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An MBSE Methodology to Support Australian Naval Vessel Acquisition Projects

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Abstract

This paper covers research to construct a Model-Based Systems Engineering (MBSE) methodology to support above-the-line, or left-of-contract stakeholders during the early stages of Australian naval vessel acquisition projects. These projects now adopt off-the-shelf (OTS) acquisition strategies as the default approach. OTS acquisition strategies change the nature of defence acquisition projects from the traditional top-down, requirements-driven approach to a middle-out approach. In the middle-out approach, the required functions are decomposed from the capability needs, whilst existing OTS offerings are scrutinised to find those that best satisfy the capability needs with minimal design changes. This scrutiny of the OTS solution space is generally undertaken without extensive design data being available to the acquirer.

The MBSE methodology that has been constructed comprises two main parts. The first part of the MBSE methodology is a concept and requirements exploration approach, which is the focus of this paper. Of significance, this stage of the methodology incorporates set-based design principles, model-based conceptual design, and design patterns. MBSE is used as the backbone of the methodology to manage and guide the early stage acquisition and analysis activities, whilst maintaining traceability to strategic needs. The paper includes an example implementation of the methodology for an indicative Hydrographic and Oceanographic Survey vessel capability.

Introduction

In the latest of a long line of reviews of the Australian Department of Defence (ADOD) undertaken on behalf of the government of the day, the ADOD was described as having a capability acquisition and sustainment system where there is a "persistence of fundamental problems … from capability planning to acquisition, delivery and finally sustainment" (Peever, 2015, p. 14). This review also noted that in the next 10 to 20 years, the ADOD acquisition system

> must deliver a significant capability modernisation program against a backdrop of strategic uncertainty including, but not limited to: rapid technological change; budget uncertainty; substantial economic growth in our region; and increasing demand for military responses. (Peever, 2015, p. 13)

Following this latest review of the ADOD, a new acquisition manual, the *Interim Capability Life Cycle Manual* (ICLCM; Defence, 2017a), was released. Compared to both the previous ADOD acquisition manual and current U.S. DoD acquisition manuals, DoDI 5000.02 (DoD, 2015b) and JCIDS (DoD, 2015a), the ICLCM provides a far less structured approach to acquisition. The ICLCM (Defence, 2017a) also provides far less guidance than the U.S. acquisition manuals on satisfying the newly established ADOD oversight function, called "contestability," that seeks to ensure that the acquisition project will acquire a capability that addresses the strategic needs of Australia. This means that ADOD acquisition professionals have been given an additional layer of oversight, whilst at the same time they have been provided with less guidance on how to produce defensible decisions based on solid, traceable evidence.

An important constraint on Australian naval vessel acquisitions is the adoption of the off-the-shelf (OTS) acquisition strategy as the default approach. This strategy is perceived as a means of reducing the acquisition cost and schedule risk (Saunders, 2013). The trade-off of in reducing these risks is that the capability option selected may not fully meet all of the user's operational needs, may not fully integrate with other in-service capabilities, and may not fully suit the local geographic and strategic circumstances (SFAD&TC, 2012). In 2017, the ADOD released its Naval Shipbuilding Plan (Defence, 2017b) that effectively mandated the acquisition of OTS naval vessels. The guiding principles of implementing the plan included the following:

- Selecting a mature design at the start of the build and limiting the amount of changes once production starts;
- Limiting the amount of unique Australian design changes. (Defence, 2017b, p. 105)

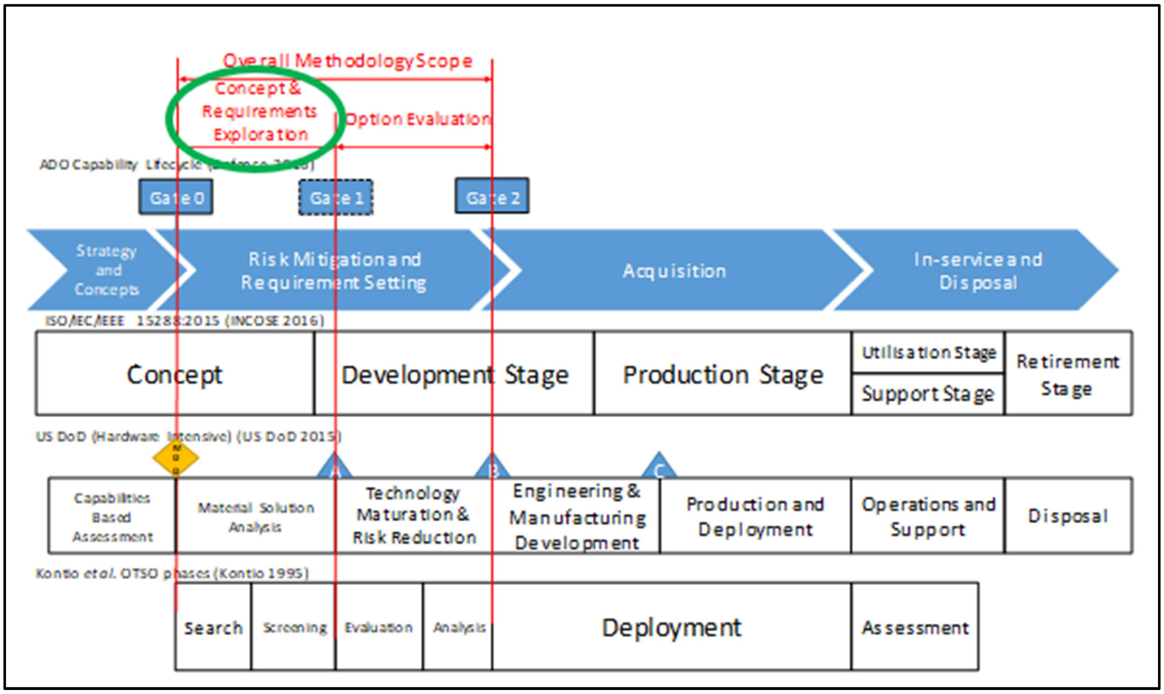
The OTS strategy appears to be analogous to the "modified-repeat" ship design strategy, where a parent design is modified, due to the perception that both the OTS strategy and modified-repeat design approach reduce acquisition cost and schedule risk (Morris, Cook, & Cannon, 2018, p. A-22). The modified-repeat design approach has, however, only been found to realise the benefits of lower acquisition costs and schedule risks, when the operational and legislative requirements are nearly identical to those that shaped the original design (Covich & Hammes, 1983). Hence, to achieve the benefits of lower acquisition cost and schedule risks in OTS naval vessel acquisitions, the project will need to identify existing OTS designs with very similar operational and legislative requirements to those for the vessel being acquired, and then specify tender requirements accordingly. Unlike a navy undertaking a modified-repeat design, the OTS acquirer will not have knowledge of the parent design's requirements, or access to detailed design data. This means the traditional "top-down" acquisition approach needs to be adjusted for OTS vessel acquisitions due to the constraint placed on the solution system by the available OTS solutions (Saunders, 2013). A “middle-out” systems engineering (SE) approach that combines top-down decomposition from strategy to functions and key performance parameters (KPPs), with bottom-up mapping from OTS naval vessel designs through the KPPs to the functions, could provide a means of enhancing rigour in contestability of OTS Defence acquisitions. A “middle-out” SE approach could also help provide an early understanding of any capability risks due to the OTS constraint.

The situation outlined above gives rise to the research issue investigated in this paper. The research issue is as follows:

> In the early stages of Australian Defence Organisation off-the-shelf naval vessel capability acquisition projects, support for traceable, defensible requirement development activities is often lacking. Concurrently, these projects are facing shortages of skilled staff and constrained financial resources. The OTS constraint also changes the nature of the acquisition’s SE approach in acquisitions that adopt this strategy.

The focus of the research covered in this paper is the activities within the early stages of Australian OTS naval vessel acquisition projects, since performing these stages well is vital for the success of any system development or acquisition project. Naval vessels, like all man-made systems have a lifecycle (Walden et al., 2015), several examples of which are shown in Figure 1. The lifecycle used in the ADOD is described in the ICLCM (Defence, 2017a). The early stage of interest for this research in the ADOD lifecycle is termed the Risk Mitigation and Requirement Setting Phase (Defence, 2017a). This phase “involves the development and progression of capability options through the investment approval process leading to a government decision to proceed to acquisition” (Defence, 2017a, p. 28). The early stages of Defence acquisitions can also be seen as a design activity (Hodge & Cook, 2014; Coffield, 2016; Cook & Unewisse, 2017), where the initial activities correspond to the concept design stage as shown in Figure 1. There is a growing understanding within the SE discipline that the process of requirements definition should include design activities. This understanding is evidenced by the statement by Crowder, Carbone, and Demijohn (2016, p. 105), “In the end, the activities which we would call design are nothing different from the activities required to create the ‘to-be’ requirements.”

The research is targeted at supporting “above-the-line” (acquirer) naval vessel acquisition stakeholders to perform the key activities of **requirements definition, requirements setting, and options refinement** in a traceable, defendable manner, during the ADOD Risk Mitigation and Requirements Setting phase.



Note. The Concept and Requirements Exploration part of the MBSE methodology in the green oval is the focus of this paper

Figure 1. Various System Lifecycles and the Stages of Interest for the Research

This paper covers the latest iteration of research undertaken to construct a Model-Based Systems Engineering (MBSE) methodology that supports acquisition stakeholders during the early stages of Australian OTS naval vessel acquisitions. The MBSE methodology is built around two main parts. The first part is a concept and requirements exploration approach tailored for OTS acquisitions and is the focus of this paper as shown inside the green oval in Figure 1. The second part of the MBSE methodology is a model-based approach to option evaluation that leverages the MBSE model built during the concept and requirements exploration part. The model-based option evaluation method has been covered elsewhere (see Morris & Cook, 2017; Morris et al., 2018). In this paper, a high-level overview of the research approach and the concept and requirements exploration part of the MBSE methodology is provided. The paper then steps through an example implementation of the concept and requirements exploration approach for an indicative Hydrographic and Oceanographic Survey Vessel capability acquisition. The paper concludes with some observations from the example implementation and recommendations for future work.

Research Approach

The research covered in this paper can be classed as being in the field of SE. The primary purpose of SE research has been identified as being to improve SE methods, tools, and techniques (Ferris, Cook, & Honour, 2005). This means the interventionist research paradigm, which includes action research, design science, and constructive research approaches, is well suited. Interventionist research has also been described as *development* research, since common characteristics of these methods include "design, constructed artefacts, and/or interventions" (Viliers, 2012, p. 240). The research methodology selected for the research covered in this paper is the constructive research approach (CRA). The CRA "implies building of an artefact (practical, theoretical, or both) that solves a domain specific problem in order to create knowledge about how the problem can be solved (or understood, explained, or modelled) in principle" (Crnkovic, 2010, p. 363). The problem in the case of the research described in this paper is the research issue given in the introduction. The CRA comprises the following features as espoused by Piirainen and Gonzalez (2013):

1. The focus is on real-life problems.
2. An innovative artefact, intended to solve the problem, is produced.
3. The artefact is tested through application.
4. There is teamwork between the researcher and practitioners.
5. It is linked to existing theoretical knowledge.
6. It creates a theoretical contribution.

The creation of a theoretical contribution that can improve SE methods, tools and techniques, makes the CRA well suited to SE research. The artefact produced in this research is the MBSE methodology.

Proposed MBSE Methodology

MBSE is used as the foundation of the methodology constructed for this research because it inherently supports traceability and provides numerous other benefits. Specifically, it enhances communications among the development team, improves specification and design quality, and promotes reuse of system specification and design artefacts (Friedenthal, Moore, & Steiner, 2009, p. 15). Morris et al. (2016) also report that applying MBSE during the early stages of the system lifecycle has yielded benefits associated with a clearer understanding of the problem space and facilitation of requirements development. In 2012, The U.S. Government Accountability Office (GAO) made a strong case for the use of MBSE in Defence acquisition projects: "Positive acquisition outcomes require the use of a knowledge-based approach to product development that demonstrates high levels of knowledge before significant commitments are made. In essence, knowledge supplants risk over time."

The MBSE methodology constructed for this research incorporates several features. The features were incorporated after assessing each for adherence to three guiding principles. These guiding principles are related to recurring issues in ADOD acquisitions identified by Peever (2015). The guiding principles are as follows:

1. Maintain traceability to the original, strategic intent of the vessel being acquired in order to ensure a defensible outcome.
2. Assist the stakeholders to make defensible decisions that account for competing goals and objectives.

3. Maximise the capacity to reuse elements, thereby reducing subsequent acquisition efforts to implement the methodology and the resources required to manage these projects.

Six key approaches were included in the MBSE methodology after assessing each against the guiding principles: model-based conceptual design (MBCD), modelling and simulation (M&S), design space exploration (DSE), resilient systems, pattern-based methods, and multi-criteria decision making (MCDM). MBCD is implemented through integrating MBSE with M&S and DSE within the concept and requirements exploration part of the methodology. Resilience is incorporated into the MBSE methodology through the use of set-based design (SBD) principles. This means ranges of design parameters are used during the concept and requirements exploration in order to ensure all feasible regions of the design space are explored prior to setting requirements. Pattern-based methods are implemented through the use of patterns of naval operations, such as that given in the Universal Naval Task List (CNO, 2007) and a functional architecture based on the "float, move, and fight" top-level functions. A MCDM approach (multi-attribute value analysis) is included in the option evaluation part of the MBSE methodology.

When implementing MBSE, a methodology comprising a collection of processes, methods and tools is used (Morris & Sterling, 2012). A metamodel, or schema, that defines the MBSE model element's concepts, terminology, characteristics and interrelationships is also used when implementing MBSE. It has been noted that "the metamodel is the method by which the underlying structure is embedded into the methodology" (Morris, 2014, p. 3). Furthermore, Logan et al. (2013) state, "The principal reason for using metamodels in MBSE is to create structure and consistency in the model and associated products" (p. 3).

During the research described in this paper, the metamodel underpinning the MBSE was refined over several iterations. The metamodel is based on the Whole-of-System Analytical Framework (WSAF) metamodel because it has gained increasing acceptance within the ADOD from repeated usage (Logan et al., 2013, p. 3). The WSAF metamodel is one of three components of the WSAF framework that has been used to support requirements definition in ADOD acquisition projects. The WSAF metamodel is also consistent with the CORE DODAF 2.02 schema (Cook et al., 2014). Several extensions to the WSAF metamodel were made during the research. A key extension was the introduction of the "analysis domain." The analysis domain allows executable analyses to be conducted, managed and the results stored within the MBSE model. A high-level overview of the key parts of the MBSE metamodel developed for the research is shown in Figure 2. The operational domain shown in green in Figure 2 allows strategic guidance from the capability needs statement to be traced to system functions and requirements. The analysis domain shown in red in Figure 2 allows executable analyses to be conducted, managed and stored within the MBSE model. The "vessel properties" element within the blue oval in Figure 2 is discussed further in later sections and detailed in Figure 8.

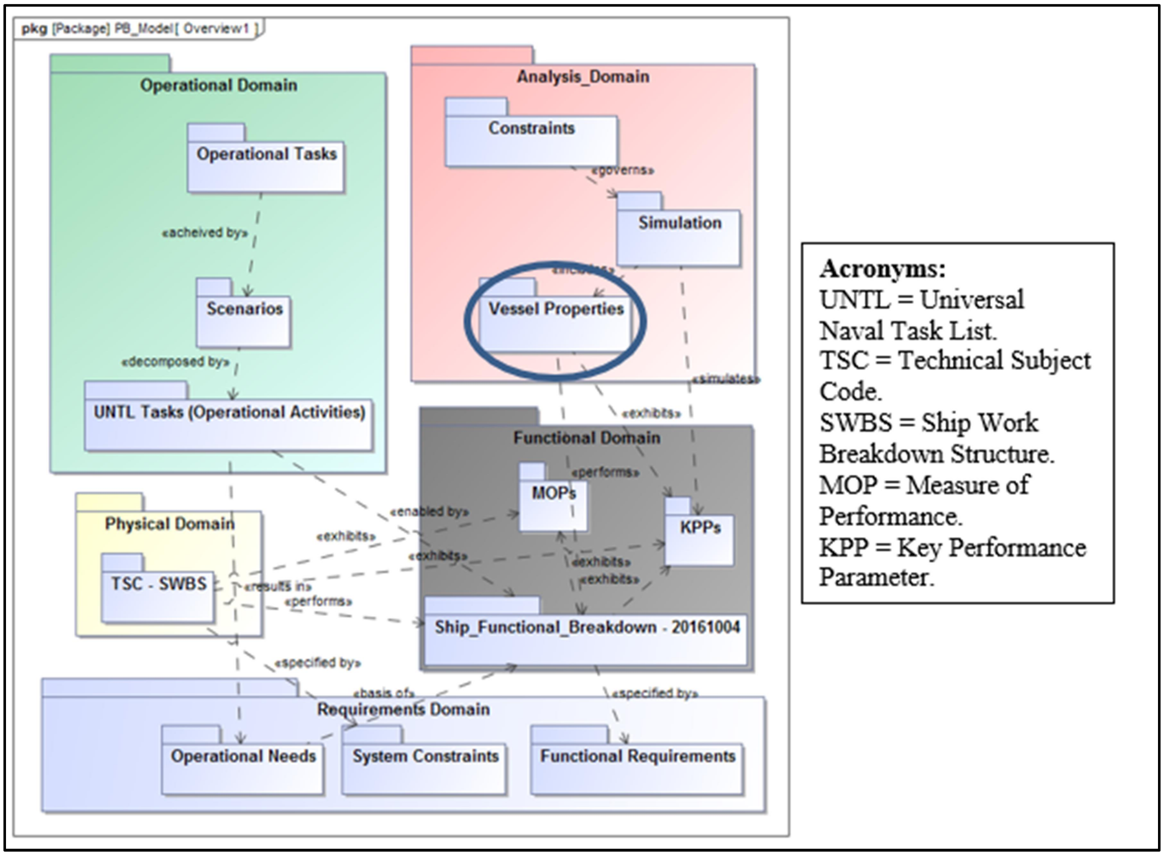


Figure 2. Overview of the MBSE Metamodel Developed as Part of the Research to Construct the MBSE Methodology

Concept and Requirements Exploration

Concept and requirements exploration (C&RE), or requirements elucidation, is an approach to early stage naval vessel design that "responds to a stated mission need with an early high-level assessment of a broad range of ship design options and technologies" (Brown, 2013). A review of the open literature found that several C&RE approaches to support the early stages of naval vessel acquisition projects have been developed in recent years. A summary of the naval vessel C&RE methodologies identified within the open literature and reviewed for this research, along with the features, or approaches they comprise is given in Table 1. The C&RE approaches in Table 1 are typically focused on identifying optimal concept designs for the operational missions the vessel will perform. This knowledge can then be used to ensure the emergent requirements are "elucidated" (McDonald, Andrews, & Pawling, 2012) in an iterative manner, through engagement between the acquirers and designers.

Table 1. Summary of Naval Vessel C&RE Methodologies Reviewed and the Approaches They Include: Model-Based Systems Engineering (MBSE), Modelling and Simulation (M&S), Design Space Exploration (DSE), and Multi-Disciplinary Analysis and Optimisation (MDAO)

C&RE Approach and Key References	MBSE	M&S	DSE	MDAO	Other	Comments
Virginia Tech. Concept & Requirements Exploration (C&RE) Brown & Thomas, 1998; Kerns, Brown, & Woodward, 2011a; Kerns, Brown, & Woodward, 2011b; and Brown, 2013	X	X	X	X	Value model (Analytical Hierarchy Process [AHP]) used for overall measure of effectiveness (MOE).	Uses MBSE to manage ship and mission architecture, separate ship synthesis, operational effectiveness models (OEMs), and MDAO models to analyse effectiveness and optimise.
Response Surface Methods (RSM) Approach Hootman, 2003 and Fox, 2011		X	X		Includes AHP for "rolling up" lower level MOPs	Approaches use separate ship synthesis and OEMs to build concept design space. No explicit link to requirements.
SubOA/IPSM Nordin, 2015; Harrison et al., 2012		X	X			Both approaches use OEMs for submarine option/configuration evaluation during conceptual design. No integration with MBSE models.
Design Building Block (DBB) Andrews, 2006 and McDonald et al., 2012		X	X		Hullform performance (e.g., seakeeping, resistance, and stability) can be simulated using a synthesised CAD model.	Approach facilitates rapid synthesis of a computer aided design (CAD) hullform based on ship functions.

The OTS constraint on the solution space, which is limited to the range of existing designs in the market, arguably not only changes the nature of the required SE approach to middle-out, but it also changes the nature of the C&RE. The need to optimise concept designs is negated and the discussion between stakeholders (especially the navy users) and acquirers changes from eliciting needs and requirements to identifying KPPs and discussing the degree to which existing designs may satisfy them. To inform this discussion, a market survey activity needs to be incorporated into the concept and requirements exploration approach in order to identify whether suitable designs for the operational needs already exist. If they do not, the needs will need to be revisited and adjusted until they reflect the marketplace, or a case needs to be made that the capability risk is unacceptable and a developmental acquisition strategy, rather than OTS, is required. An overview of the C&RE part of the MBSE methodology to support Australian OTS acquisitions, which includes its latest refinements, is shown in Figure 3.

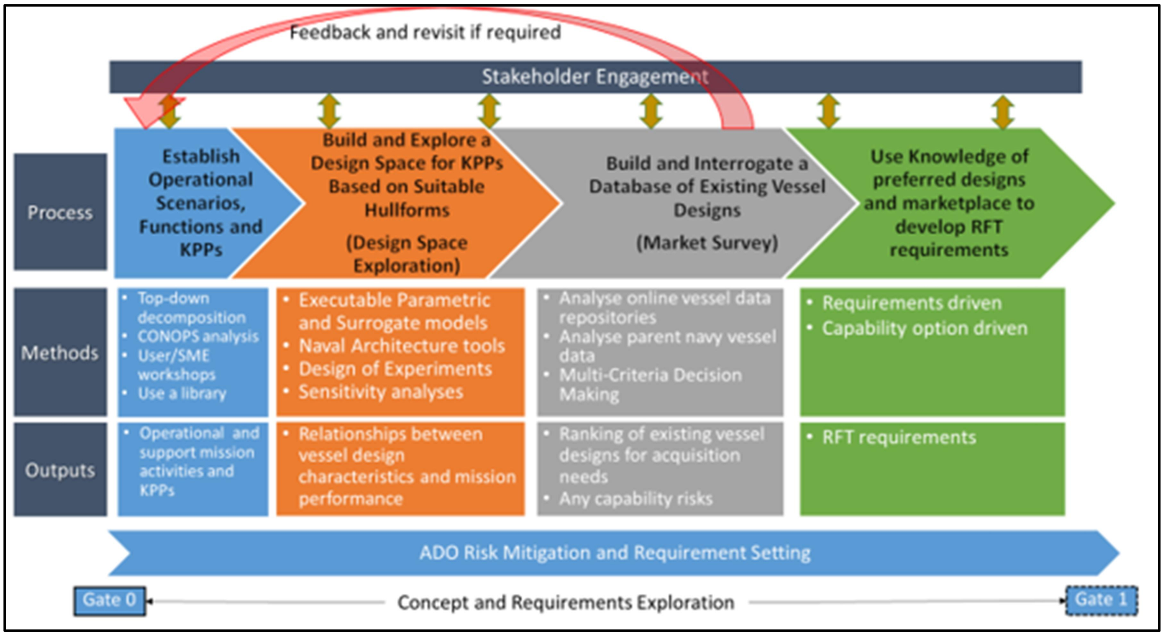


Figure 3. Overview of the Off-the-Shelf Concept and Requirements Exploration Methodology

From Figure 3 it can be seen that three of the features from the existing C&RE approaches in Table 1, MBSE, design space exploration, and modelling and simulation, can be used in the OTS C&RE approach. It is also noteworthy the OTS C&RE approach can be used to support activities and tasks within the ISO/IEC/15288:2015 (ISO/IEC/IEEE, 2015) technical processes: Business or Mission Analysis (e.g., defining the problem space), Stakeholder Needs and Requirements Definition (e.g., analyse stakeholder requirements), System Requirements Definition (e.g., maintain traceability of requirements) and Architecture Definition (e.g., relate the architecture to design). Rather than discuss each stage of the C&RE approach in detail here, in the following section an example implementation of the C&RE part of the MBSE methodology to support Australian OTS naval vessel acquisitions is covered. This provides an overview of each step and the methods that can be used to generate the necessary outputs in the context of an indicative acquisition of a hydrographic and oceanographic survey capability.

Hydrographic and Oceanographic Survey Capability Example Implementation

The example implementation covered in this section was undertaken as part of the constructive research approach, where the artefact (in this case the MBSE methodology) is tested through application. The case study is based on an exemplar strategic need for a military hydrographic and oceanographic survey capability. The assumed solution system concept employs a ship in combination with an array of uninhabited systems that perform the survey functions. This concept could use a range of vessel types, so part of the study involved investigating the suitability of three hullform types currently in service with the Royal Australian Navy. To bound the design space, several assumptions were made: firstly, the vessel hullform was assumed to be monohull; secondly, the vessel length was constrained to be a maximum of 95 metres; and finally, the area of operations was assumed to have sea-state four conditions as the most commonly occurring conditions. Constraints such as these would typically be imposed on a naval acquisition due to considerations such as the planned area of operations and the need to utilise existing port infrastructure.

Step 1: Establish the Mission Scenario and Key Performance Parameters

The first step in the C&RE part of the MBSE methodology is to identify the missions, scenarios, and key performance parameters (KPPs) for the capability being acquired. This step is performed in a top-down manner, where the top-level needs are decomposed into mission scenarios comprising the required operational activities. The operational activities can then be traced through the system functions to the KPPs for the capability. The KPPs are considered to be "a critical subset of the performance parameters representing those capabilities and characteristics so significant that failure to meet the threshold value of performance can be cause for the concept or system selected to be re-evaluated or the project reassessed or terminated" (Roedler & Jones, 2005).

As shown in the suitable methods for step one in Figure 3, the top-down decomposition of the top-level capability needs to establish the mission scenarios and KPPs can be undertaken using information developed and captured in a concept of operations, or by consulting subject matter experts (SMEs). The use of MBSE enables this top-down decomposition to be captured in a model, which can then be linked to the potential design space via the KPPs as discussed in the next step. Using MBSE also enables the model to be reused for subsequent naval vessel acquisitions. In line with guiding principle number three above, MBSE models can be collected over several acquisitions to form a repository, or library, containing SME knowledge of the mission scenarios and KPPs for naval missions.

Figure 4 is a partial view from the MBSE model developed during the example implementation that shows the top-down decomposition from the strategic needs to the KPPs for the "move" and "launch and recover objects to/from the sea" system functions (only some of the operational needs, system functions, and performance characteristics are shown for clarity). In the example implementation the representative mission scenario (the "operational activity" stereotype elements within the blue rectangle in Figure 4) and KPPs (the "MOP [Performance Characteristic]" stereotype elements in the red rectangle in Figure 4) were elicited from SMEs in a workshop setting. In this manner, the design space exploration process undertaken in the next step of the methodology allows capability acquisition stakeholders to trace design decisions through to the capability need. Hence, stakeholders will gain a better understanding of the relationship between design decisions and the requirements, assisting the requirements definition process.

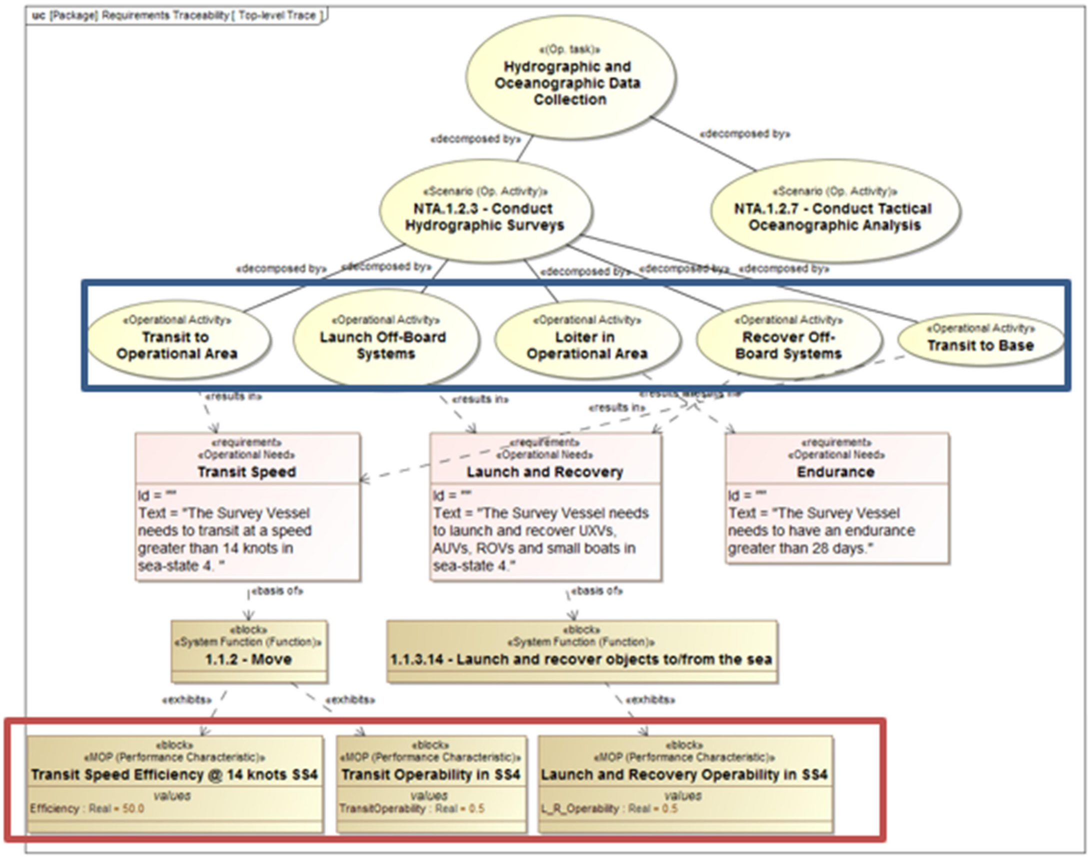


Figure 4. Decomposition From High-Level Guidance Through to the KPPs Related to the Transit Speed and Launch and Recovery Operational Needs

Step 2: Generate and Explore a Design Space Based on Existing Hullforms

In this step, models to calculate KPPs for vessel designs are developed and used to generate a design space that provides stakeholders with insights into relationships between vessel design characteristics and mission performance. These models can range from low-fidelity parametric and surrogate models of relationships between MOPs and ship design parameters, to higher fidelity simulation models that use three-dimensional ship geometries and linear or non-linear solvers. A multi-fidelity approach that uses a combination of high and low-fidelity models can be adopted for this step as the computational and human effort required to implement only high-fidelity simulations at this early stage of the lifecycle is not practical. Basing the models on existing hullforms ensures realistic, feasible design spaces are generated with the OTS constraint in mind. Again, libraries of models can be built over time and reused in subsequent acquisitions.

After tracing in a top-down manner from high-level guidance to the KPPs in the MBSE model during the previous step of the MBSE methodology, in this step, a representation of an existing vessel is captured as value properties in an instantiation of a "vessel properties" stereotype element in the MBSE model. The vessel properties element can then be traced through simulation model element, and KPPs calculated for the instantiation. This is shown in Figure 2 in the red analysis domain elements, where the vessel properties package containing a representation of a vessel "exhibits" the KPPs. The simulation element in Figure 2 (within the red analysis domain package) is linked to executable models through parametric diagrams containing the "constraints" that are built within the MBSE model. Used in conjunction with model integration software or parametric diagram solving software, this approach enables analyses to be conducted, managed and stored from within an MBSE model.

In the example implementation for the hydrographic survey capability, a multi-fidelity approach was used. This approach included the use of the low-fidelity empirical model given by Mennen (1982) to predict the calm-water resistance of the ship representation, as well as the use of a higher fidelity frequency domain seakeeping program (McTaggart, 1997) to predict the motions, as well as the added resistance of the ship representation in waves. The ship representation was a set of roughly 20 design parameters that were extracted from a three-dimensional CAD model. To build views of the design space for the KPPs identified in the previous step, three parent hullforms were systematically varied between the upper length constraint of 95 metres and a lower limit of 65 metres in length. The three hullforms investigated were a hydrographic survey vessel hullform, a frigate hullform, and an offshore patrol vessel hullform. These hullforms were selected as the concept of using a range of uninhabited systems to undertake the data collection activities could conceivably use any available navy ship as a transport platform provided the uninhabited systems are modular in nature. To help ensure the generated design spaces were realistic, the hydrographic vessel and frigate hullforms currently in service with the Royal Australian Navy were used as the parent hullforms that were systematically varied.

A Design of Experiments (DOE) approach (1000 run orthogonal array) was adopted to create a matrix of vessel designs across the design space that were run through the seakeeping and resistance simulation models to calculate their KPP values. This investigation, which was covered in Dwyer and Morris (2017), identified the hydrographic survey hullform as having superior performance with respect to the launch and recovery and transit operability KPPs, as well as being a more efficient hullform when transiting in 14 knots in sea state 4. This means the hydrographic survey hullform is the most suitable for the operational needs in this example implementation. A scatterplot of the results for the hydrographic survey vessel hullform’s seakeeping operabilities during transit and launch and recovery operations, as well as the transit speed efficiency (a measure of the total vessel resistance relative to its displacement) at a transit speed of 14 knots, are shown in Figure 5. The data from the DOE shown in the scatterplot can be used to ascertain the vessel particulars of the best performing generated designs on the pareto front (designs inside the red triangle in Figure 5). These designs exhibit the combinations of highest operabilities and lowest total resistance per tonne of displacement. Some of the vessel particulars for the best performing designs that were generated in the DOE from the pareto front within the red triangle on Figure 5 are shown in Table 2. The block coefficient of these designs is provided to give an indication of the hullform fullness.

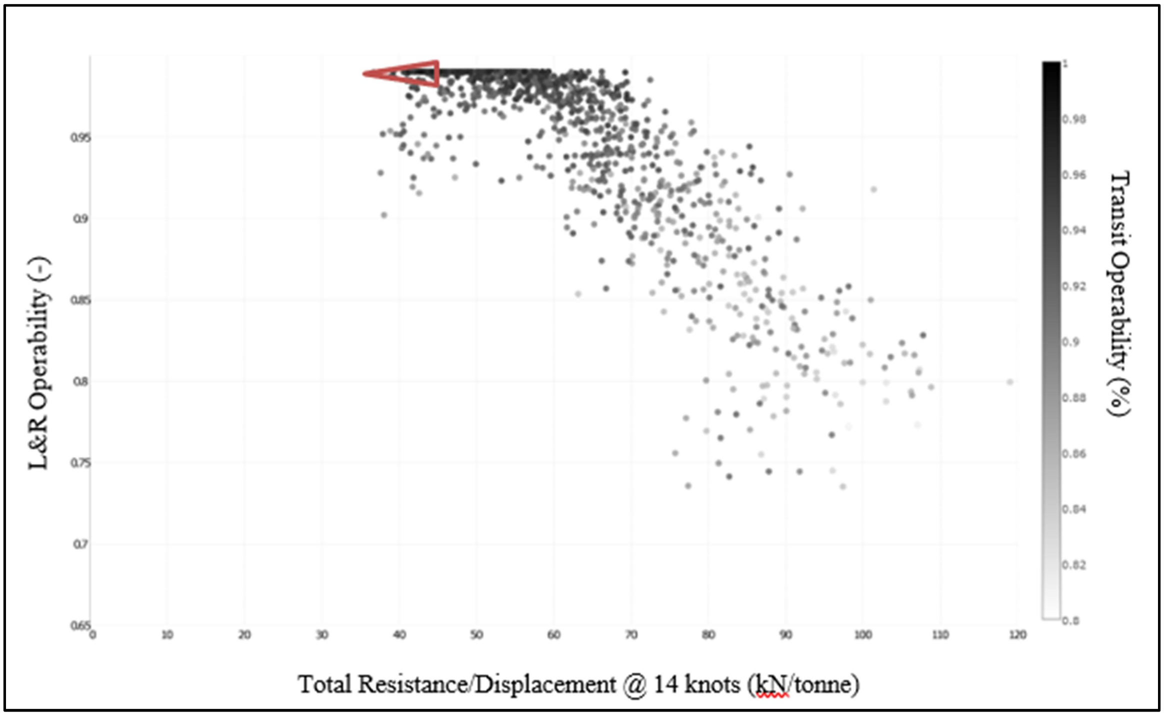


Figure 5. Scatterplot of the 1000 Run DOE for the Hydrographic Survey Vessel Hullform in Sea State 4

Table 2. Vessel Particulars of the Best Performing Designs From the DOE in Sea State 4

Generated Design	Length Overall (m)	Length/Beam	Beam/Draft	Displacement (tonnes)	Block Coefficient
775	95	4.12	3.34	9135	0.6089
337	94.2	4.26	3.47	7871	0.5926
786	95	4.09	3.97	7850	0.6085
796	95	4.48	3.50	7301	0.5971
334	94.2	4.36	3.59	7018	0.5840
785	95	4.26	3.86	7055	0.5785
135	93.4	4.12	3.95	7252	0.6024
482	87.7	4.05	3.56	6443	0.5628
317	90.2	4.16	3.70	7155	0.6322

Furthermore, by analysing the vessel data from the design space using standard correlation techniques, the sensitivity of the vessel performance relative to its design parameters can be established. This sensitivity can be used to identify favourable combinations of design parameters that maximise mission performance. Figure 6 shows the design parameter sensitivities for the transit operability in sea state 4 KPP. This shows that vessel length has a large positive influence on transit operability as it increases and that the length-to-beam ratio has a negative influence as it increases. This shows that as both the vessel length and length-to-beam ratio increase there is a positive influence and negative influence on transit operability respectively.

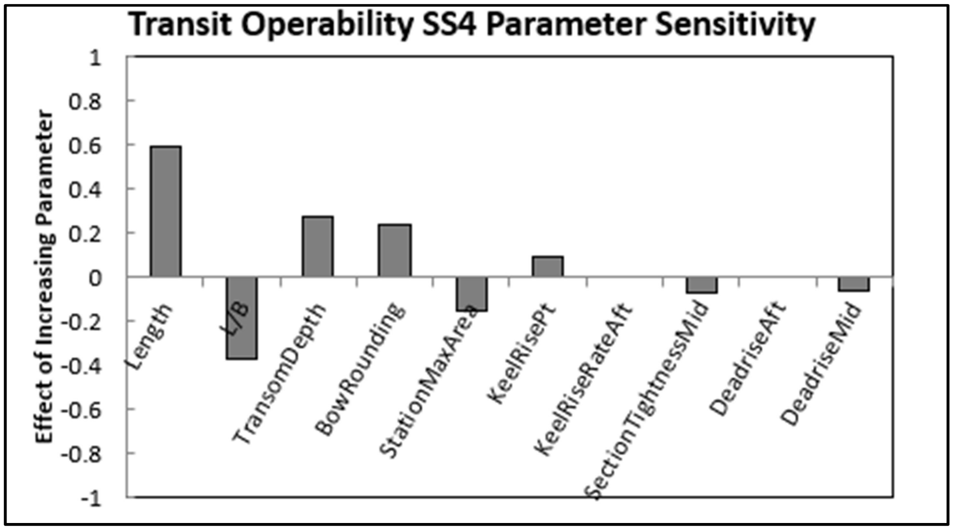


Figure 6. Vessel Design Parameter Sensitivity for the Transit Operability in Sea State 4 KPP

Figure 7 shows the vessel design parameter sensitivities for the launch and recovery operability in sea state 4 KPP. Figure 7 also shows that like the transit operability, increasing both the vessel length and length-to-beam ratio has a positive influence and negative influence on the launch and recovery operability respectively, even though the limits are different for launch and recovery. These aspects are likely to be intuitive to the naval architect, however, this exploration of the design space allows other stakeholders to quantify the effects and make decisions on requirements definition based on robust analysis.

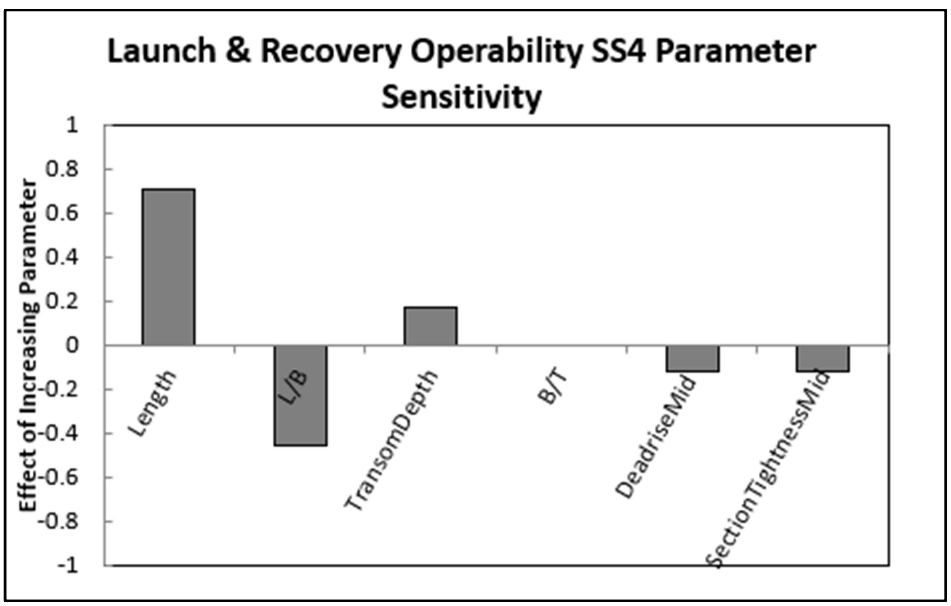


Figure 7. Vessel Design Parameter Sensitivity for the Launch and Recovery Operability in Sea State 4 KPP

Step 3: Build and Interrogate Database of Existing Designs

This step within the concept and requirements exploration part of the MBSE methodology is a preliminary market survey activity. This activity supports the definition of requirements that reflect the OTS naval vessel design marketplace in a bottom-up manner by constraining the solution space to existing designs. Furthermore, this step in the methodology can assist in identifying any capability risks associated with the OTS constraint, as the mission performance of OTS can be estimated using the data from the previous step.

This step uses the knowledge gained from the previous step to build, then rank a database of existing vessel designs based on the preferred combinations of design parameters. For the hydrographic survey vessel example implementation, a database of existing designs was built from relevant existing vessel design data contained in the Janes IHS database (IHS, 2017). Then, using the knowledge gained about the vessel design parameter sensitivities in the previous step of the MBSE methodology, the vessels in the database were ranked. Two key design parameters were used to rank the designs. The first ranking criterion was vessel length, since increasing vessel length had the highest sensitivity metric and therefore the greatest influence on both operabilities, as well as the transit efficiency. The second ranking criterion is the length-to-beam ratio, since the length-to-beam ratio had the second greatest sensitivity metric considered in the example implementation. Other vessel design parameters could have been used to rank the designs, however, a shortcoming of the database used in this example implementation was the limited number of vessel design parameters it contained. This will be a shortcoming present in most OTS acquisitions as the acquirer is unlikely to have access to extensive OTS vessel design data.

In the hydrographic survey vessel example implementation, the vessel ranking was performed using the multi-attribute value analysis method, where the overall weighted value of each vessel in the database was calculated based on a summation of the swing weights of its length and length-to-beam ratio. The weights were calculated from the ranks of the sensitivities of the vessel design parameters (vessel length first and length-to-beam-ratio second) using the Rank Order Centroid technique from Buede (2000). Value curves for length (greater value as it increases) and the length-to-beam ratio (greater value as it decreases) were assumed to be linear with a positive and negative gradient respectively. Design data for the top 10 vessels in the database with lengths between 65 and 95 metres is shown in Table 3.

Table 3. Top 10 Entries in the Existing Vessel Database Based on the Vessel's Length and Length-to-Beam Ratio

Rank	Displacement (tonnes)	Length (m)	Beam (m)	Length/Beam	Speed (knots)	Range (nm)	Crew
1	6421	89.9	19.1	4.71	15	12000	33
2	2889	87	14.6	5.96	15	12000	31
3	3477	85.7	15	5.71	14	11000	58
4	3455	83.5	16	5.21	15	11300	22
5	2991	85	14.1	6.03	14	10060	23
6	3024	72.5	15.24	4.76	12	10500	20
7	2164	76.8	12.8	6.00	14.5	10000	24
8	2205	71.2	15.2	4.68	14	18000	61
9	2382	67.5	15.3	4.41	16.5	22000	22
10	2298	68.3	13.1	5.21	11	19000	49

The database and interrogation tool were set up in a spreadsheet application, which was then wrapped into the MBSE model as an external analysis via model integration software. The key vessel design parameter's ranks and the gradients of the values curves are held as SysML value properties in a Block type element, "key design parameters" within the "vessel properties" package in the MBSE model as shown in Figure 8. The "vessel properties" package is an element within the analysis domain in the metamodel as shown in the blue oval in Figure 2.

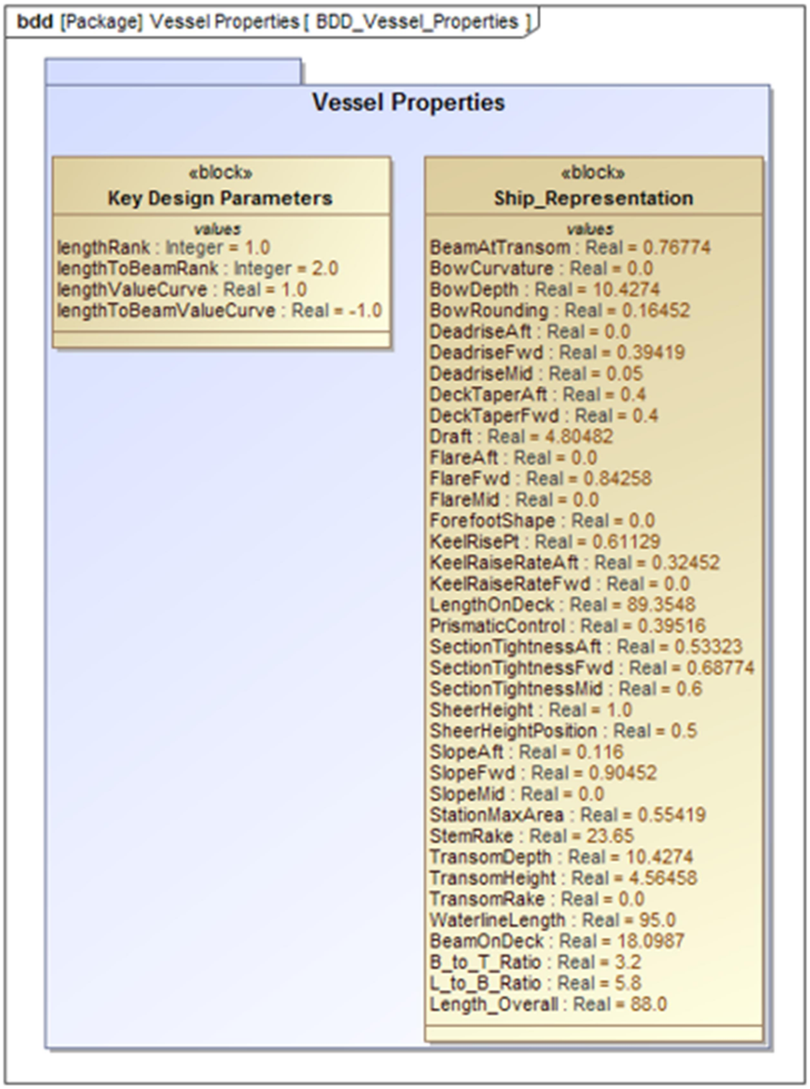


Figure 8. Vessel Properties Package Within the MBSE Model Built During the Example Implementation

The top-ranked designs from the database can be investigated further to establish their suitability for the capability needs. In this stage of the investigation, aspects such as the operating navy, year of design, and country of origin of the designer can be established, as well as refinement of the top-ranking vessels based on any key criteria, such as the range and crew size. The year of design should be an important consideration, since, as the aforementioned analogy between the OTS strategy and "modified repeat" ship design approach highlighted, the approaches work best when the follow-on ships have nearly identical legislative and operational requirements.

In considering whether there are any capability risks for the operational needs due to the OTS constraint for the hydrographic and oceanographic survey vessel example implementation, the data from the top-ranking existing vessels can be cross-checked against the data from the design space generated in the previous step. By comparing the top-ranked existing designs in Table 3 with the top performing generated designs in Table 2, some inferences can be drawn. Firstly, there does not appear to be many existing designs with vessel particulars similar to the optimal designs in Table 2. This could suggest some of the top performing generated designs may be unrealistic, or conversely, there is a gap in the marketplace. To investigate further, relationships between vessel length and the KPPs were generated from the 1000 run hydrographic survey vessel hullform DOE as shown in Figure 9. From Figure 9, it can be seen that the slope of both the launch and recovery (L&R) and transit operabilities decreases as the vessel length grows from approximately 85 metres to 95 metres. This means there is likely to be only marginal improvements in the operability of hullforms to be gained in acquiring a design longer than 90 metres up to the 95 metre limit used in this implementation. This provides a degree of confidence, that the existing vessels larger than roughly 85 metres in length, provided they have a typical hydrographic survey vessel hullform, will have high L&R operability and be capable of meeting the operational needs for the example implementation. This implies there is only low capability risk and that there is no need to revisit the missions and KPPs established in the first step of the MBSE methodology as shown in Figure 3. However, it is a concern that only the top-ranked existing design in Table 3 appears to be close to the optimal region of the design space for the KPPs considered in this example implementation. In a full implementation there would be other KPPs such as acquisition and through-life costs that would impact the decision on whether to revisit the missions and KPP and step through the methodology again.

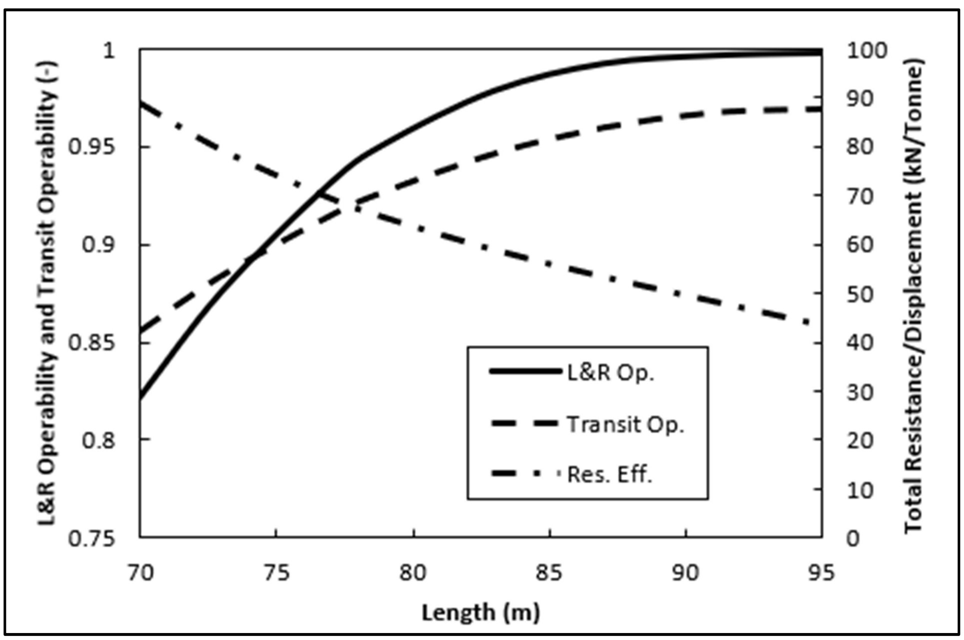
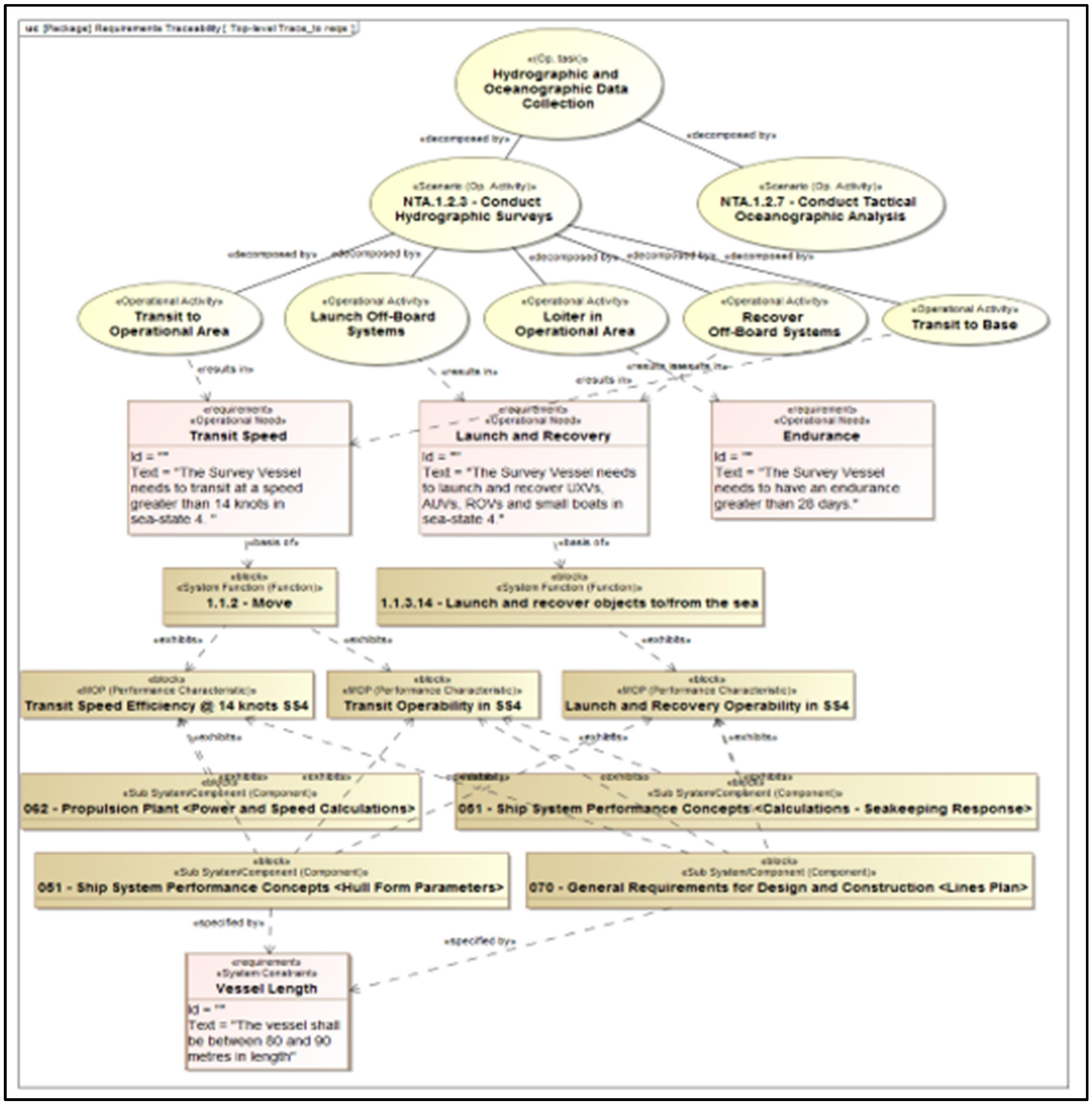


Figure 9. Relationships Between Vessel Length and the Operabilities (L&R Op. and Transit Op.) in Sea State 4 KPPs and Transit Speed Efficiency (Res. Eff.) in Sea State 4 KPP for the Hydrographic Survey Hullform

A final point worth noting in this step is that differences between the optimal combinations of vessel design parameters identified in the design space exploration and the suitable existing vessel designs identified in this step could provide opportunities for design changes. Although this technically violates the OTS constraint, some design changes from the existing design are typically made due to legislative and other requirements differences. If the design changes are affordable, it seems to make sense to pursue changes that could increase performance for the KPPs of the naval vessel being acquired. These design changes could be driven by the requirements released to industry as discussed in the next step.

Step 4: Set Request-for-Tender Requirements

For the hydrographic and oceanographic survey vessel example implementation, the design space exploration (Step 2) and interrogation of existing designs (Step 3) have shown that we can be reasonably confident there are vessels in the marketplace that have been designed to meet similar needs. We can narrow the field of potential respondents to the request for tender by including a constraint on the vessel size to be between 80 and 90 metres in length. We can do this with a degree of confidence that there are existing designs in the marketplace within this range and it will also limit responses to those that are most likely to meet the operational needs. Including the constraint in the request for tender (RFT) requirements can be done in a traceable manner within the MBSE model by continuing the traceability to the KPPs shown in Figure 4, through the ship systems that exhibit the KPPs to the system constraint or requirement. As an example, the vessel length constraint can be included in the MBSE model as shown in Figure 10. Other constraints and requirements can be set and included in the RFT in a similar manner.



Note. Only a partial mapping is shown for clarity.

Figure 10. MBSE Model View Showing the Traceability of the "Vessel Length" Constraint to Be Included in the RFT Requirements to the High-Level Guidance That Triggered the Acquisition

By imposing constraints in the request for tender requirements using the knowledge gained of optimal designs during the design space exploration step, it could encourage designers to propose variants of existing designs that are already close to the optimum. This should not pose a significant risk to the acquisition provided the designer is an established and reputable designer.

Conclusions

This paper covered the latest iteration of research to construct an MBSE methodology to support Australian OTS naval vessel acquisitions. The focus was on the concept and requirements exploration part of the methodology, which was refined to include an explicit market survey activity during this latest iteration. Previously, the C&RE approach relied on parametric and surrogate models based on existing vessel design data to generate a design space representative of the OTS vessel marketplace.

Two main recommendations for further work arose during the research covered in this paper. Firstly, it is recommended to test the MBSE methodology for an actual acquisition in order to satisfy the “holistic market test” part of CRA. This would gain valuable insights into the utility MBSE methodology and provide data for further refinements. Secondly, further research is required to investigate techniques that could be used to estimate the value of KPPs for existing designs based on a low-level of design data being available. This is the situation the above-the-line acquirer is faced with during the early stages of naval vessel acquisitions. Generally, the acquirer will only have access to publicly available design data, which is often insufficient (as shown during the market survey step in the example implementation above) to make a robust estimate of the design’s performance.

In response to the research problem identified in the introduction to this paper, an easily implementable MBSE methodology has been developed that supports knowledge generation, capture and reuse during Australian off-the-shelf naval vessel acquisitions. The methodology supports defensible decision making through evidence-based analysis and traceability to the strategic capability needs.

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