A METHODOLOGY TO SUPPORT EARLY STAGE OFF-THE-SHELF NAVAL VESSEL ACQUISITIONS

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SUMMARY

This paper describes a research programme to construct a Model-Based Systems Engineering (MBSE) methodology that supports acquiring organisations in the early stages of Off-the-Shelf (OTS) naval vessel acquisitions. A structured approach to design and requirements definition activities has been incorporated into the methodology to provide an easily implemented, reusable approach that supports defensible acquisition of OTS naval vessels through traceability of decisions. The methodology comprises two main parts. Firstly, a design space is developed from the capability needs using Set-Based Design principles, Model-Based Conceptual Design, and Design Patterns. A key idea is to employ Concept and Requirements Exploration to trim the design space to the region of OTS designs most likely to meet the needs. This region can be used to specify Request for Tender (RFT) requirements. Secondly, the methodology supports trades-off between the OTS design options proposed in the RFT responses using a multi-criteria decision making method. The paper includes an example implementation of the methodology for an indicative Offshore Patrol Vessel capability.

NOMENCLATURE

ADO	Australian Defence Organisation
AHP	Analytical Hierarchy Process
C&RE	Concept and Requirements Exploration
CONOPS	Concept of Operations
DBB	Design Building Block
DSE	Design Space Exploration
ESWBS	Expanded Ship Work Breakdown Structure
INCOSE	International Council on Systems Engineering
IPSM	Integrated Platform System Model
KPP	Key Performance Parameter
M&S	Modelling and Simulation
MAUT	Multi-Attribute Utility Theory
MAV	Multi-Attribute Value Analysis
MBCD	Model-Based Conceptual Design
MBSE	Model-Based Systems Engineering
MCDM	Multi-Criteria Decision Making
MDAO	Multidisciplinary Design Analysis and Optimisation
MOP	Measure of Performance
MSC	Medium Security Cutter
NFR	Non-Functional Requirement
OEM	Operational Effectiveness Model
OTS	Off-the-Shelf
OTSO	Off-the-Shelf Option
OWV	Overall Weighted Value
PBSE	Pattern-Based Systems Engineering
RFT	Request for Tender
ROC	Rank Order Centroid
ROM	Rough Order of Magnitude
RSM	Response Surface Method
SBD	Set-Based Design
SE	Systems Engineering
SME	Subject Matter Expert
SysML	Systems Modelling Language
UNTL	Universal Naval Task List
US	United States of America
USCG	United States Coast Guard
VT	Virginia Polytechnic Institute and State University
WSAF	Whole-of-System Analytical Framework

1. INTRODUCTION

Given the increasing complexity and interoperation of military systems, the acquisition of new materiel solutions, such as naval vessels needs to be undertaken in the context of the overall national defence strategic setting (Hodge and Cook, 2014). Furthermore, it is recognised that developing requirements for a defence capability is a design process, the output of which is the definition of the materiel need (Hodge and Cook, 2014; Coffield, 2016; Cook and Unewisse, 2017) along with all the non-materiel aspects of capability. Systems of Systems Engineering approaches are gathering momentum in defence organisations around the world to capture and co-ordinate the wider defence context and are routinely used to define new capability needs. However, it is customary to find that this work needs to be enhanced by a project-specific capability design process performed by the individual capability acquisition project offices.

An important constraint on the capability acquisition process for naval vessels is the adoption of strategies that give preference to Off-the-Shelf (OTS) designs. This has become commonplace in countries with modest Defence budgets like Australia. In fact, the Australian government recently mandated the selection of a ‘mature design’ for naval vessel acquisitions (Defence, 2017), which has been interpreted to mean OTS solutions. OTS strategies change the nature of defence acquisition projects from the traditional top-down requirements-driven approach to a middle-out approach. This approach is based on defining the functions that are needed (capability goals) and then searching through existing OTS offerings to find the one that best satisfies the needs with the lowest level of customisation.

The OTS acquisition strategy for naval vessels appears to be analogous to the 'repeat', or 'modified-repeat' naval vessel design approach, since they both rely on adapting an existing design to address a naval capability gap. The modified-repeat design approach uses an existing design as the parent hullform, which is modified (to varying degrees) into what is assumed to be a 'mature' design (Keane Jr and Tibbitts, 2013). This is similar to many OTS naval vessel acquisitions, where the OTS design (the parent) is modified (to varying degrees) into what is promoted as a mature design. Both modified-repeat design and OTS acquisition have been perceived as a means of reducing the acquisition cost and schedule risks for naval vessel capability acquisition programs (Saunders, 2013 and Keane Jr and Tibbitts, 2013). An analysis of the cost and schedule benefits associated with the modified-repeat ship design approach showed these perceptions can be realised if the operational requirements for the new design are nearly identical to the existing design (Covich and Hammes, 1983). Furthermore, to maximise the potential of these approaches the existing vessel design will ideally still be in production, since evolving legislative requirements can necessitate significant design changes for older parent vessels (Covich and Hammes, 1983). Hence, to realise the benefits of lower acquisition cost and schedule risks in OTS naval vessel acquisitions, the project will need to identify existing OTS designs, or a region in the OTS design space, with very similar operational and legislative requirements to those for the new vessel and then specify tender requirements accordingly. Unlike the navy undertaking a modified-repeat design approach to address a capability gap, the OTS acquirer will not have knowledge of the parent design's requirements and design data. These aspects, as well as the aforementioned middle-out nature of OTS acquisitions, mean the OTS constraint presents a rather different class of challenge to the acquisition community; one that requires a different class of procurement approach and related methods, processes, and tools.

This paper describes a Model-Based Systems Engineering (MBSE) methodology constructed to support key OTS naval vessel acquisition project activities such as: defining requirements, selecting the preferred technical solution, developing and managing the early stage design information, and maintaining requirement and decision traceability. Figure 1 illustrates the temporal focus of the methodology described in this paper against various system lifecycle models. The emphasis is on the Risk Mitigation and Requirements Setting Phase of the Australian Defence Organisation (ADO) lifecycle and the corresponding early stages in other lifecycles. Andrews (2013) notes "it is often acknowledged that the initial (or concept) design phase is the most critical design phase, because by the end of this phase most of the cost is incorporated in the design…" The methodology seeks to improve the quality of the output of these early design stages using an easily implemented approach to support defensible acquisition of OTS naval vessels. The methodology comprises two main stages. The first stage is a model-based approach to ship Concept and Requirements Exploration (C&RE). This stage focuses on assisting stakeholders to build knowledge about possible OTS solutions to the capability needs. Knowledge is gained by exploring and progressively narrowing an existing OTS design space that is linked through appropriate Measures of Performance (MOPs) and Key Performance Parameters (KPPs) to the capability needs and constraints. This knowledge of the OTS design space supports the elucidation of a set of feasible and traceable request-for-tender (RFT) requirements. The second stage of the methodology is a model-based approach to option evaluation. This stage supports final design activities to refine the existing OTS design as well as the selection of a preferred design from those offered and refined in response to a RFT.

The paper opens with a review of some elements of early stage naval vessel acquisition that are incorporated into the methodology. These elements include Model-Based Conceptual Design (MBCD), Set-Based Design (SBD), Modelling and Simulation (M&S), Design Space Exploration (DSE), Multi-Criteria Decision Making (MCDM) and Pattern-Based Systems Engineering (PBSE). Together these provide defensible support to decision making during the early stages of naval vessel acquisition. After presenting the overall methodology, a brief exemplar implementation is given for a United States Coast Guard (USCG) Concept of Operations (CONOPS) for a Medium Security Cutter (MSC). Following a discussion on the findings from implementing the methodology, the paper concludes with suggestions for further work.

2. ELEMENTS OF EARLY STAGE DESIGN RELEVANT TO NAVAL VESSELS

The latest in a long line of reviews of the Australian Department of Defence, the First Principles Review, highlighted a number of recurring themes from earlier reviews (Peever, 2015: p. 92). Three of these themes provide the impetus for the guiding principles used in the construction of the proposed methodology:

1. Maintaining traceability to the original, strategic intent of the vessel being acquired in order to ensure a defensible outcome.
2. Assisting the stakeholders to make defensible decisions that account for competing goals and objectives.
3. Maximising the capacity to reuse elements – thereby reducing subsequent acquisition efforts to implement the methodology and the resources required to manage these projects.

With these principles in mind, a review of the literature identified six key elements for inclusion in the methodology. These are described in the following sub-sections.

2.1 MODEL-BASED CONCEPTUAL DESIGN

A key recent practice in early stage design is Model-Based Conceptual Design (MBCD). Reichwein et al. (2012: p. 1), state that "Model-based concept(ual) design is often used to allow engineers to describe and evaluate various system aspects". They highlight the wide range of models that can be used during conceptual design, which include (Reichwein et al., 2012: p. 1): mathematical models, geometric models, software models, system models, control system models, multi-body system models, requirement models and function models. An INCOSE MBCD Working Group (WG) was chartered in 2013 and has defined MBCD as "...the application of MBSE to the Exploratory Research and Concept stages of the generic life-cycle defined by INCOSE..." (Robinson, 2013: p. 1). Using MBSE during conceptual design has been found to provide a "clearer understanding of the problem space" (Morris et al., 2016: p. 11). Campbell and Solomon (2011) list some of the benefits of an MBSE approach, particularly in the Defence context as: process independence, reduction in overall effort required, improved accuracy of the output, provision by the tools of a central repository, and traceability throughout the whole project/product lifecycle.

In the Australian defence context, the Whole-of-System Analytical Framework (WSAF) MBCD approach has been applied to the early stages of many complex system acquisition projects (Cook et al., 2015). While naval vessel concept design has been described as having a 'wicked' nature (Andrews, 2013), the OTS constraint serves to effectively bound the initial problem space to one that can be clarified through the use of approaches from other domains. Since MBCD can incorporate MBSE and provides understanding of the problem space, WSAF succeeds in meeting the first and third principles outlined in Section 2. However, WSAF was not intended to support the engineering design and engineering analysis aspects of MBCD and additional elements are needed to cover these activities.

Although no specific mention of MBCD was identified in naval architecture literature, several examples of applying model-based methodologies during naval vessel conceptual design have been found. These methodologies and the features of MBCD they include are summarised in Table 1. While there are some issues associated with implementing MBCD in terms of engagement within organisations (Morris et al., 2016), the structure and traceability provided through MBSE, as well as the ability to reuse models, means MBCD adheres to the three guiding principles for constructing a methodology to support early stage OTS naval vessel acquisitions.

2.2 SET-BASED DESIGN

SBD is an emerging paradigm in naval vessel design (Singer et al., 2009). SBD differs from the traditional point-based iterative approach to design by using sets of values of design parameters, rather than a single value (Hannapel, 2012). Arising from a study of Toyota's automobile design approach in the mid 1990's, the features of the SBD process have been identified as (Parsons, 2003): broad sets are defined for design parameters to allow concurrent design to begin, these sets are kept open much longer than typical to reveal trade-off information, the sets are gradually narrowed until a more global optimum is revealed and refined.

SBD is claimed to offer two main advantages over the point-based approach (Hannapel, 2012). Firstly, the amount of design rework is reduced as SBD uses narrowing sets of design parameters rather than iterations of a single set of design parameters that may change from iteration to iteration. Secondly, design decisions are made when more information is available as the decisions are purposely delayed in the SBD approach.

In other literature covering naval vessel conceptual design, the principle of "*requirements elucidation*", rather than requirements engineering (Andrews, 2011), emerges. In this approach "…the initial design phase is characterised by the need to elucidate what the requirements should be…" (Andrews, 2012: p. 895). Andrews (2012: p. 895) also notes the consistency between the European *requirements elucidation* principle and the US SBD approach with the statement "…this more realistic emphasis in requirements elucidation can then (be) seen to be consistent with the approach of deferred commitment or SBD…"

SBD appears to build upon a proposal to use "concurrent engineering design" for ships from the 1990s. Both concurrent engineering design and SBD share themes regarding the benefit of having more information on which to base design decisions. Mistree *et al* state (Mistree et al., 1990: p. 567): "Conceptually, it is evident from any perspective that as a design process progresses and decisions are made, the freedom to make changes as one proceeds is reduced and knowledge about design increases … at the same time, there is a progression from soft to hard information." Both concurrent engineering and SBD are descriptive, rather than prescriptive models of design, hence their utility for the designer is diminished (Mistree et al., 1990: p. 567). However, they seem well suited to the early stages of OTS naval vessel acquisition as they focus on informing stakeholders on a conceptual design space, rather than providing information on a single point in that space (Morris, 2014). This means SBD adheres to principle two described in Section 2. In OTS acquisitions, there is no need to pursue a point-based approach, since the role of the acquiring organisation is to develop requirements that specify suitable OTS designs from within the OTS design space, as well as to identify any capability risk arising from the OTS constraint, not to produce a specific design.

2.3 MODELLING AND SIMULATION

Modelling and simulation (M&S) has been identified as being valuable for conceptual design for many years. Aughenbaugh and Paredis (2004) term the conceptual design phase of the system development lifecycle, *decomposition* as it aligns with the left hand side of the SE "vee" model (See Forsberg and Mooz, 1991 and Elliott and Deasley, 2007). Aughenbaugh and Paredis, while referring to early stage exploratory design, assert that M&S can help reduce the likelihood that requirements will not be satisfied later in the lifecycle by "supporting exploration of the design during the decomposition process" (Aughenbaugh and Paredis, 2004: p. 2). They also argue that M&S can inform decisions on trimming the design space during conceptual design by helping to "estimate the (system) attributes that would result from a particular decision" (Aughenbaugh and Paredis, 2004: p. 3). This means M&S can be used in OTS acquisitions to build knowledge of the performance characteristics of OTS designs without having specific design details. In turn, this knowledge could support the identification of a region within the design space containing OTS designs with similar operational requirements to those of the acquisition project.

M&S is an element of all of the naval vessel MBCD methodologies in Table 1. However, only two of the MBCD methodologies in Table 1 incorporated integrated MBSE and M&S (WSAF (Morris, 2014) and OTS C&RE (Morris and Thethy, 2015)) to combine MBSE's traceability benefits with the analytical rigour of M&S. It is worth noting these two MBCD methodologies utilised simple M&S models (parametric and surrogate models) to build a Rough Order of Magnitude (ROM) design space. The other naval vessel MBCD methodologies utilised more complex M&S models (Operational Effectiveness Models (OEMs) or the Design Building Block (DBB) model, which provides a vessel representation that can be simulated) and maintained either separate M&S and MBSE models, or no MBSE model. When discussing effective implementation of MBSE, Haveman and Bonnema state: "ideally, all models must be able to interact", whilst also noting: "currently, there are few approaches that effectively integrate high-level models in MBSE" (Haveman and Bonnema, 2013: p. 296). If MBSE and M&S models can be integrated, this will align with principles one and two as MBSE will facilitate traceability to the strategic intent of the capability. In addition, application of M&S during conceptual design can provide evidence to aid defensible decision making.

2.4 DESIGN SPACE EXPLORATION

Kang *et al*. define Design Space Exploration (DSE) as "the activity of discovering and evaluating design alternatives during system development" (Kang et al., 2010: p. 1). Other authors, such as Spero et al. (2014), along with Ross and Hastings (2005) refer to DSE as Tradespace Exploration, with Ross and Hastings defining the tradespace as "the space of possible design options" (Ross and Hastings, 2005: p. 2).

In naval vessel concept design, DSE is synonymous with C&RE, or "requirements elucidation" depending on which side of the Atlantic Ocean the author resides. Brown states: "During C&RE we use a total systems approach, including an efficient search of the design space…" (Brown, 2013: p. 2). Similarly, McDonald *et al*. (McDonald et al., 2012: p. 210) state: "the issue in the initial design of complex ships, such as naval combatants, is that the exploration should be as wide as possible so that all conceivable options are explored and the emergent requirements are "elucidated" from this comprehensive exploration." All the naval vessel MBCD approaches reviewed in Table 1 contained DSE in either a value-driven (C&RE), data-driven (RSM and WSAF), or informal manner, where a range of solution options within the design space were evaluated (SubOA, IPSM and DBB). In the OTS acquisition case, the concept exploration will be constrained to a search of the existing vessel design space.

2.5 MULTI-CRITERIA DECISION MAKING

An evaluation of responses to a request for tender (RFT) to select the most viable design needs to be performed prior to the acquisition stage of an OTS naval vessel acquisition. This evaluation is likely to be a focus of any oversight committee due to the typically large amount of taxpayer money at stake. The evaluation of naval vessel design options is a decision problem where consideration will need to be given to a number of competing objectives (e.g. performance and cost), as well as the views and knowledge of a range of stakeholders (Buede, 2000: p. 360). Multi-Criteria Decision Making (MCDM) is a field of research that has grown since the late 1970s (Mollaghasemi and Pet-Edwards, 1997) to deal with such decision problems. MCDM methods have been developed "to help the decision maker think systematically about complex decision problems and to improve the quality of the resulting decisions" (Mollaghasemi and Pet-Edwards, 1997: p. 3).

MCDM approaches typically fall into two categories: one to address either multiple-objective problems or multiple-attribute problems (Mollaghasemi and Pet-Edwards, 1997: p. 4). Multiple-objective problems are those with a large number of feasible solution alternatives, whereas multiple-attribute problems have relatively fewer solution alternatives (Mollaghasemi and Pet-Edwards, 1997: p. 4). Naval vessel option evaluation during tender evaluation, where the number of alternatives is small and there are a relatively large set of attributes to consider, is an example of a multiple-attribute problem.

Methods of MCDM for multiple-attribute problems include; scoring methods, multi-attribute value analysis (MAV), multi-attribute utility theory (MAUT) and the Analytical Hierarchy Process (AHP) (Mollaghasemi and Pet-Edwards, 1997). The MAV method appears to be the most suitable for naval vessel option evaluation leading up to and during tender evaluation. This is due to there being no need at this stage of the acquisition to incorporate the uncertainty aspects, such as requirements and technology maturity that are included in multi-attribute utility theory. MAV also uses value functions for the evaluation criteria, which are not included in simple scoring methods. These provide a means of representing the relative value of evaluation criteria over a range of values between the minimum acceptable value (threshold) and goal value (objective). Common value function curves for increasing and decreasing value can be found in references such as Buede (2000), which are shown in Figure 2. The need to make pairwise comparisons of attributes in the AHP, make it infeasible for naval vessel evaluation due to the large number of attributes that will be considered. MCDM strongly aligns with guiding principle two for the construction of the methodology to support the early stages of OTS naval vessel acquisitions.

2.6 PATTERN-BASED SYSTEMS ENGINEERING

PBSE has its foundations in the design patterns used by architects and planners in the late 1970s, which were adopted by software engineers in the early 1990s (Pfister et al., 2012: p. 322). Pfister *et al*. describe design patterns as "...a way practitioners can represent invariant knowledge and experience in design" (Pfister et al., 2012: p. 323). Schindel and Peterson (2014) assert that their approach to PBSE, which they call the S*Pattern approach "…includes not only the platform, but all the extended system information (e.g., requirements, risk analysis, design trade-offs & alternatives, decision processes etc.)" (Schindel and Peterson, 2014: p. 5). This means that using PBSE adheres to principle three described in section 2. Architectural design patterns, and design patterns of the associated system information could be reused in subsequent naval vessel acquisitions and reduce the effort required to define the capability.

While none of the naval vessel MBCD methodologies explicitly included PBSE, evidence of patterns in naval vessel design was found. Naval vessel physical architectural patterns included the Expanded Ship Work Breakdown structure (ESWBS) (Cimino and Tellet, 2007). Naval vessel functional architecture patterns were also found, including the work of Andrews (2006), who describes a functional breakdown comprising categories of float, move, fight/operation, and infrastructure. A pattern of naval mission tasks and associated measures of effectiveness is provided in the Universal Naval Task List (UNTL) (CNO, 2007). (However, the utility of the measures provided in the UNTL for naval vessel concept design can be variable as they appear to be more suited to operational testing and evaluation.) Using a design pattern comprising a predetermined list of naval vessel non-functional requirements (NFRs) is suggested by Gabb and Henderson with the statement (Gabb and Henderson, 1995: p. 13):

"All NFRs need to be considered and specified. The use of a comprehensive checklist by Navy would assist in this regard."

It is conceivable that these separate patterns could be amalgamated into a single pattern through the use of an appropriate MBSE metamodel.

3. PROPOSED METHODOLOGY TO SUPPORT EARLY STAGE OTS NAVAL VESSEL ACQUISITIONS

The early stages of naval vessel acquisitions, regardless of whether they are OTS or developmental programs, can be seen as a design activity or process (Finkelstein and Finkelstein, 1983). Finkelstein and Finkelstein (1983: p. 216) state for design in general:

"The design process consists of a sequence of stages starting from the perception of a need and terminating in a final firm description of a particular design configuration. Each stage is itself a design process..."

When considering how to perform early naval vessel design when the OTS constraint has been applied to the solution space, a useful counterpoint is provided by Kroll (2013: p. 180) with:

"Innovative design should be considered a discovery process and not a search over an existing solution space."

Recalling the earlier analogy between the modified-repeat ship design approach and the OTS naval vessel acquisition strategy, it follows from the statement of Kroll above, that early stage design in OTS acquisitions *should* comprise a search of the existing, or parent design space. Using SBD principles, an existing design space that is linked through mission performance measures to the capability needs can be developed. From this, acquisition stakeholders will gain an understanding of the vessel characteristics of OTS, or parent designs that are likely to meet the capability needs of the acquisition project without the need to have detailed parent design data. Exploration of this existing design space allows the acquiring agency to conduct trade-offs and identify the most suitable regions for the capability needs, as well as elucidate a set of RFT requirements and constraints in a 'middle out' SE manner. This is essentially the screening stage of the Kontio et al. (1995) OTSO process shown in Figure 1. Once responses are received for an RFT, the acquiring agency will then need to perform final design activities as well as a design option evaluation to select the preferred tenderer.

Using this reasoning, along with the elements outlined in the previous section that were identified as having alignment with the guiding principles, a methodology to support the early stages of OTS naval vessel acquisitions is proposed in Figure 3 and Figure 4. Figure 3 captures the first part of the methodology for conducting C&RE pre-gate one in the ADO capability lifecycle. Figure 4 captures the design option evaluation stage of the methodology to support tender evaluation between the decision points at gates one and two in the ADO lifecycle.

MBSE underpins the methodology as it facilitates traceability between the military roles of the capability need and early stage acquisition activities. This traceability is shown for the example covered in the next section in Figure 5. The methodology adopts and extends the WSAF MBSE metamodel described in Section 2.1 to include an analysis domain. The inclusion of the analysis domain (shown as a red package in the upper right corner of Figure 5) facilitates the analysis and design activities undertaken when implementing the methodology. It also allows these activities to be managed and design information to be retained within the MBSE model as shown in the model package elements within the analysis domain in Figure 5.

4. TESTING THE METHODOLOGY USING A USCG MEDIUM SECURITY CUTTER (MSC) EXAMPLE

The methodology has been tested by implementing it for an indicative Patrol Vessel capability. The implementation used a descoped CONOPS for a USCG Medium Security Cutter (MSC) (USCG, 2008) found on the internet as its basis. The test implementation was covered in detail in earlier papers by the lead author ((Morris and Thethy, 2015) and (Morris and Cook, 2017), so only key aspects and refinements to the methodology are provided here.

For the test implementation, the hullform was constrained to be of a monohull displacement/semi-displacement type of less than 80 metres in length and the main machinery was assumed to be high-speed marine diesels. The patrol vessel was assumed to be of low-end warfighting capability. While this can be seen to be limiting concept exploration, these constraints are representative of those typically imposed on naval vessel acquisitions in the authors' experience. Such constraints could arise from the need to berth the vessel using existing infrastructure, commonality across fleets and navy doctrine.

4.1 CONCEPT AND REQUIREMENTS EXPLORATION

4.1 (a) Establish Mission Scenarios and KPPs

The first step in the C&RE stage methodology is to define the operational and support mission scenarios. It is vital that these scenarios capture all of the operational needs for the capability to be procured. From the set of mission scenarios, the operational activities and KPPs can be identified using Subject Matter Expert (SME) input, or an appropriate design pattern of naval missions and activities. The KPPs, which are the "minimum number of performance parameters needed to characterise the major drivers of operational performance, supportability and interoperability" (Roedler and Jones, 2005: 11), are also used as the mission performance evaluation criteria during option evaluation.

The MSC CONOPS (USCG, 2008) contained the high-level roles for the vessel and missions it would perform. These missions were entered into the MBSE model and traced to the design pattern of naval operational activities found in the UNTL (CNO, 2007). Within the MBSE model, these operational activities were then decomposed and traced through a ship functional architecture design pattern, to the KPPs. An overview of the MBSE model that shows the mapping from the missions through to the mission performance KPPs for the MSC implementation is given in Figure 5.

4.1 (b) Determine Relationships between KPPs and Design Parameters

Relationships between KPPs and design parameters can be developed using parametric or surrogate modelling. Parametric modelling is a commonly used method in engineering design for making initial estimates of system design parameters such as physical, performance, engineering characteristics, and costs (ISPA, 2008). The estimates are based upon relationships between the design parameters and are typically generated using linear regression or other curve fitting techniques from the historical data of similar systems (Parsons, 2003).

In the case where a sufficient set of historical data is unavailable for developing a parametric model, this can be overcome by running a range of validated simulations of mission performance where the system/sub-system design parameters are systematically varied. Surrogate modelling techniques can then be used to take the results of such a set of simulations across a design space to construct an approximate relationships between design parameters and responses (Mavris and Pinon, 2012). Parametric and surrogate techniques have been utilised previously in a naval vessel concept exploration model by Eames and Drummond (1977), who also discuss constraining concept exploration and using it to identify suitable parent designs (Eames and Drummond, 1977: p. 30):

"The concept exploration model provides a rapid way of exploring all reasonable boundaries of dimensions and hullform … It is comparatively crude, but used with intelligent caution, it can assist the designer to select the most appropriate basis ship…"

Parametric and surrogate models are relatively straightforward to develop compared to high-fidelity physics-based simulations, which makes them suitable for resource constrained acquisition environments. Furthermore, using existing OTS design data as the basis of these models will help ensure the existing design space is feasible, which in turn, should lead to realistic RFT requirements being developed.

For the MSC test implementation, both parametric and surrogate modelling techniques were used to develop relationships between the KPPs identified in the previous step, and ship design parameters. These relationships were provided in Table 4 of Morris and Thethy (2015).

4.1 (c) Develop Simple Numerical Model

In this step, the relationships between KPPs and ship design parameters are built into a numerical model that can be exploited to construct an existing design space for use in subsequent steps. In this test implementation, numerical models were initially built using Excel® (Microsoft, 2010). Subsequently, numerical models of the parametric and surrogate relationships were implemented using *Mathematica*® (Wolfram, 2011), which were wrapped into Phoenix Integration's ModelCenter® (PI, 2014). This approach was taken to enable the analyses to be managed from the MBSE tool, which can also be wrapped into ModelCenter®. As covered in Morris (2014), the addition of an analysis domain into the Whole-of-System Analytical Framework (WSAF) metamodel, facilitates the management and execution of the analysis from within the MBSE tool. The analysis domain containing the executable elements used in the MSC implementation can be seen in the upper right corner of Figure 5.

4.1 (d) Design and Conduct Experiments

This step of the methodology requires consideration of the number of design parameters and how they can be used to develop the ROM design space from the viewpoint of the mission KPPs. When there are more than five variables for an experiment, Schmidt and Launsby (2005) recommend splitting the experiment into two parts: screening and modelling experiments. However, the approach of using parametric and surrogate techniques to build a simple numerical model does not impose a significant computational overhead, which facilitates jumping straight to modelling experiments. There is a need to account for unrealistic combinations of design parameters when conducting the experiment so infeasible regions of the design space are not generated. In the MSC test implementation, unrealistic combinations included:

- High propulsive power with low displacement or length
- Low propulsive power with high displacement or length
- Low displacement with high length/high displacement with low length

A Monte-Carlo design was used for the modelling experiment in the MSC test implementation.

4.1 (e) Build and Explore the ROM Design Space

Using the results from the modelling experiment for the MSC test implementation, the statistical and graphical methods available in the ModelCenter® software, primarily a prediction profiler, were used to build a view of the design space. Hootman (2003) describes a prediction profiler as "not (the) most elegant method of presenting information, but it is one of the most informative ones" (Hootman, 2003: p. 73). A prediction profiler provides a matrix of graphs where the KPPs (responses) are plotted on the vertical axes and the design parameters (inputs) are along the horizontal axes. The slope of the lines in the graphs represents the change in effect the design variable has on the KPP. The prediction profiler developed for the MSC example is presented in Morris and Thethy (2015).

To walk through how the design space can be explored and requirements elucidated for a specific example, the original design space for the endurance time KPP is shown in Figure 6a. Each red point in the design space is a "design" with the combination of ship length and endurance speed (horizontal axes) resulting in an endurance time KPP on the vertical axis. The design space is the result of a 1000 run Monte-Carlo experimental design, with the length ranging from 30-80 meters and the endurance speeds ranging from 8-30 knots. This was the corresponding range of speeds from the existing patrol vessel designs we could find within the Jane's Fighting Ship vessel database (IHS, 2014).

The application of two threshold KPP values for a minimum endurance time and range trims the design space as shown in Figure 6b. In this figure, designs that meet the KPPs are in red whereas those that do not are shown in grey and would not be considered further. From Figure 6b, it can be seen that the smallest length that can meet these threshold values is 45 meters and that there are a larger number of red designs at the higher end of the length scale. This suggests larger vessels are better suited to the capability needs and there is a capability risk associated with the smaller vessels.

On the other hand, if competing KPPs are considered, such as the annual lifecycle cost KPP, for which the constrained design space is shown in Figure 6c, it can be seen that a trade-off between endurance time and the annual lifecycle cost needs to be made. A vessel that can be deployed for longer will need to be larger, which will result in higher sustainment costs. Once all KPPs are considered, stakeholders could use the design space, in combination with their preferences to specify a requirement, such as a minimum length that would help ensure responses to an RFT would be more likely to meet capability needs. Since the KPPs are traceable to the capability needs and the existing design space developed using sound techniques, these requirements will be traceable and defendable. For the MSC example, Concept and Requirements Exploration highlighted that the most suitable designs for the capability needs would be those with a size at or near the upper limit of 80 meters in length.

4.2 OPTION EVALUATION

4.2 (a) Set Evaluation Scope

Once responses to a suitable RFT are received in a naval vessel acquisition (which will occur between gate one and two in the ADO capability lifecycle), an evaluation of the design options provided needs to be performed. When setting the option evaluation scope, Pahl and Beitz note that the evaluation criteria "…must cover the decision relevant requirements and constraints as completely as possible (Pahl and Beitz, 2007: p. 110). The competing objectives of performance, costs, schedule and growth potential will typically be present in naval vessel acquisitions. There may be various strategic factors that have the potential to influence the evaluation as well. The top-level scope of naval vessel option evaluations are likely to include:

- mission performance factors
- economic factors
- schedule and technical risk factors
- non-functional requirements factors
- strategic factors

All these factors were used in the MSC example and their importance weighted in a subsequent step.

4.2 (b) Establish Traceable Evaluation Criteria

For the MSC example, traceable mission performance criteria were established using the KPPs from the first step of the Concept and Requirements Exploration stage of the methodology.

Economic factors capture the cost objectives of the project. The evaluation criteria for economic factors proposed for the USCG MSC evaluation were: acquisition costs and operating costs over the USCG MSC lifecycle. The approach for capturing the traceable technical and schedule risk evaluation criteria can be linked to the risk management activities of the acquisition project.

Evaluation criteria related to non-functional requirements (NFRs) are important for naval vessel acquisitions and as noted by Andrews (2017: p. 72) are "a key hidden decision in the ship's style from the beginning of any ship design study". NFRs have been termed *quality attributes, constraints, goals, or extra functional requirements* (Chung et al., 2000) or "*ilities"* (Mirakhorli and Cleland-Huang, 2013). NFRs relevant to naval vessels could include: reliability, availability, maintainability, logistic supportability, compatibility, interoperability, training, human factors, safety, security and resilience.

In addition, strategic option evaluation factors need to be considered. These can include strategic partnerships and other influencers such as domestic and international politics. Strategic partnerships are likely to wield significant influence on the success (or otherwise) of any major project, however, they are not easy to make traceable! Strategic partnerships can be formed between the acquiring government and other entities including: the designer, the shipbuilder, the in-service support entity, and other navies that operate the same design.

4.2 (c) Determine Evaluation Criteria Value Functions and Weights

The weights and value functions for the evaluation criteria were elicited from Navy and naval architecture SMEs for the MSC test implementation. The threshold and objective values for the evaluation criteria were determined either from the MSC CONOPS, or based on engineering judgement. Weights were derived from the SME rankings of the criteria importance using the Rank Order Centroid (ROC) technique, which has been demonstrated to produce accurate weightings (Buede, 2000: p. 368). SME's selected a value function from the set of eight shown in Figure 2 for each evaluation criteria.

4.2 (d) Estimate Evaluation Criteria Values for Each Design Option

The fourth step in the option evaluation stage of the methodology is to estimate the evaluation criteria value for each option. This can be done using either: designer data from a submitted tender response, M&S, or parametric and surrogate relationships developed for KPPs using curve fitting techniques. For the Medium Security Cutter example, two design options at the upper limit of the size range (which was identified as being the most suitable region of the design space during C&RE), were identified from an internet search and the evaluation criteria values sourced from freely available internet searches. Where values for the design could not be found, they were estimated using engineering judgement or parametric relationships.

4.2 (e) Calculate Overall Value and Compare Options

In evaluating technical products, weighted summation of the evaluation criteria, provided they are reasonably independent, is the usual method of calculating the overall value (Pahl and Beitz, 2007). In the MSC test implementation, the overall weighted value (OWV) for the mission performance factors evaluation criteria (KPPs) was calculated as a weighted summation using a spreadsheet. The spreadsheet was wrapped into a Systems Modelling Language (SysML)-based MBSE model via model integration software. This allowed the evaluation criteria values, ranks and value curve identifiers to be held as value properties in SysML blocks. When executing the evaluation, the value properties were read from the MBSE model and sent to the spreadsheet that calculated the weighted values for each evaluation criteria (column *w.v(KPP)* in Table 2) and the OWV that was subsequently stored back in the model. The mission performance subset of the evaluation is shown in Table 2. From the green highlighted cells in Table 2, it can be seen that design option B had a higher OWV than design option A for the mission performance evaluation criteria shown.

4.2 (f) Estimate Uncertainty and Identify Weak Spots

Since the evaluation criteria values were estimated rather than provided as RFT response data, the level of confidence in the MSC example evaluation is low. However, the values were sufficient for a test implementation of the methodology as it was the methodology, rather than the designs that were under evaluation. To investigate the sensitivity of the OWV to changes in the evaluation criteria rankings, a Design of Experiments study was conducted. The study found the OWV result changed in less than 33% of the experiments due to changes in the criteria rankings.

Weak spots in each design option can be identified by looking for relatively low values of individual evaluation criteria (Pahl and Beitz, 2007). These are particularly important for promising design options that exhibit good overall value. Once identified, these weak spots can be addressed through design changes (Pahl and Beitz, 2007). The yellow highlighted cells in Table 2 indicate the largest differences between the two designs for the mission performance evaluation criteria considered. These highlighted cells indicate there are relative weaknesses of option A for the Endurance Time, Range and Seaboat Average Size KPPs. A weakness of option B relative to design option A is the Crew Accommodation Capacity KPP. If there was scope to change design B to accommodate more crew, this could be a change worth pursuing to increase its overall weighted value for mission performance. It is worth noting that while a design change technically violates the OTS acquisition strategy, changes to OTS designs are commonplace where value or legislative compliance issues need to be considered. It is worth noting any design change will be highly constrained and may impact on other design aspects, the effects of which may not be revealed until the vessel is in service.

5. DISCUSSION

It is worth noting that several of the C&RE methods reviewed for this research included multidisciplinary design analysis and optimisation (MDAO). Due to the OTS constraint, it was assumed there is no need to optimise the design space in order to converge on single point design during the early stages of the lifecycle. Hence, it was not included in the methodology. Furthermore, there is some disagreement on the value of optimisation during the early design stages. Andrews (2006) notes the need to recognise the limitations of optimisation during conceptual design to achieve a creative and divergent approach. Rhodes and Ross also note this challenge with MDAO (and Design Space Exploration), together with a potential conflict between MDAO, Design Space Exploration and system resilience (Rhodes and Ross, 2014: p. 37-38).

The application of Set-Based Design principles in the methodology provides a means of presenting sets of ship design parameters to build an existing design space. This requires less human and computational effort to implement than several of the Concept and Requirements Exploration methodologies referenced in Table 1, which utilise ship architecture models to synthesise multiple single point conceptual designs. The reduction of effort is primarily due to the use of parametric and surrogate models to build the ROM existing design space. Furthermore, there is a large amount of design data available for monohull surface warships and parametric design method has been used in ship concept design since before the use of computers in ship design (Parsons, 2003). Notwithstanding this, there is uncertainty associated with parametric modelling due to inaccuracy in the historical data used in the generation of relationships between design parameters, the correlation between the relationships developed and the historical data points upon which they are based. In the case where curve fitting is used to generate relationships, statistical techniques can be utilised to quantify the level of correlation (Parsons, 2003). Using Set-Based Design principles in the methodology also facilitated the exploration of the design space. During the exploration, trends between the design parameters and KPPs were readily identifiable from the plots. This supports identification of the most suitable combinations of design parameters for the capability needs. The trends also support identification of combinations of design parameters that present capability risk. These aspects suggest SBD is well suited to the conceptual design stage to build knowledge and to inform decisions on combinations of design parameters to take forward into preliminary and detailed design.

5.1 NOVELTY AND CONTRIBUTION

The novelty of the research covered in this paper stems from the incorporation of several different methods into a MBSE based methodology. Through the introduction of the analysis domain into the WSAF metamodel, the research extended the use of MBSE to establish, manage and guide the early stage acquisition, analysis, and tender evaluation activities, whilst maintaining traceability to strategic guidance and requirements. As shown in Figure 5, this extension will allow acquisition project stakeholders to demonstrate the links between capability needs and design activities, thereby building in 'contestability' and SE rigour into the acquisition process. The traceability that has been set up in the methodology also allows for rapid investigation of the impact of requirement changes. Reversing the traceability path allows for an assessment of the impact on requirements of vessel design changes. These contributions should result in better outcomes for naval vessel acquisitions that employ the methodology.

The inclusion of design patterns in the methodology enables reuse of MBSE models and domain knowledge in naval vessel acquisition projects, thereby reducing the level of effort required, provided the original domain knowledge is suitable and accurate. Pre-existing MBSE models could be exploited in subsequent acquisition efforts to rapidly trace through from naval missions to operational activities and their KPPs. Furthermore, reuse of knowledge from previous projects could also inform acquisition stakeholders of previous sources of risks and opportunities during early lifecycle activities (Morris and Cook, 2017). The example implementations performed for this research provides a starting point for building implementation knowledge from the MBSE models that were developed.

6. CONCLUSIONS

This paper covered a body of research undertaken to construct an MBSE methodology to support the early stages of naval vessel acquisitions. These stages of the lifecycle are vital to the success of the project but are difficult and have a history of being poorly performed in Defence acquisitions. The recent proliferation of oversight and contestability functions is evidence of this history and suggests that methods of supporting naval vessel acquisitions are required. Constraining the solution space to OTS naval vessels also presents a challenge to the acquisition community due to the 'middle-out' nature of requirements development. In a similar manner to the modified-repeat design approach, the OTS acquisition strategy is likely to have a higher success rate if the parent OTS vessel is based on a design with similar operational requirements. The methodology proposed in the previous sections seeks to address these challenges by leveraging a range of features from various disciplines. Firstly, a design space linked to the capability needs is developed using set-based design principles, model-based conceptual design, pattern-based systems engineering, and modelling and simulation. Secondly, Concept & Requirements Exploration is used to identify regions within the design space of combinations of design parameters from existing designs that are most likely to have similar performance characteristics to those derived from the OTS acquisition's capability needs. This region can be used to inform the RFT requirements in an OTS naval vessel acquisition in a traceable and defendable manner. Finally, the methodology supports trade-offs and the final design of the OTS design options proposed in RFT responses using a MCDM method.

Testing of the methodology has highlighted that the need to undertake naval vessel design activities, to understand and explore the existing design space, does not diminish when adopting OTS acquisition strategies. These design activities are essential to ensure the requirements released to industry are realistic and that any capability risks associated with the OTS constraint are identified early.

Further work to refine the approach would include fully implementing the methodology for another naval vessel acquisition project in order to gain more stakeholder feedback on its utility and or weaknesses. A final recommendation for further work is to include the development of a 'clean-sheet' concept design option for the capability needs as part of the C&RE process. This could be done using higher fidelity ship architectural or geometry models coupled with M&S tools as in the approaches of Andrews and Pawling (2003) or Dwyer and Morris (2017). Comparing the KPPs and other evaluation factors of the clean-sheet design option to the OTS design options could provide additional information and support to the acquisition stakeholders to determine whether the OTS constraint is likely to be value for money.

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8. COPYRIGHT

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APPENDICES

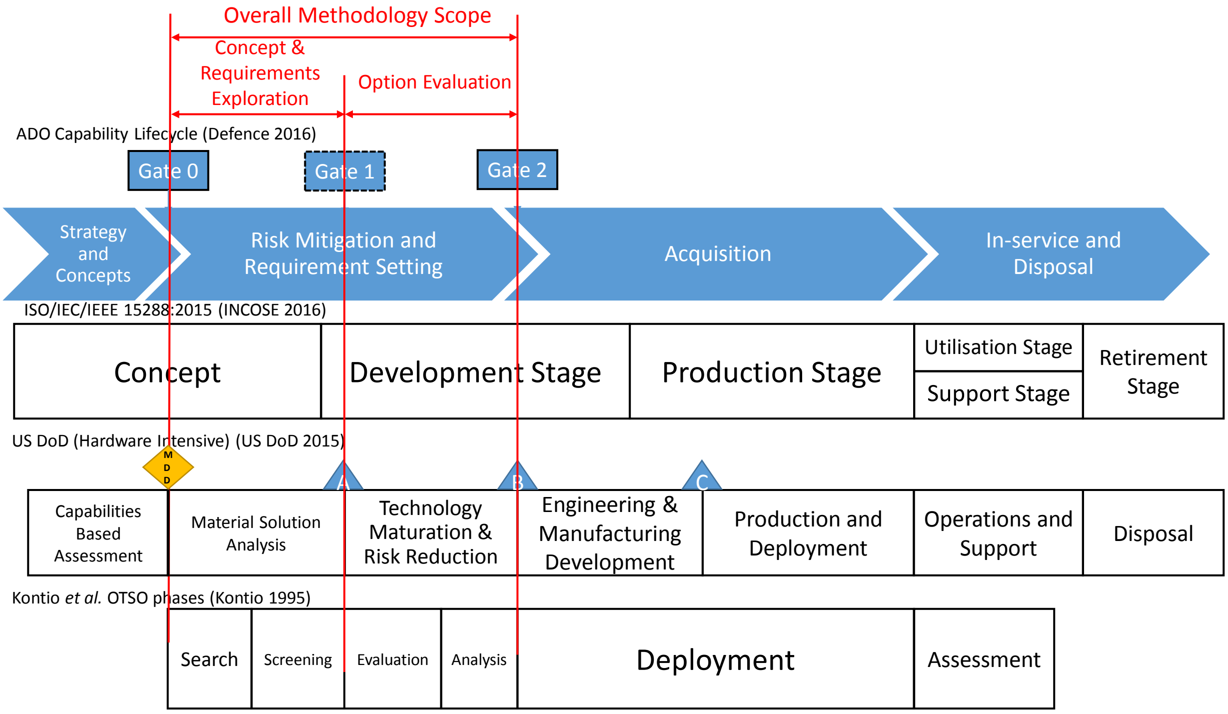


Figure 1: Various system lifecycles and the stages of interest for the research covered in the paper. The methodology constructed as part of the research covers the ADO risk mitigation and requirements setting stage as shown.

Table 1: Summary of naval vessel MBCD methodologies reviewed and the features they include

MBCD Methodology and Key References	MBSE	M&S	DSE	Other	Comments
VT C&RE (Brown and Thomas, 1998), (Kerns et al., 2011a), (Kerns et al., 2011b) and (Brown, 2013)	X	X	X	Also uses Multidisciplinary Design and Analysis.	Uses MBSE to manage ship and mission architecture, Separate ship synthesis, OEMs and MDAO models to analyse effectiveness and optimise. Value model (AHP) used for Overall Measure Of Effectiveness.
OTS C&RE (Morris and Thethy, 2015)	X	X	X	Uses integrated MBSE and M&S.	Uses MBSE for requirements, architecture and parametrics, along with integrated M&S and DSE. OTS Option analysis can be performed during DSE.
RSM Approach (Hootman, 2003) and (Fox, 2011)		X	X		Approaches use separate ship synthesis and OEMs to build concept design space. No explicit link to requirements.
WSAF (Morris, 2014)	X	X	X		MBSE integrated with M&S via parametrics.
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.
DBB (Brown and Thomas, 1998) and (McDonald et al., 2012)		X	X	Uses CAD models	Approach facilitates rapid synthesis of a CAD hullform based on ship functions. Hullform's performance (e.g. seakeeping, resistance and stability) can then be simulated. No integration with MBSE.

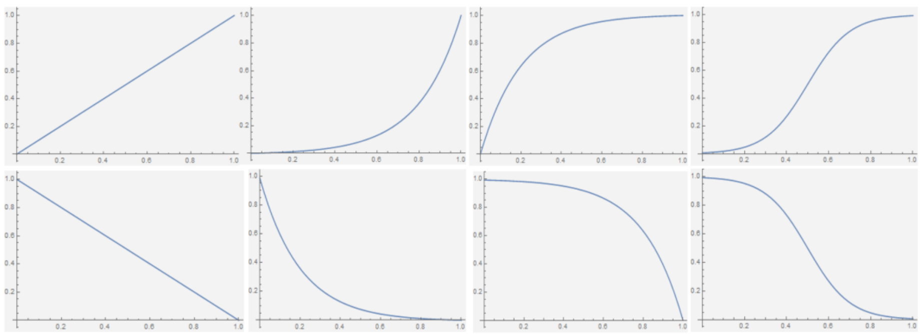


Figure 2: Common value function ($v_i(x_i)$) curves, normalised between threshold and objective values, for increasing utility (top) and decreasing utility (bottom) (Buede, 2000).

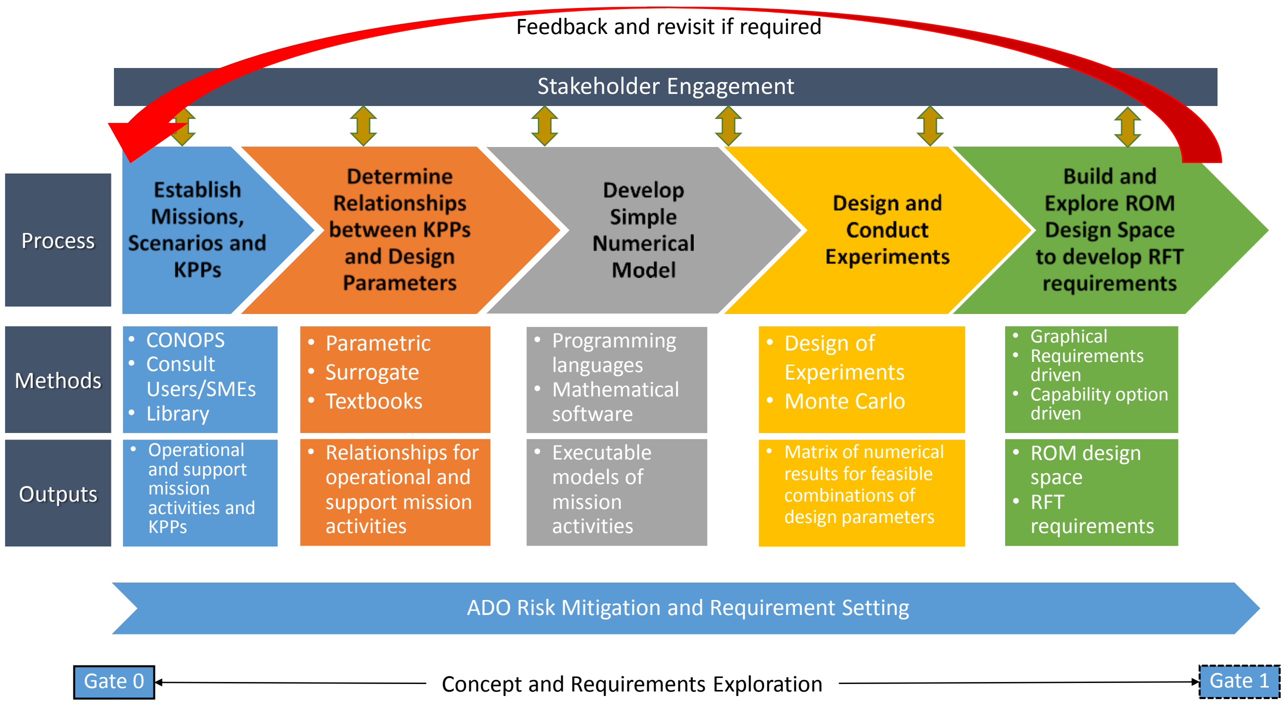


Figure 3: Concept and Requirements Exploration Stage of the methodology supports activities between decision points at Gate 0 and Gate 1 of the ADO capability lifecycle.

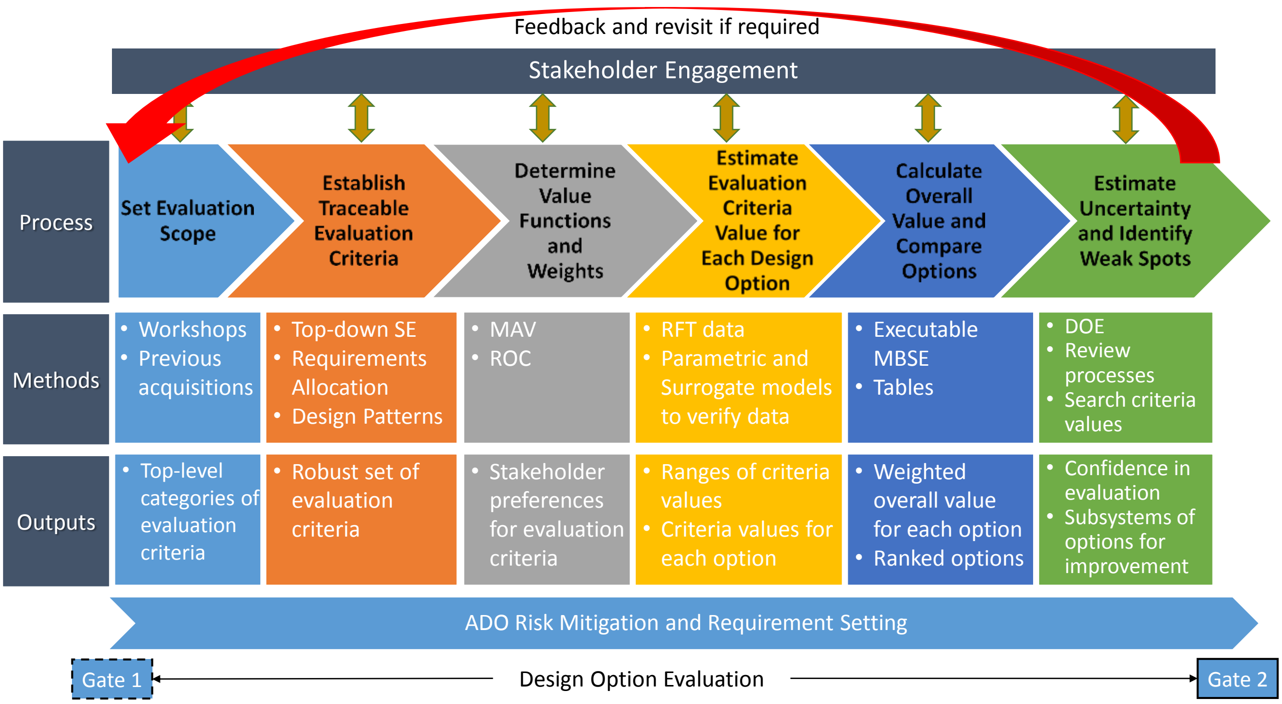


Figure 4: Design Option Evaluation stage of the methodology supports activities between decision points at Gate 1 and Gate 2 in the ADO capability lifecycle.

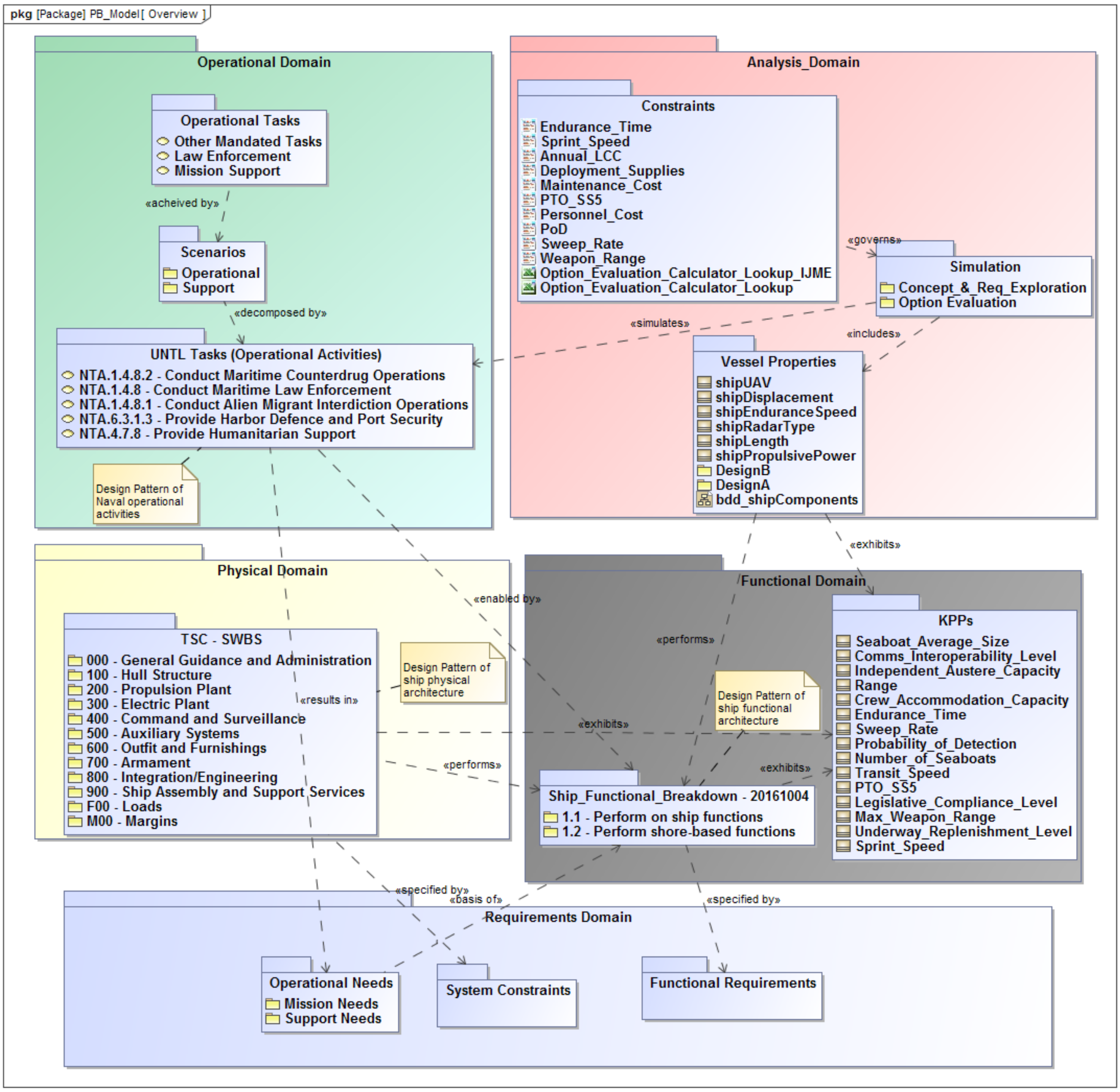
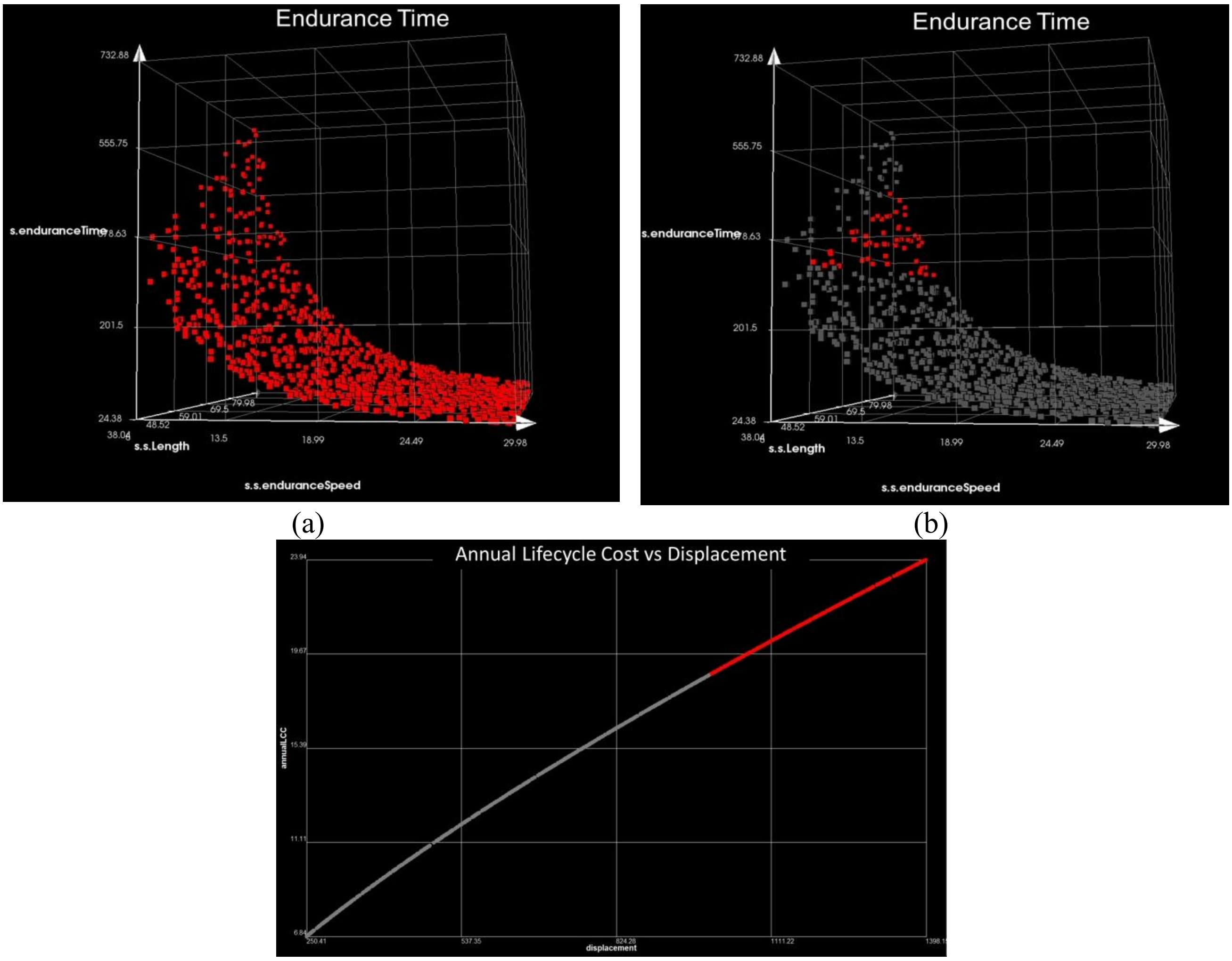


Figure 5: Overview of the MBSE model developed for the USCG MSC implementation. The figure shows the different domains in the extended WSAF metamodel and the relationships between the elements within each of these domains.



(a) (b)

(c)

Figure 6: (a) Design space for the Endurance time KPP before constraining the design space to threshold values, and (b) after constraining the design space to threshold values of endurance time and range, and (c) the constrained design space for the competing annual lifecycle cost KPP. The red design points in (b) and (c) represent combinations of transit speed, ship length and displacement design parameters that will achieve the threshold endurance time and range values based on relationships from existing ship design data.

Table 2: Option evaluation table for mission performance criteria. The largest differences between the two designs indicate the weak spots. The weak spots of option A relative to option B are for the Endurance Time, Range and Seaboat Average Size KPPs. The weak spot of option B relative to option A is the Crew Accommodation Capacity. The higher OWV for option B infers it is the most suitable of the two designs for the evaluation criteria considered.

KPP	**Rank**		**KPP**				**Option A**		**Option B**	
Name		**ROC Weight (*w*)**	**Units**	**Threshold**	**Objective**	**Value Curve ***	**KPP**	***w**v (KPP')* ^+**	**KPP**	***w**v (KPP')* ^+**
Seaboat_ Average_ Size	3	0.0929	Metres	5	11	1	6	0.0155	8	0.0464
Comms_Intero perability_ Level	3	0.0929	Ordinal Scale: 1 - Poor 5 - Excellent	2	5	7	4	0.0781	4	0.0781
Independent_ Austere_ Capacity	15	0.0044	Persons	20	50	1	20	0.0000	30	0.0015
Range	3	0.0929	Nautical Miles	7500	10000	5	7500	0.0000	8600	0.0329
Crew_Accom modation_ Capacity	7	0.0375	Persons	30	55	1	54	0.0360	30	0.0000
Endurance_ Time	1	0.1879	Hours	336	672	7	504	0.0939	672	0.1866
Sweep_Rate	7	0.0375	km^2/hr	100	400	7	350	0.0362	350	0.0362
Number_of_ Seaboats	3	0.0929	Number	1	3	7	2	0.0464	2	0.0464
PTO_SS5	1	0.1879	Percent	50	90	7	80	0.1736	80	0.1736
Probability_ of_ Detection	7	0.0375	Probability	0.3	0.75	7	0.7	0.0367	0.7	0.0367
Transit_ Speed	7	0.0375	Knots	8	12	5	12	0.0375	12	0.0375
Legislative_ Compliance_ Level	13	0.0118	Ordinal Scale: 1 - Poor 5 - Excellent	2	5	5	4	0.0114	4	0.0114
Underway_ Replenishment _Level	13	0.0118	Ordinal Scale: 1 - Poor 5 - Excellent	1	5	1	4	0.0088	4	0.0088
Sprint_Speed	7	0.0375	Knots	20	30	5	20	0.0000	22	0.0238
Max_Weapon_ Range	7	0.0375	Metres	6500	15500	5	13800	0.0371	15500	0.0375
							OWV	**0.6112**	**OWV**	**0.7575**

* Value curves 1, 3, 5 and 7 are the increasing utility value curves in the top row of Figure 2. Value curves 2, 4, 6 and 8 are the decreasing utility value curves in the bottom row of Figure 2.
^ *KPP'* is the normalised value of the KPP over the range between its threshold and objective values.
+ *v(KPP')* is the ordinate of the value function at the normalised KPP abscissa.