviews in a virtual environment using an interviewer and note-taker. Other nations performed interviews in person or in a virtual environment, sometimes with two interviewers and sometimes one. The workshops (see Section 7) were used to validate information collected during the interviews and examine the scenarios in more detail.

6.0 PROCESSING AND VISUALISATION OF INTERVIEW DATA

Processing the information collected during the interviews is dependent on the method of analysis and visualisation techniques to present the information. For the study, Journey Maps were the chosen method of data visualisation. A Journey Map is a graphical, temporal visualisation technique used to present the emotional state of persona fulfilling their duties when operating or managing the system [11, 12]. A persona is a stakeholder associated with the system and may include anyone ranging from operators through to supervisors or higher. Many personas may be presented on one Journey Map. The emotional experiences of each persona can be presented in Cartesian coordinates. The abscissa represents discrete timestamps; and the ordinate represents the persona's satisfaction ranging from, say, 'unsatisfied' to 'satisfied' at each discrete timestamp. The discrete timestamps are referred to as 'touch points', representing key events or decision points in the journey to support the scenario. The following subsections represent Steps 5 to 7 of the methodology presented in Section 3.

6.1 Journey Maps for the TTCP Digital Twin CoI Study

Four Journey Maps were created for the study, one for each scenario, using processed interview data for the respective scenario. The personas were interview respondents experienced with performing duties relating to the scenario. Processing the interview data was subjective, interpreting the emotional state of interview respondents. Each respondent may have differing experiences for their respective scenario, depending on, for example, their role, the services and data available to them in that role, and country of origin.

An example Journey Map is presented in Figure 1, representing experiences of persona in roles supporting *Scenario 2: Platform Class Life-of-Type Management*. Table 1 defines the touch points at which each persona shared experiences supporting that stage in the management of the platform. Note the touch point timeline in Figure 1 is a generalisation representing the different stages in support of platform class life-of-type management.

Figure 1 presents diverse experiences; however, there are occasions when there is broad alignment. Interviewee responses at each touch point provide more insights relating to their 'pains' and 'gains'. The following (summarised) insights are an amalgamation from each nation involved in the study. The primary focus of discussion during the study was the pain points and, similarly, the focus of the following summary is the pain points. This does not preclude the importance of the gain points. It is important not to negatively affect those processes that are performed well. Further, gain points may be improved by capabilities provided by a Digital Twin. Therefore, it is necessary to document the requirements associated with the gain points identified during the analysis.

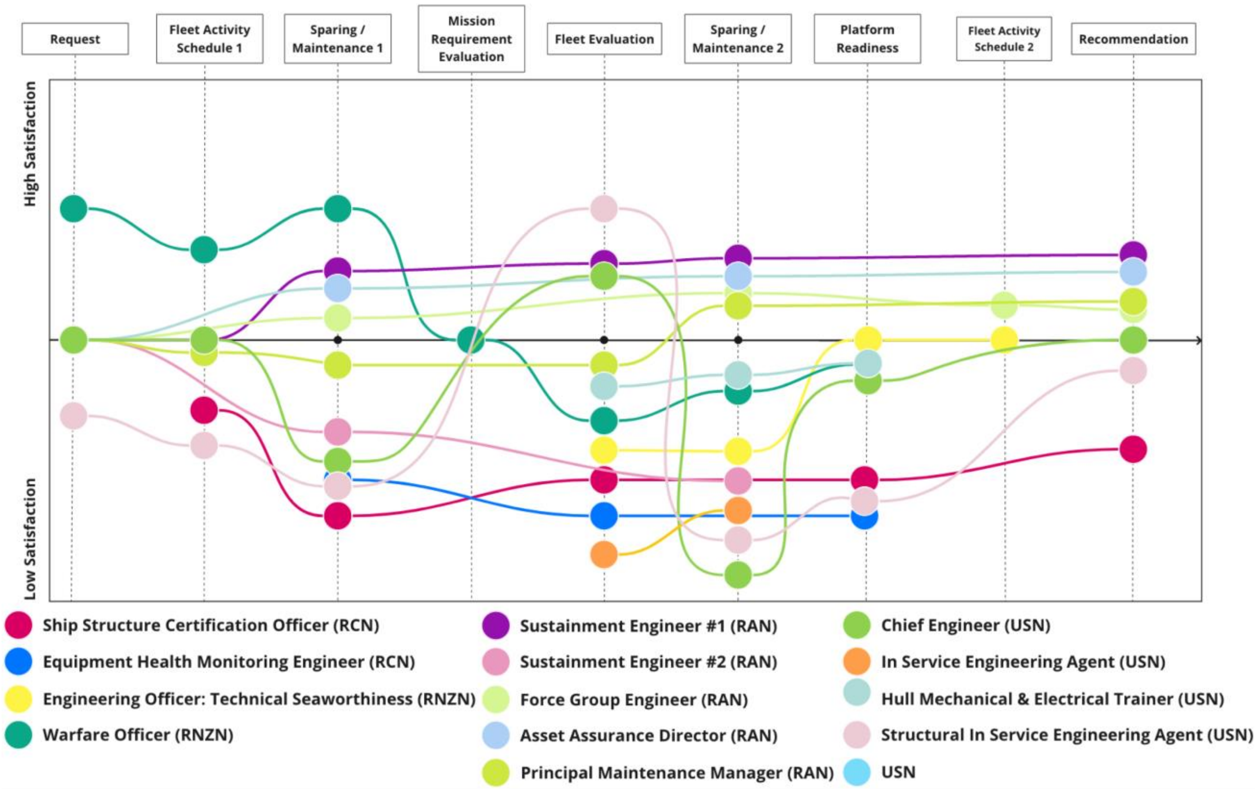

Figure 1: Persona Journey Map for *Scenario 2: Platform Class Life-of-Type Management*.

Table 1: Definition of touch points for *Scenario 2: Platform Class Life-of-Type Management*.

Touch Point	Definition
Request	The commencement of the scenario (though, technically, this scenario is an ongoing process from acceptance into service through to disposal).
Fleet Activity Schedule (FAS) 1	Programmed movements and activities for all platforms over a period of time.
Sparing/Maintenance 1	The application of sparing and maintenance policies to ensure platform readiness in accordance with needs dictated by the FAS.
Mission Requirement Evaluation	Review the Command Aims to identify capability requirements.
Fleet Evaluation	Identify platforms capable of achieving Command Aims; identify platform readiness.
Sparing/Maintenance 2	Apply sparing and maintenance policies to ensure readiness.
Platform Readiness	Risk analysis of defects, and planning for crew and platform workup process to ensure seaworthiness/readiness.
Fleet Activity Schedule 2	Review the programmed movements and activities for all platforms.
Recommendation	Advise the need for each platform on an ongoing basis.

Request: the primary concern at this touchpoint was the identification of maintenance to be performed during a maintenance period and identifying maintenance that can be carried over to another maintenance period. Consideration needs to be given to, for example:

- prioritising and managing configuration changes;
- temporal maintenance versus condition-based maintenance (CBM); and
- budgetary constraints.

Fleet Activity Schedule (FAS) 1: the outcomes from the *Request* touch point should inform the development of the FAS. However, there were several issues and considerations, including:

- a disconnect between the operational and maintenance schedules;
- managing constraints imposed by the availability of shipyards and facilities; and
- needing to avoid overcommitting to operations by sacrificing maintenance requirements.

Sparing/Maintenance 1: policies exist to ensure readiness in accordance with the FAS. Issues and considerations associated with the application of these policies included:

- a lack of adequate current and historical maintenance information;
- difficulties identifying failures for a single maintenance defect; and
- duration of the sparing acquisition process can be too long to be useful.

Mission Requirement Evaluation: no identified pains or gains.

Fleet Evaluation: the ability to select an appropriate platform and ensure seaworthiness had several identified issues, for example:

- data relating to hull loading and remaining useful life was not, generally, available;
- difficulty establishing the importance of fatigue cracks in one platform for the entire class; and
- policies often constrain an identified, suitable action or activity plan rather than providing clarity up the chain-of-command.

Sparing/Maintenance 2: policies are applied to each platform to ensure readiness in accordance with Command Aims. Issues and considerations associated with application of these policies included:

- a need to justify repairs that have a through-life benefit but may not be the most cost-effective option to effect an immediate repair;
- quantifying the effect of hull fouling and minor hull damage on seakeeping, and justifying related repairs; and
- inability to monitor in-situ during deployment.

Platform Readiness: this includes maintenance, sparing and integrated logistics support such as risk analysis of unrectified defects against seaworthiness to achieve Command Aims. Issues included:

- difficulty in quantifying platform health and condition;
- cost to recall a platform to the shipyard to rectify mistakes; and
- uncertainty regarding the remaining service life for any given platform.

Fleet Activity Schedule 2: this represents a cyclical review of the FAS. Issues included:

- implementing CBM increases remaining operating hours for machinery but does not consider the effect on associated scheduled maintenance; and
- existing data is often not consolidated.

Recommendation: there is a need to continuously provide recommendations relating to the needs of each platform. Issues included:

- ability to forward plan using available data and asset assurance of performed maintenance;
- a lack of trained personnel to operate and exploit current databases; and

- a lack of consistency relating to the responses from different port engineers for the same type of information requirement.

Similar Journey Maps were generated for each scenario. No Journey Map validation occurred prior to further analysis or the workshops. Instead, the intent was to validate the Journey Maps during the workshops; however, in retrospect, follow-on interviews to further validate Journey Maps may have been advantageous. Validation of the Journey Maps during the workshop resulted in participant confusion due to not understanding the premise of the Journey Map and the information conveyed. Consequently, the recommendation is to perform follow-up interviews to refine and validate information contained within the Journey Maps prior to follow-on work.

7.0 WORKSHOPS

Facilitator–led workshops can have the benefit of encouraging informed discussion and debate to collect a large volume of information quickly. Workshops with a large number of participants will benefit from "breakout sessions", whereby the cohort is divided into smaller groups of equal numbers. This will enable all voices to be heard, with a consensus report to the cohort at the conclusion of each breakout session.

In this study, four workshops were convened – one for each scenario – with participants invited based on their knowledge and experience for the respective scenario. Participants were introduced to the Digital Twin concept, via a video presentation created for the workshops [7]. After the presentation, the scenario and the scenario Journey Map were explained. The cohort then separated into smaller groups for *Breakout Session 1* to validate the respective Journey Map. Brief reports were then presented to the cohort for further discussion. After this, the cohort was, again, separated into smaller groups for *Breakout Session 2* to identify applications for the Digital Twin supporting the respective scenario, in particular, to overcome the identified pain points in the Journey Maps.

8.0 IDENTIFICATION OF CONCEPTUAL APPLICATIONS SUPPORTING THE SCENARIOS

During *Breakout Session 2*, teams were encouraged to: ask questions of the Digital Twin concept; discuss application of Digital Twin to the specific scenario; and identify applications within the scenario they deemed suitable and unsuitable for a Digital Twin capability. Applications that were deemed suitable were grouped into high-level themes. For *Scenario 2: Platform Class Life-of-Type Management*, discussion primarily centred on CBM and system health and usage monitoring (HUM). Table 2 presents an extract of some themes identified for *Scenario 2: Platform Class Life-of-Type Management*.

There was acceptance by the cohort regarding the beneficial outcomes from implementing a Digital Twin capability; however, questions were asked of the significant investment that might be required to: develop and implement sensors on the platforms; and develop analysis tools and models to support decision-making and automation. Questions were also asked of the economics of implementing a Digital Twin capability for small fleet sizes. Other concerns related to a paradigm shift that might result in changes to policy. Consequently, it was deemed a cost-benefit analysis will be required prior to implementation of any Digital Twin.

To ensure a beneficial outcome, platform operators need to trust the Digital Twin. They must also have the ability to understand uncertainties in the data and output. When they have that trust and confidence with the Digital Twin, they would be able to utilise its capabilities to perform 'what if...?' analysis and perform risk analysis. Without that trust, the benefits afforded by the Digital Twin capability will be negligible because operators are unlikely to utilise the output.

Table 2: Application themes supporting *Scenario 2: Platform Class Life-of-Type Management*.

Discussion Point	Themes
Questions relating to life-of-type management that a Digital Twin capability will need to address	Condition Monitoring/HUM: - identification of systems needing to be monitored; - availability and suitability of appropriate sensors; - effect of mission requirements on platform serviceability; - incorporating HUM into FAS development; and - leveraging from experiences of other nations. Data Collection: - method of collection (automation versus manually entered); - digital thread to connect disparate data sources; - ability to utilise data for platform class society certification; - data validation and verification; and - trust in decision-making.
Unsuitability of Digital Twin for Platform Selection and Readiness	Policy and Procedures: - when a calendar-based maintenance regime is utilised to generate the FAS; - when policies do not change accordingly; and - when there is over-reliance on Digital Twin output for decision-making without physical verification (for example, hull surveys). Data: - when the data is unsuitable/insufficient; - inability to validate/verify the data and outputs; and - when data aggregation becomes a security risk. Implementation: - cost-benefit of implementing the Digital Twin.
Suitability of Digital Twin for Platform Selection and Readiness	Condition Monitoring/HUM: - tracking of materiel state; - real-time monitoring of systems, including performance and operating hours; - vibration monitoring to identify trends leading to failures; - tracking hull life and predicting remaining hull life; and - platform class certification. Fleet Evaluation: - fleet wide condition monitoring utilising consolidated data; - equalisation of platform life across the fleet; and - informed platform selection for deployments. Maintenance regime change/optimisation: - predictive capability to plan platform maintenance; - sparing analysis for: ships allowance parts list; ensuring lead times for spares availability; and CBM; and - prioritisation of maintenance activities. Risk Analysis: - to explore 'what-if…?'; - defect risk evaluation for operational performance analysis to enable platform operations to occur with known defects; and - risk evaluation for unresolved defects after maintenance. Performance Verification: - quantify platform state and the effect on performance and mission effectiveness. Fatigue Life Tracking (hull and onboard systems): - monitoring of platform exposure to environmental conditions; - monitoring of platform motion and hull flexure; - predictive through-life capability of the fleet; and - comparative analysis of platforms within a class.

Conversely, there was concern platform operators might become over-reliant on the capabilities offered by the Digital Twin. Consequently, operators may make decisions without consideration of further evidence. In particular, some decision-making requires physical evidence, such as visual inspection of the hull. Digital Twin can be an enabler for reducing logistics cost of ownership; however, it was deemed unlikely a Digital

Twin would have capability that replaces the need for physical inspection required for compliance and survey purposes.

During discussion within the workshop cohort, affinity clustering was utilised to group themes. The output was a number of identified application domains supporting life-of-type management:

- Condition Monitoring/HUM;
- Defect Trend Analysis;
- Sparing and Inventory Analysis;
- Platform Capability Management;
- Fleet Evaluation;
- Maintenance Regime Change/Optimisation/Prioritisation;
- Risk Evaluation and Verification;
- Performance Verification;
- Modernisation/Upgrade Planning;
- Fatigue Life Tracking; and
- Disposal Planning.

The cohort then voted to identify the top three application domains they considered the most important. There were two voting categories:

- most impact: applications believed to have the most benefit in supporting the scenario; and
- most feasible: applications believed to be the most feasible to implement.

Voting was via a ballot and the subjective opinion of operator experts forming the cohort. The outcome of the voting revealed:

- application deemed most feasible to implement: *Fatigue Life Tracking*;
- application deemed to have the most impact if implemented: *Condition Monitoring/HUM*; and
- most impact and most feasible: *Maintenance Optimisation*.

The next step was to identify the advantages and disadvantages of those applications deemed to be the most important to support platform life-of-type management. This was referred to as “making the case”.

9.0 MAKING THE CASE FOR THE MOST IMPORTANT APPLICATIONS

During making the case, the cohort is to consider why an application would benefit from improved digital engineering practises (such as the implementation of a Digital Twin). In particular, for this study, the applications were considered with respect to identifying:

- why Digital Twin supports the application;
- how the application would contribute to supporting the scenario;
- risks/concerns that might need to be overcome or managed to implement the application as a Digital Twin supported capability;
- changes to processes, policy or tools that might occur with implementation of the application;

- issues that might impede implementation of the application; and
- benefits resulting from implementation of the concept.

Making the case for the top three applications occurred during *Breakout Session 3*. Each breakout team was tasked with championing an application arbitrarily assigned to the team. The process included identifying the value of the application to platform management. Conversely, risks associated with each application needed identification. The case for the application of *Condition Monitoring/HUM* is presented in Figure 2 and discussed briefly in the following subsections.

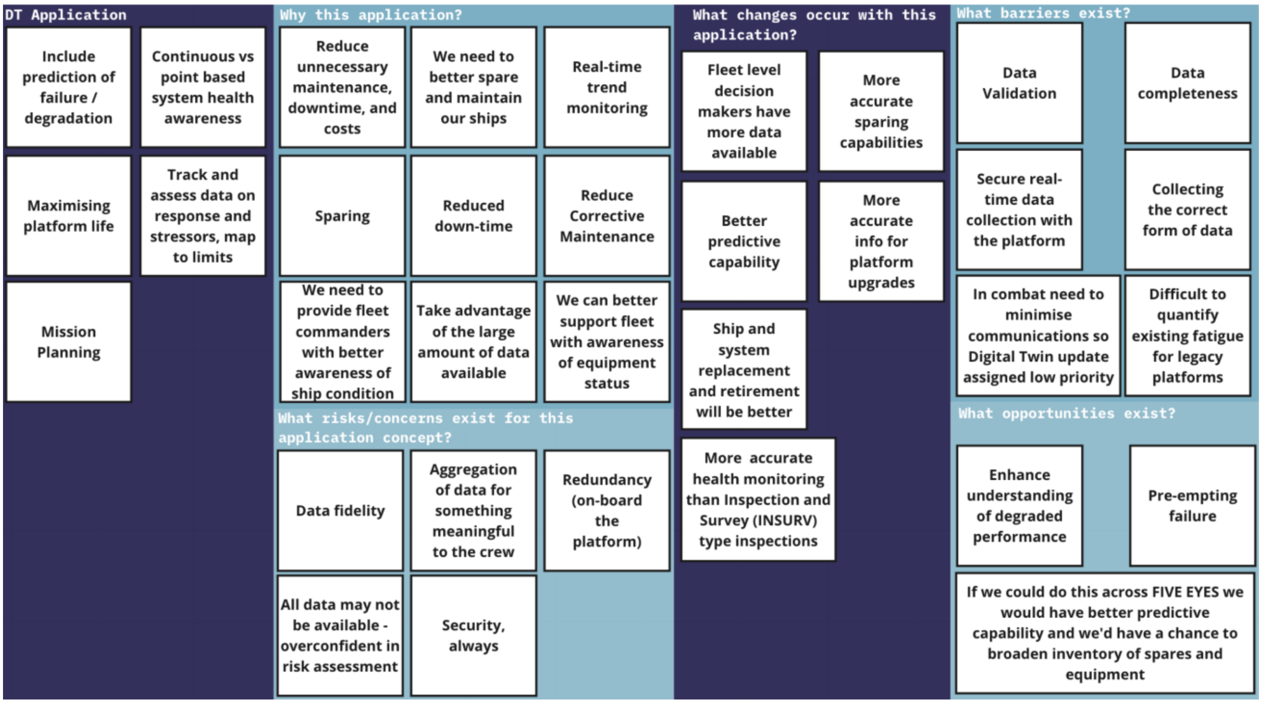

Figure 2: Making the case for a Digital Twin in support of *Condition Monitoring/HUM.*

9.1 Opportunities for a Digital Twin Supporting *Condition Monitoring/HUM*

Condition Monitoring/HUM was perceived to be an enabler for efficient fleet management; ensuring operating availability (of systems and platform); and for end-of-life planning. There is a possibility higher resale values will be realised when the platforms are "paid off". This latter consideration may not be a concern for the crew, maintainers or capability managers, but it may affect decision-making of the respective government regarding the fate of the platform post decommissioning. Example benefits include, maximising resale potential; donating to a foreign navy to strengthen regional security and diplomatic relations; using as a trials platform; donating to a museum; or for use as a memorial.

9.2 Risks and Barriers for a Digital Twin Supporting *Condition Monitoring/HUM*

A strong reliance on decision support analysis provided by the Digital Twin capability may complicate accountability. In particular, when models are reliant on artificial intelligence (AI), there was concern regarding traceability and transparency of decision-making. Consequently, there will be a need to develop specific policies and procedures to account for AI decision-making.

Information security issues onboard the platform were of concern, in particular relating to real-time communication with shore facilities that might be supporting decision-making and performing condition monitoring. Other concerns included data fidelity, transmission speed, and bandwidth.

9.3 Making the Case – the Final Vote

After each breakout team had developed the case for their respective application, they argued that case to the cohort. The cohort then performed a final vote to identify the application they deemed to have the most impact if implemented and the most feasible to implement. The results for *Scenario 2: Platform Class Life-of-Type Management* were:

- application deemed most feasible to implement: *Fatigue Life Tracking; and*
- application deemed to have the most impact if implemented: *Condition Monitoring/HUM.*

10.0 STUDY ANALYSIS

Sections 5 to 9 exemplified the data collection and analysis process for an individual scenario. The other three scenarios were examined similarly. The output from the final vote for making the case for all four scenarios was:

- applications deemed to be the most feasible to implement:
  - *Quantifying Platform Health* (Scenario 1);
  - *Fatigue Life Tracking* (Scenario 2);
  - *HUM* (Scenario 3); and
  - *Connectivity to Shore Bases* (Scenario 4);
- applications deemed to have most impact if implemented:
  - *Forecasting Platform State and Defect Prediction* (Scenario 1);
  - *Condition Monitoring/HUM* (Scenario 2);
  - *Rapid Evaluation of Alternatives for Mission Planning* (Scenario 3); and
  - *Situation Awareness of Platform and System State* (Scenario 4).

There were commonalities between each of the identified applications. For example, the ability to monitor platform health and the ability to forecast future platform health is a major contributor supporting platform management and operations. The data requirement for these applications is also similar to that of other applications, such as *Rapid Evaluation of Alternatives for Mission Planning*. The intent of *Rapid Evaluation of Alternatives for Mission Planning* is to support decision-making based on current platform health to identify the ability to achieve the current Command Aims when system functionality and capability has been degraded or lost. Further, this application also entails identifying alternative options to achieve the Command Aims if functionality and/or capability had been lost.

10.1 Risks and Barriers

Common risks and barriers were identified for all the scenarios. In particular, there was concern relating to data acquisition and reliability. There is, also, a need to validate the modelling software and related algorithms, the models, and the output. Trusting and understanding the output from the Digital Twin for use in decision-making was deemed to be a challenge.

At an enterprise-level, the requirement for significant organisational and procedural change to accommodate a Digital Twin paradigm shift in maintenance practices may present a barrier. Specifically, the transition from calendar-based maintenance to CBM and predictive maintenance will need to be addressed to satisfy organisational requirements.

Implementation of relevant Digital Twin capability was expected to facilitate maintenance planning and FAS development. The concern was a possible need for external service providers to change their operating practises. Due to the costs involved (to change operating practises), service providers may be resistant to such changes.

10.2 Prognostic and Predictive Analysis

Prognostic and predictive analysis is one of the primary drivers for developing Digital Twin capability in industry [13, 14]. Similar application of Digital Twin was proposed during each of the workshops for the four scenarios. Participants believed a Digital Twin capability would enhance decision-making by providing situation awareness; analysis of key decisions; analysis of resourcing requirements; and prioritisation of defect repair and system recovery operations. Analysis would also support residual structural assessment and platform stability.

10.3 Shore-based Support

The primary advantages perceived to emerge from a shore-based support facility were the ability to provide increased computing power not readily available on a deployed platform; and the provision of ‘reach back’ to suitable experts for analysis and decision support (see, for example, [15]). To realise these advantages, there will be requirement for reliable data acquisition, and potentially data fusion, onboard the platform. System redundancy will need to be considered. A damaged platform may, for example, lose power thereby preventing data acquisition and communication to the shore base.

11.0 TRANSLATING CONCEPTS TO USER REQUIREMENTS FOR A DIGITAL TWIN CAPABILITY

The aim of the study was to understand the benefits that might be afforded by a Digital Twin in support of naval platform management and operations. Further, there was a need to identify impediments that affect the successful implementation of the Digital Twin. It was not the aim of the study to identify specific user requirements. However, user requirements can be derived utilising information obtained at each stage of the study, such as the raw data available in the interview transcripts, the identification of application themes, and information from making-the-case.

One method to derive user requirements is to perform a thematic analysis [16] using the data collected during the study. This technique was examined in a follow-on study to the TTCP Digital Twin CoI study. Using the raw interview data collected during interviews with RAN operator experts, Magoga et al. [17] performed a thematic analysis to derive user requirements to support RAN platform management and operations.

Thematic analysis is a qualitative data analysis method to identify patterned meaning, or themes within a dataset. Themes are identified via a process of data familiarisation, data coding, and theme development and revision [16]. Thematic analysis can be inductive to identify themes and meaning from the information. Inductive thematic analysis assumes no preconception of the data – all themes and meaning are emergent features. Thematic analysis can also be deductive, such that analysts may have preconceived ideas regarding themes and meaning is then identified with respect to the preconceived themes. The analysis performed by Magoga et al. [17] was an inductive thematic analysis; however, the applications identified in Section 7 can be used as themes for deductive reasoning. Note, there is overloading of the definition of “themes” as used in the TTCP Digital Twin CoI study compared to themes in thematic analysis. Themes identified in Section 7 can be used as themes in thematic analysis; however, the affinity clustering of themes in Section 7 consolidated overlapping and similar themes and to identify overarching application domains. These application domains provide a better basis for themes to use in thematic analysis.

Table 3 presents the results of inductive thematic analysis to identify themes within the RAN interview data. Also included are key words and phrases (labelled 'Code') identified within the interview data associated with each theme. Themes were grouped according to whether they were activities performed at shore-based support facilities or onboard the platform while on deployment.

Table 3: Identify themes from inductive thematic analysis of RAN interview data.

Shore-based (Scenario 1 and Scenario 2)		Sea-based (Scenario 3 and Scenario 4)	
Code	Theme	Code	Theme
Seaworthiness Risk Assessment Risk Deployment Maintenance	Ability to Deploy the Platform	Command Risk Capability Communication	Maintaining Mission Capability
Upkeep Cycle Usage Maintenance Availability Contractor Risk Defect	Provision of Maintenance	DC DC Board DC Huddle Repair Base IPMS Fire Command Priority Communication	Platform Survivability
People	Experience of People	People Training Management Communication	People at Sea

The interview data was then examined, using the codes as search terms and phrases to identify context within the interview data for the respective theme. Table 4 presents an abridged context for each theme identified within the interview data. Note, Table 4 only relates to RAN interview data.

The next step was to convert the information contained within Table 4 into user requirements. Consider, for example, 'data validation and trend monitoring' (*Maintaining Mission Capability*). This context feature consists of two user requirements: (1) a requirement to perform data validation; and (2) a requirement to monitor data trends. Examination of other context features also reveals overlaps in user requirements. For example, 'data validation and completeness checking' (*Ability to Deploy the Platform*), 'data validation and trend monitoring' (*Maintaining Mission Capability)* and 'data validation and integration' (*Platform Survivability*) have 'data validation' as a common element. The context features require further analysis to ensure understanding of the user requirement(s) they convey. For example, 'predicting and planning maintenance requirements against the state of the platform' (*Provision of Maintenance*) contains the explicit requirements: 'the ability to predict maintenance requirements'; and 'the ability to plan maintenance'. It also contains the implicit requirement 'the ability to assess the state of the platform' to enable assessment of maintenance requirements against the platform state. To assess the state of the platform, there is need to monitor platform systems (including the hull) and perform trend analysis. This latter requirement also supports 'trend monitoring/analysis' (*Provision of Maintenance* and *Maintaining Mission Capability)* and platform 'situation awareness and assessment' (*Platform Survivability*). Furthermore, 'situation awareness and assessment' (*Platform Survivability*) also encompasses the situation external to the platform and internal to the platform (such as understanding the progression of fire, smoke and flooding). To perform trend

Table 4: Contextual information relating to identified themes within the interview data.

Theme	Context features in support of the theme
Ability to Deploy the Platform	- quantitative seaworthiness assessment: o perform engineering analysis; o perform data validation and completeness checking; and o risk assessment against the operational and support intent (OSI), deployment with a known defect, and deployment with incomplete maintenance; - policy manuals (tracking and connectivity); - operational endurance analysis and balancing maintenance risks; and - crewing.
Provision of Maintenance	- predicting and planning maintenance requirements against the state of the platform; - metrics to estimate duration of maintenance activities and de-conflict work packages within maintenance periods; - reliability, availability and maintainability (RAM) and trend analysis; and - identifying and maintaining the maintenance baseline.
Experience of People	- tracking and provision of training; and - workforce management.
Maintaining Mission Capability	- capability impact statements; - system monitoring, requirements and reconfiguration; - defect tracking, risk identification and acquittal; - maintenance planning, performing and close out; - explainable decision-making; - endurance monitoring and management; and - data validity and trend monitoring.
Platform Survivability	- situation awareness and assessment; - identification and restoration of capability baseline; - response planning and prioritisation; - resource prioritisation, tracking and management; - data validation and integration; and - setting Command Aims and Command Priorities.
People at Sea	- tracking of training, skills, and experience; - resilience and location monitoring (during a damage event); and - personnel deficiency reports and filling of vacancies.

monitoring/analysis and situation awareness and assessment, there will also be that need for data validation, completeness checking and remediation. This will likely be followed by a need for data aggregation suiting the respective user requirement.

Considering the above discussion, Table 5 presents a set of user requirements required of a Digital Twin in support of *Quantitative Seaworthiness Assessment*. Similar user requirements were derived for all the context features presented in Table 4 [10]. One important highlight identified within all the user requirements is an overlapping of functionality to support many of the key features. This is worth considering when developing a Digital Twin capability for one specific theme or key feature. Functionality within one capability may be utilised to support other capabilities. Consequently, with proper planning, a Digital Twin may be naturally evolved to incorporate new capability utilising existing functionality.

12.0 DISCUSSION AND RECOMMENDATIONS

One concern expressed by operator experts during the workshops was operator and service provider uptake of a Digital Twin. However, with adoption of Industry 4.0 [3, 4], some of the drivers for change, including the use of Digital Twin, are emanating from the service providers. For example, providers, such as BAE

Table 5: Abridged user requirements supporting the capability to perform quantitative seaworthiness assessment.

Context Feature	User Requirement
Quantitative Seaworthiness Assessment	– A need to perform engineering analysis: o ability to model systems; o requirement for system breakdown structure; o ability to map systems against mission requirements; o ability to monitor trends; o ability to perform trend analysis; and o database connectivity (maintenance, defects, sparing, system data, manuals). – A need to perform data validation and completeness checking: o ability to validate data; – Ability to perform risk assessment against the OSI, deployment with a known defect, and deployment with incomplete maintenance: o ability to model systems; o ability to map systems against to mission requirement; o ability to perform risk assessments; o ability to perform and access failure modes, effects and criticality analysis; o ability to perform and access (failure, system usage) trend analysis; and o ability to track maintenance.

Systems and Navantia [18, 19]. Therefore, the deployment of new digital engineering technologies supporting aspects of naval platform management and operations is a certainty. Consequently, there will be a need to ensure operator trust in the services provided by these digital engineering technologies, including Digital Twin, and there will be a need to provide transparency and traceability to support operator decision-making. Subsequently, investment in the domains of 'Trusted Autonomous Systems' [20] and 'Explainable AI' [21, 22] would be suitable when developing respective tools for a Digital Twin capability to support operators in their decision-making.

Prognostic and predictive analysis will require models depicting connectivity of platform components and systems. These models will need to be mapped to platform capability for assessment of Command Aims. Relevant modelling and simulation capability will also be required. For example, during damage situations with shore-based support, fire and flood modelling might facilitate predictive assessment and the formulation of response plans [15, 23].

The implementation of suitable tools and functionality within the Digital Twin will require analysis of off-the-shelf technologies and/or research for the development of bespoke software and hardware tools. The underlying system models, modelling tools, and data validation functionality will likely be similar (or, even, the same) for many of the application domains. If the requisite requirements analysis is performed, implementing a Digital Twin capability for one specific application should allow for growth to include further applications.

Consequently, an adaption to the methodology presented in Section 3 is to perform follow-on interviews during Step 4. A recommendation is to also use the knowledge elicitation technique known as Critical Decision Method (CDM) [24, 25]. This will provide a structured process to develop and validate the Journey Maps; and develop a detailed understanding of the decision-making and decision-making requirements for each scenario.

After collecting detailed interview data, an inductive thematic analysis may be performed instead of the workshops. However, facilitated workshops will provide more insights to allow for the identification of themes to guide deductive thematic analysis. Both processes will require resources (time and suitable operator experts familiar with supporting the respective scenarios).

13.0 CONCLUSION

The TTCP Digital Twin CoI performed a study to explore the application of Digital Twin in support of naval platform sustainment management and survivability (damage control and recoverability). The study involved interviews with operators to gain insight regarding the application of policies, decision-making, and data requirements to support the decision-making. Utilising the information obtained during the interviews, Journey Maps were developed to depict the satisfaction of the operator experts performing their duties to support the platforms. Four workshops were convened to validate the Journey Maps and explore concepts that might enable or improve process of supporting naval platforms.

There was optimistic consensus from the workshop cohort regarding the opportunities afforded by implementation of a Digital Twin capability. Common opportunities included: improvement to fleet maintenance and scheduling; ability to improve operational planning based on platform condition; and prioritisation of mission-enabling maintenance. The workshops also provided insights regarding concerns navy operators may raise with the implementation of new technology. Addressing these concerns may increase trust and confidence when utilising a Digital Twin capability.

The presented methodology requires refinement. The methodology would benefit from follow-up interviews for the generation and validation of the Journey Maps. This should aid in setting the direction for the workshops. Combining detail collected during the workshops with the raw interview data will aid with performing a deductive thematic analysis for the identification of functional requirements for a Digital Twin supporting naval platform management and operations.

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