A Model-Based Systems Engineering Methodology to Support Early Phase Australian Off-the-Shelf Naval Ship Acquisitions

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Thesis submitted for the degree of
Doctor of Philosophy
Entrepreneurship, Commercialisation and Innovation Centre
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University of Adelaide, Australia
May 2019

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Acronyms

ACCS	Australian Capability Context Scenarios
ADO	Australian Defence Organisation
AHP	Analytical Hierarchy Process
ANAO	Australian National Audit Office
APA	Additional Performance Attribute
APM	Aligned Process Model
ASDL	Aerospace Systems Design Laboratory
ASH	Acquisition System Handbook
ASOM	Acquisition System Operating Model
ASW	Anti-Submarine Warfare
AUSDAF	Australian Defence Architecture Framework
BoM	Bill-of-Materials
C&RE	Concept and Requirements Exploration
C2	Command and Control
CAD	Computer Aided Design
CADMID	Concept, Assessment, Demonstration, Manufacture, In-service, Disposal
CADMIT	Concept, Assessment, Demonstration, Migration, In-service, Termination
CBA	Capability-Based Assessment
CDD	Capability Definition Documents
CDF PD	Chief of the Defence Force Planning Directive
CLC	Capability Life Cycle
CND	Canadian National Defence
CONOPS	Concept of Operations
COTS	Commercial Off-the-Shelf
CPD	Capability Production Document
CRA	Constructive Research Approach
DAF	Defence Architecture Framework
DBB	Design Building Block
DLoD	Defence Lines of Development

DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
DoDI	Department of Defense Instruction
DOE	Design of Experiments
DOTmLPF-P	Doctrine, Organisation, Training, materiel, Leadership, Personnel, Facilities, Policy
DPG	Defence Planning Guidance
DS	Design Science
DSE	Design Space Exploration
ERS	Engineered Resilient Systems
ESWBS	Extended Ship Work Breakdown Structure
FACT	Framework for Assessing Cost and Technology
FIC	Fundamental Input to Capability
FPR	First Principles Review
FPS	Function and Performance Specification
FSM	Future Submarine
GATech	Georgia Institute of Technology
ICD	Initial Capabilities Document
ICLCM	Interim Capability Lifecycle Manual
IJME	International Journal of Maritime Engineering
IMCSE	Interactive Model-Centric Systems Engineering
INCOSE	International Council on Systems Engineering
IPSM	Integrated Platform System Model
IPT	Integrated Project Team
IRPDA	Independent Review Panel for Defence Acquisition
JCIDS	Joint Capabilities Integration and Development System
JEON	Joint Emergent Operational Need
JROC	Joint Requirements Oversight Committee
JUON	Joint Urgent Operational Need
KPP	Key Performance Requirement
KSA	Key System Attribute
M&S	Modelling and Simulation
MAUT	Multi-Attribute Utility Theory

MAV	Multi-Attribute Value Analysis
MBCD	Model-Based Conceptual Design
MB-PLE	Model-Based Product Line Engineering
MBSE	Model-Based Systems Engineering
MCDM	Multi-Criteria Decision Making
MDAO	Multi-Disciplinary Analysis and Optimisation
MDO	Multi-Disciplinary Design Optimisation
MEANS	Middle-out Early-phase Above-the-line Naval Ship
MoD	Ministry of Defence
MODAF	Ministry of Defence Architecture Framework
MOE	Measure of Effectiveness
MOM	Measure of Merit
MOP	Measure of Performance
MSC	Medium Security Cutter
NA	Naval Architecture
OA	Operations Analysis
OCD	Operational Concept Document
ODASD(SE)	Office of the Deputy Assistant Secretary of Defense Systems Engineering
OEM	Operational Effectiveness Model
OPLAN	Operational Plan
OPM	Object Process Methodology
OPV	Offshore Patrol Ship
OTS	Off-the-Shelf
OTSO	Off-the-Shelf Option
OV	Operational View
OVM	Orthogonal Variability Modelling
PBSE	Pattern-Based Systems Engineering
PhD	Doctor of Philosophy
PLE	Product Line Engineering
RFI	Request for Information
RFT	Request for Tender
ROC	Rank Order Centroid

ROM	Rough Order of Magnitude
RSM	Response Surface Method
SBD	Set-Based Design
SE	Systems Engineering
SMEs	Subject Matter Experts
SoS	System-of-Systems
SOSA	System-of-Systems Approach
SRD	System Requirements Document
StT	Strategy-to-Task
SV	System View
SysML	Systems Modelling Language
T&E	Test and Evaluation
TEMP	Test and Evaluation Master Plan
TSA	Total Systems Acquisition
TSE	Tradespace Exploration
TSF	The Strategy Framework
UAS	Unmanned Aerial System
UK	United Kingdom
UML	Unified Modelling Language
UNTL	Universal Naval Task List
US	United States of America
USCG	United States Coast Guard
UTE	Unified Trade-off Environment
V&V	Verification and Validation
WBS	Work Breakdown Structure
WG	Working Group
WMSM	Maritime Security Cutter, Medium
WP	White Paper
WSAF	Whole-of-System Analytical Framework
WSTA	Whole Systems Trade Analysis

Abstract

A significant capability modernisation program and a wide-ranging review of Defence has meant that Australian naval ship acquisitions are now being undertaken with both increasing pace and increasing oversight. This comes at a time when naval ship acquisition has also swung away from the top-down approach of designing a ship to meet unique Australian requirements, to the strong preference to use off-the-shelf (OTS) ship designs from overseas. This situation creates a need for new approaches to support stakeholders with naval ship concept definition and acquisition methodologies (which include methods, tools, techniques, and processes) that can develop robust, defensible business cases for milestone decisions by government. This thesis addresses this important need through the construction of a structured Model-Based Systems Engineering (MBSE) methodology that combines ship design aspects with technical and trade-off analyses to enable evidence-based decision making by Defence and government on the preferred technical solution to a capability need.

The research utilised the Constructive Research Approach to produce an artefact, the Middle-out Early-phase Above-the-line Naval Ship (MEANS) MBSE methodology. The methodology is focused on the Risk Mitigation and Requirements Setting Phase (early conceptual design) in the Australian Defence capability lifecycle as this is the key stage in determining the outcome of an acquisition project. Specifically, the MEANS MBSE methodology supports requirements definition through a concept and requirements exploration approach. This approach facilitates the definition of traceable, defensible requirements based on top-down requirements analysis and design space exploration, combined with a bottom-up market survey of the existing naval ship design space. Furthermore, the MEANS MBSE methodology uses multi-criteria decision making to provide robust evaluation of candidate OTS naval ship design options to select the preferred solution and identify design weaknesses, or relative deficiencies in each design. The MEANS MBSE methodology encourages design to take place in the modelling environment (as opposed to simply recording the design) and supports iterative "what-if" solution option analysis to evaluate proposed design changes.

The research produced a validated, exemplar MBSE methodology, and a body of work on early-stage ship design approaches that together have much to offer Australian

Defence for future ship acquisitions. Specifically, it extended the use of MBSE to establish, manage and guide early stage design and analysis activities, whilst simultaneously maintaining traceability to Defence strategic guidance and capability needs. This extension allows capability development stakeholders to demonstrate the links between strategy, design activities, and requirements definition, thereby making ‘contestability’ and Systems Engineering rigour inherent in the specification of the required naval ship. The novelty of the research arises from the novel synthesis of several proven system design and analysis methods into a bespoke MBSE methodology that provides unique functionality and assistance to ship acquisition stakeholders.

The thesis is presented in a combined conventional narrative and publications format, with the publications upon which the body of the thesis is based included in the appendices.

Directly Relevant Publications Developed During Candidature

Morris, B. and Sterling, G., 2012. “Linking the Defence White Paper to System Architecture Using an Aligned Process Model in Capability Definition.” In *SETE APCOSE 2012*, Brisbane, Australia. (Included in Appendix A).

Morris, B.A., 2014. “Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships.” In *SETE2014* Adelaide. (Included in Appendix B).

Morris, B.A. and Thethy, B.S., 2015. “Towards a Methodology for Naval Capability Concept and Requirements Exploration in an Off-the-Shelf Procurement Environment.” In *Pacific 2015 International Maritime Conference*. 2015: Sydney, Australia. (Included in Appendix C).

Morris, B.A. and Cook, S.C., 2017. “A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms.” In *INCOSE International Symposium*, Vol. 27, No. 1, pp. 688-703. (Included in Appendix D).

Morris, B.A., Cook, S.C., and Cannon, S.M., 2018 “A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions.*”* In *International Journal of Maritime Engineering*, **160** (Part A1 2018): p. 21-40. (Included in Appendix E).

Morris, B.A., Cook, S.C., Cannon, S.M., and Dwyer, D.M., 2018. “An MBSE Methodology to Support Australian Naval Ship Acquisition Projects.” In *15th Annual Acquisition Research Symposium*. Naval Postgraduate School, Monterey, CA. (Included in Appendix F).

Other Relevant Publications Developed During Candidature

Logan, P.W., Morris, B., Harvey, D. and Gordon, L., 2013. “Model-Based Systems Engineering Metamodel: Roadmap for Systems Engineering Process.” In *SETE 2013*, Canberra, Australia.

Morris, B.A., Harvey, D. and Do. Q., 2015. “Survey of Model-Based Conceptual Design Challenges.” In *SETE 2015*, Canberra, Australia.

Morris, B.A., Harvey, D., Robinson, K.P. and Cook, S.C., 2016. “Issues in Conceptual Design and MBSE Successes: Insights from the Model-Based Conceptual Design Surveys.” In *INCOSE International Symposium*, Vol. 26, No. 1, pp. 269-282.

Morris, B.A. and Tait S., 2019. “Progress Report on an Option Evaluation Method for RAN Surface Ship Acquisitions during Risk Mitigation and Requirements Setting.”. (For-Official-Use-Only) Defence Science and Technology Group, Department of Defence (In publication).

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide.

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I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Brett Morris.

Acknowledgements

The research project covered in this thesis was undertaken on a part-time basis over nearly eight years. This has necessitated a great deal of patience and support to be displayed by my supervisors, collaborators, colleagues, family and friends. My academic supervision has been primarily provided by Stephen Cook, who I thank for his interesting discussions, sage advice, and tireless review of my “backwards” writing style. My industry co-supervisor, Stuart Cannon, has been a constant supporter of my work, which I have always appreciated and thank him for. The Australian Defence Science and Technology Group, particularly my Group Leader Andrew Tynan, have provided me with tremendous support throughout the research project.

To my wonderful wife Kylie, thankyou for your constant love and support, as well as the time and space that you gave me to work on this project. I have been a passenger in our lives on many occasions while working on this thing! To my children Lexie and Phoebe, who were not even born when I started out on this journey, thankyou for coming into my life and helping me understand questions much bigger than the research questions posed in this thesis.

As someone who didn’t fully appreciate the value of academic endeavour as a teenager and young adult, I am proud to have undertaken this research project. I hope that it makes a contribution that may one day help the sailors and officers who go to sea in naval ships, to do so in the most suitable ships for the dangerous missions they undertake. Finally, I look forward to *not* having to answer the question “How’s the PhD going?”

Chapter 1: Introduction

1.1 Background

In general terms, system development projects are undertaken to create a specific product, service or result while balancing several competing constraints [1]. These interlinked constraints are: scope, quality, schedule, budget, resources and risks [1: p. 5]. With Defence capability acquisition projects, the result is the delivery of a capability to the nation's armed forces. These projects share the overriding, interlinked constraints of needing to deliver the capability within budget, on schedule, and with the specified performance within the bounds of available resources and an acceptable level of risk.

The latest in a long line of reviews of the Australian Department of Defence (Defence), the First Principles Review (FPR) [2], notes that in the next 10 to 20 years, Defence [2: p. 13]:

> '…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…'

The delivery of this capability modernisation program will be the responsibility of the Defence capability acquisition and sustainment system that has exhibited:

> '…persistence of fundamental problems…from capability planning to acquisition, delivery and finally sustainment' [2: p. 14].

Several recurring themes across recent Defence reviews of areas for improvement were noted in the FPR. Areas of improvement related to Defence acquisition processes include the following [2: p. 92].

- Initial entry of a project into the Defence Capability Plan warrants close attention – indicating specific linkages between national and Defence strategy and the project needs and requirements could be strengthened.

- Lack of independent scrutiny of capability proposals – indicating that historically, proposals have lacked a robust business case justifying their value to Defence. Ideally, they should be developed in a traceable, rigorous manner underpinned by robust methods providing justifiable, defensible evidence to support the proposed acquisition.
- Turnover and critical shortages of skilled capability development staff – indicating acquisition processes should facilitate reuse of the knowledge built from previous projects as well as be easily implemented and consistent in nature, despite staff turnover and shortages.
- Analysis of costs and risks associated with setting requirements that cannot be met by off-the-shelf equipment – suggesting that any capability risks arising from the off-the-shelf (OTS) acquisition strategy need to be identified early in an acquisition project. This could also support a defensible case to undertake a developmental, rather than OTS acquisition.

Turning to naval ship acquisition specifically, an Australian National Audit Office (ANAO) audit of acceptance into service of navy capability [3] noted several aspects that make naval ship acquisitions unique [3: p. 24]:

> ‘In an environment where project durations can extend over many years, it is not uncommon for technological advances to occur and/or operational requirements to change during a project’s course. It is to be expected that reasonable efforts are made to keep pace with those changes, including seeking prior necessary government approvals. It is also reasonable to expect that, from the Systems Engineering (SE) perspective, adherence to properly conducted configuration management processes will enable agreed changes to occur in a controlled manner.’

The ANAO report [3] also notes the need to ‘streamline all key capability definition, acquisition and materiel support processes’ and that this ‘would generally not involve developing new processes, but rather ensuring more efficient, effective and streamlined use of existing processes’ [3: p. 31]. This need is also highlighted by the FPR noting in 2015 ‘the current (Defence) … processes are complicated, slow and inefficient in an environment which requires simplicity, greater agility and timely delivery’ [2: p. 13].

While calling for simpler processes in Defence acquisition, the FPR simultaneously recommends the establishment of an internal contestability function responsible for ‘ensuring the force structure, portfolio of capability assessments and individual projects deliver government policy objectives and the strategic needs as directed by the Government in the White Paper’ [2: p. 25]. This recommendation is consistent with recent developments in defence acquisition in other countries, where previously inconsistent acquisition performance has resulted in increased scrutiny through the establishment of oversight panels. These panels include the Joint Requirements Oversight Committee (JROC) in the United States of America (US) Department of Defense (DoD) and the Independent Review Panel for Defence Acquisition (IRPDA) in Canadian National Defence (CND).

Furthermore, the FPR proposes the adoption of a ‘smart buyer’ model for Defence acquisition, where the smart buyer is one who can ‘accurately define the technical services needed, recognise value during the acquisition of such technical services and evaluate the quality of services ultimately provided’ [2: p. 33].

Following the FPR, Defence released a new acquisition manual, the Interim Capability Lifecycle Manual (ICLCM) [4]. This manual provides a high-level overview of Defence’s new approach to acquisition and states acquisition activities will be driven by factors that include [4: p. 45]:

- ‘capability decisions based on purposeful evidence-based analysis aligned to strategic intent; and
- robust information management that is underpinned by contestability functions, transparent options development and prioritisation activities, decision support and advice to government.’

The historical performance of Australian Defence acquisition projects suggests capability acquisition stakeholders will appreciate support to be ‘smart buyers’. This will become increasingly important over the coming years due to an intensification of capability acquisition activities and increased oversight. Suitable support could be provided through easily implementable approaches that can facilitate knowledge generation, capture and reuse, as well as maintain links to the strategic needs during acquisition projects. In the United States (US), The US Government Accountability Office (GAO) supports this view with: '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' [5: p. 19]. This thesis proposes such an approach for the early phases of the Australian Defence capability lifecycle.

1.2 The Research Problem and Guiding Questions

In the context of the situation described in the previous section, the research problem statement for this Doctor of Philosophy (PhD) research project is:

> *'In the early phases of Australian Defence naval ship acquisition projects, support for traceable, robust capability definition activities is often lacking. Concurrently, these projects are facing shortages of skilled staff.*
>
> *An easily employed methodology needs to be developed that supports knowledge generation, capture and reuse during naval ship acquisitions. The methodology should also support defensible business case development through evidence-based analysis and traceability to the strategic needs.'*

The overall guiding question for the research is: During the early phases of Australian Defence naval ship acquisition, how can stakeholders be supported to develop robust, defensible business cases that result in the acquisition of a naval ship that appropriately addresses the capability need? This gives rise to the following sub-questions:

- *How are the activities between Gate 0 and Gate 2 presently performed? What processes and tools are currently employed to support this class of activity?*
- *What approaches can be used to support the early phases of naval ship acquisitions that can enable and enhance rigour and traceability between strategic objectives and capability development?*
- *How can MBSE-based approaches enhance the current process and what is their utility?*

1.3 Study Focus

The focus of the research undertaken for this thesis is the early phases of Australian OTS naval ship acquisition projects. Naval ships, like all man-made systems have a lifecycle [6], several examples of which are shown in Figure 1. The lifecycle used in Defence at the time of writing is described in the ICLCM [4]. The early phase of interest for this research in the Defence lifecycle is termed the Risk Mitigation and Requirements Setting Phase [4]. This phase ‘involves the development and progression of capability options through the investment approval process leading to a government decision to proceed to acquisition’ [4: p. 28].

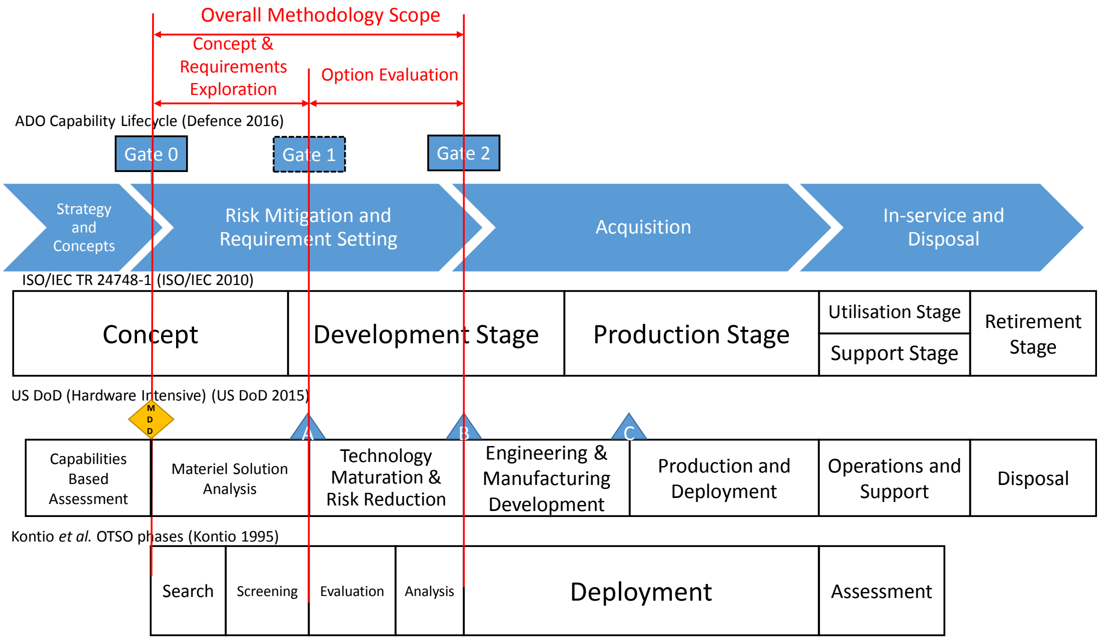

Figure 1: Various system lifecycles and the phases of interest for the research project.

The early phases of Defence acquisitions can also be seen as a design activity [7-10], where the initial activities correspond to concept design as shown in Figure 1. Two key assumptions have been made while conducting the research project. The first assumption is that a naval ship has been identified as the solution to the capability need in the Joint Capability Needs Statement developed during the Defence Strategy and Concepts Phase. The second key assumption is that the Joint Capability Needs Statement is traceable to a capability gap and describes the capability needs in sufficient detail to act as the foundation of the Risk Mitigation and Requirements Setting Phase capability definition activities.

Performing the Risk Mitigation and Requirement Setting Phase well is vital to the success of any system development or acquisition project. The International Council on Systems Engineering (INCOSE) Systems Engineering (SE) Handbook notes: ‘if the work is done properly in the early phases of the lifecycle, it is possible to avoid recalls and rework in later stages’ [6: p. 29]. Yaroker *et al*. note: ‘One of the most influencing factors determining the success and longevity of any developed system is the quality of its underlying conceptual design’ [11: p. 381]. Finally when discussing naval ship design, Andrews [12] 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 research project is focused on developing a methodology supporting ‘above-the-line’, or ‘left-of-contract’ (acquirer) naval ship acquisition stakeholders throughout the Risk Mitigation and Requirements Setting Phase. The key activities acquisition stakeholders need to perform during this phase are **requirements definition**, **requirements setting** and **options refinement**. The research is also focused primarily on the major system (i.e. ship) fundamental input to capability[1]. However, some investigation into methods to supporting acquisition activities to define and set the requirements for the other fundamental inputs to capability is undertaken and covered in the researcher’s publication Morris and Thethy [13], which is summarised in Chapter 6.

An important contextual shaper of the research project is the adoption of OTS strategies for the acquisition of complex defence systems. Naval ships are a prime example of complex defence system where OTS acquisition strategies are now routinely implemented. For naval ship acquisitions, the OTS strategy is perceived as a means of reducing the acquisition cost and schedule risk [14]. The trade-off for 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

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[1] In Australian Defence, capability is deemed to have nine elements that are termed the Fundamental Inputs to Capability (FIC). They are: Organisation, Command and Management, Personnel, Collective Training, Major Systems, Facilities and Training Areas, Supplies, Support, and Industry.

fully suit the local geographic and strategic circumstances [15]. In 2017, Defence released its Naval Shipbuilding Plan [16] that effectively mandated the acquisition of OTS naval ships. The guiding principles of implementing the plan included [16: p. 105]:

- ‘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.’

As noted previously by the researcher, the ‘mature design’ principle ‘…has been interpreted to mean OTS designs’ [17: p. 2].

A Systems Engineering (SE) approach is routinely adopted in Defence acquisition projects. SE has been defined as [18: p. vii]

> ‘…an interdisciplinary approach and means to enable the realisation of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the whole problem…’

Implementing SE processes is a means of reducing acquisition project risks [6: p. 47]. Furthermore, research indicates that project outcomes are highly correlated with the quality of the SE embodied in the project [19]. Given the issues in Defence acquisitions identified above, the research project focuses on leveraging SE by identifying and incorporating suitable SE processes into a Model-Based Systems Engineering (MBSE) methodology. However, the typical SE approach used in Defence acquisitions is ‘top-down’, or requirements driven in nature. The SE approach needs to be adjusted for OTS naval ship acquisitions due to the constraint placed on the solution system by the available OTS solutions [14]. A ‘middle-out’ SE approach that combines top-down tracing from strategy to requirements, with bottom up mapping from OTS naval ship designs through functions to the requirements, could provide a means of enhancing contestability in OTS Defence acquisitions. A ‘middle-out’ SE approach could also help provide an early understanding of any capability risks associated with the performance of OTS ship designs.

1.4 Model-Based Systems Engineering and Model-Based Conceptual Design

The researcher's interest and previous experience in Model-Based Systems Engineering (MBSE) led to the decision to undertake the research with a focus on investigating whether the technology could be used to support OTS naval ship acquisitions. MBSE 'enhances communications among the development team, specification and design quality and reuse of system specification and design artefacts' [20: p. 15]. The focus of the research on the early phases of a system's lifecycle, as shown in Figure 1, also led the author to become involved in the INCOSE Model-Based Conceptual Design (MBCD) Working Group (WG) while undertaking the research project. The MBCD WG initially defined MBCD as '...the application of MBSE to the Exploratory Research and Concept phases of the generic life-cycle defined by INCOSE...' [21: p. 1]. The researcher believes MBCD is broader than this definition and has preferred the description provided by Reichwein *et al.* [22: p. 1] who state that 'Model-based concept design is often used to allow engineers to describe and evaluate various system aspects'. Reichwein *et al.* also highlight the wide range of models that can be used during MBCD, including [22: p. 1]: mathematical models, geometric models, software models, system models, control system models, multi-body system models, requirement models and function models.

To increase understanding of the issues and successes associated with MBCD, as well as taking a snapshot of the state of MBCD practice, the researcher undertook two surveys of MBCD practitioners and conducted a workshop to review the results. The insight gained from these surveys was used to guide the research undertaken during the research project. From the two surveys, it was found that the most prominent benefits of using MBCD were that it provided 'clearer understanding of the problem space' and that MBCD 'helped inform requirements development' [23]. Using MBCD was also useful for 'identifying system dependencies' [23].

The results of the surveys provided evidence that judicious application of MBCD would be beneficial during the early phases of Defence acquisition projects. This reinforced the decision to base the research on MBSE-based approaches to inform and support

Australian Defence OTS naval ship acquisitions. MBCD is covered in more detail in Chapter 3.

1.5 Thesis Summary

This thesis adopts the University of Adelaide Combined Conventional and Publication format[2]. The conventional part of the thesis begins in chapter one with an introduction that situates the research and states the research problem and sub-questions. This is followed by a review of the literature on topics relevant to the research problem in chapters two and three. Chapter four provides a discussion on the identification and selection of a suitable research methodology for the research problem. The body of this thesis (chapters five to eight) comprises contextual statements to situate and summarise the publications the researcher has published during his candidature, as well as some additional information not included in the publications. The publications are included as appendices to the thesis.

The research project uses the Constructive Research Approach (CRA) to construct an MBSE methodology to support above-the-line (i.e. acquirer) stakeholders during the Risk Reduction and Requirements Setting phase in Australian OTS naval ship acquisition projects. The methodology implements a middle-out SE approach and is dubbed the Middle-out Early-phase Above-the-line Naval Ship (MEANS) MBSE methodology. The MEANS MBSE Methodology comprises two main parts. The first part is a model-based approach to Concept and Requirements Exploration (C&RE). This supports capability definition activities between Gate 0 and Gate 1 in the Defence lifecycle. The C&RE informs requirements development by giving stakeholders a view of the existing naval ship design space that is linked to the capability Key Performance Parameters (KPPs). Morris *et al.* [17: p. 2] note:

> ‘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.

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[2] See https://www.adelaide.edu.au/graduatecentre/handbook/07-thesis/03-combination-format-thesis/

> This knowledge of the OTS design space supports the elucidation of a set of feasible and traceable request-for-tender (RFT) requirements.’

The second part of the MEANS MBSE methodology is a model-based approach to option evaluation that supports the selection of a preferred design from those designs shortlisted during C&RE. This part of the methodology focuses on the second part of the Defence Risk Mitigation and Requirements Setting phase, which overlaps with the engineering and manufacturing development stage of the US DoD lifecycle as shown in Figure 1. Morris *et al.* [17: p. 3] note:

> ‘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 an RFT.’

The high-level overview of the overall PhD research is given in Figure 2.

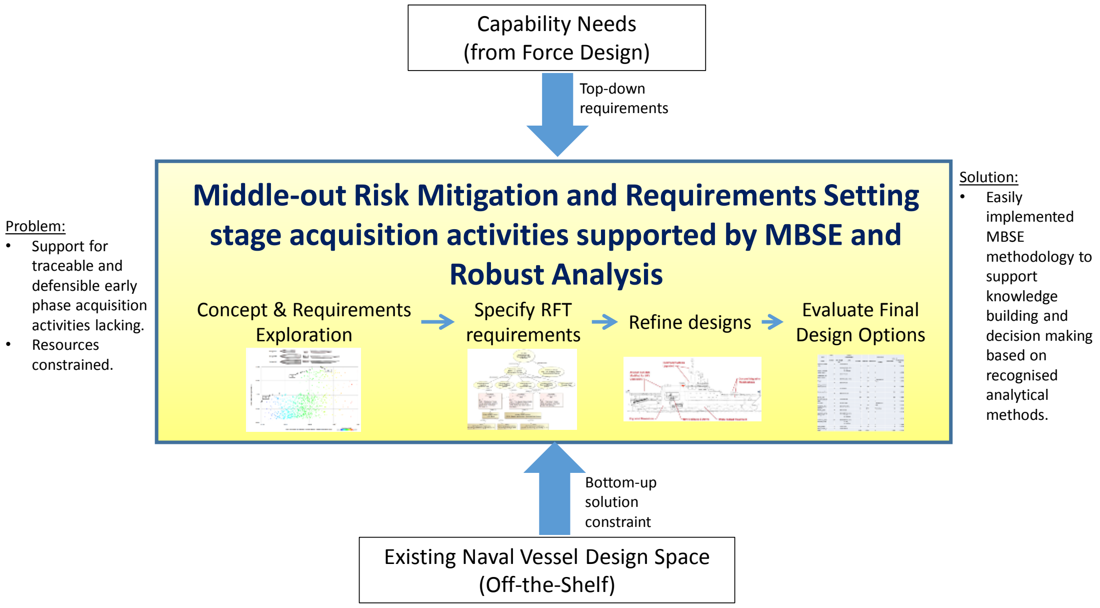


Figure 2: High-level overview of the research covered in the thesis.

The following subsections provide a brief summary of each chapter in the thesis.

1.5.1 Chapter Two - Literature Review 1: Defence Acquisition Manuals and OTS Acquisition

Chapter 2 sets the scene for the research by providing a review of defence acquisition manuals from Australia, the United States of America (US) and the United Kingdom (UK). The review focused on reviewing literature that answers the first research sub-question of the PhD:

> *How are the activities between Gate Zero and Gate Two presently performed? What processes and tools are currently employed to support this class of activity?*

The review finds three key activities within the Risk Mitigation and Requirements Setting phase of the Defence Capability Life Cycle, which are: **requirements definition**, **requirements setting** and **options refinement**. The Defence Interim Capability Life Cycle Manual (ICLCM) [4] only provides high-level guidance on what these activities involve and how they should be performed. This lack of specific guidance, such as processes or methods, compared to the US acquisition, is a recurring theme of the Defence ICLCM [4]. The lack of guidance presents a knowledge gap that is seemingly left up to the project manager to address in each acquisition.

This chapter also covers a brief review of literature covering the OTS acquisition strategy adopted by Defence to gain an understanding of whether the processes and methods from the manuals and standards remain applicable. The review finds the processes, tools and methods given in the acquisition manuals and SE standard remain suitable when an OTS strategy is adopted for an acquisition. However, adjustments should be made in the sequencing of the activities due to the need to understand the constraint an OTS strategy places on the solution space. This means a market survey activity, or an exploration of the existing design space, needs to be performed concurrently with requirements definition activities.

1.5.2 Chapter Three - Literature Review 2: Concept Design and Approaches to Support Early Stage OTS Naval Ship Acquisition

Chapter 3 covers a review of the conceptual design and Model-Based Conceptual Design (MBCD) open literature. It highlights that there is a growing understanding within the Systems Engineering discipline that the process of **requirements definition** should include design activities. This understanding is evidenced by the statement by Crowder, Carbone *et al.* [7]: 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.’

This review was undertaken to identify the features, elements, or approaches that have been used in other domains and those that appear in the academic naval platform acquisition literature. These elements are scrutinised for their utility to support and enhance the early phases of naval ship acquisition projects in Australia in line with the second sub-question for the research project:

> *What approaches can be used to support the early phases of naval ship acquisitions that can enable and enhance rigour and traceability between strategic objectives and capability development?*

In light of the key recurring themes facing Australian Defence capability acquisition projects identified in the First Principles Review [2] and outlined above, three guiding principles were generated to guide selection of the most suitable tools, methods and processes that could be used to construct a methodology to support OTS naval ship acquisitions. The three guiding principles are [17: p. 2]:

1. *Maintain traceability to the original, strategic intent of the ship being acquired - thereby ensuring 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.*

The review identified that the tools and methods that most closely adhered to these principles were MBCD, Set-Based Design (SBD), Modelling and Simulation (M&S), Design Space Exploration (DSE), Multi-Criteria Decision Making (MCDM) and pattern-based methods.

1.5.3 Chapter Four - Identifying a Suitable Research Methodology

Chapter 4 discusses suitable research methodologies for the problem domain being tackled by this research project and culminates in selecting the research approach subsequently employed. The interventionist research paradigm, which includes action research, design science and constructive research, was found to be well suited to this task. (This type of research has also been described as *development* research, since common characteristics of these methods include 'design, constructed artefacts, and/or interventions' [24: p. 240]). The research methodology ultimately selected for the research project is the Constructive Research Approach (CRA). The CRA entails 'building 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' [25: p. 363]. In the case of this research project, the domain specific problem is the research problem outlined in Section 1.2, and the artefact built to solve it is the MEANS MBSE methodology. The CRA comprises the features as translated by Piirainen and Gonzalez [26]:

1. A focus 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.

1.5.4 Chapter Five - Using MBSE to link Strategy to Naval Ship Capability Development

Chapters 5, 6, 7 and 8 comprise the body of the thesis. The body covers the construction of the MEANS MBSE methodology to support Australian OTS naval ship acquisitions that was undertaken to address the third research sub-question:

> *How can MBSE-based approaches enhance the current process and what is their utility?*

Chapter 5 covers the development of the MBSE metamodel that underpins the MEANS MBSE methodology and extracts the key developments presented in the following publications:

- Morris, B. and Sterling, G., 2012. "Linking the Defence White Paper to System Architecture Using an Aligned Process Model in Capability Definition." In *SETE APCOSE 2012,* Brisbane, Australia. [27] (Included in Appendix A).
- Logan, P.W., Morris, B., Harvey, D. and Gordon, L., 2013. "Model-Based Systems Engineering Metamodel: Roadmap for Systems Engineering Process." In *SETE 2013,* Canberra, Australia. [28]
- Morris, B.A., 2014. "Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships." In *SETE2014* Adelaide. [29] (Included in Appendix B).
- Morris, B.A. and Cook, S.C., 2017. "A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms." In *INCOSE International Symposium,* Vol. 27, No. 1, pp. 688-703. [30] (Included in Appendix D).
- Morris, B.A., Cook, S.C., and Cannon, S.M., 2018 "A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions.*"* In *International Journal of Maritime Engineering,* **160** (Part A1 2018): p. 21-40. [17] (Included in Appendix E).
- Morris, B.A., Cook, S.C., Cannon, S.M., and Dwyer, D.M., 2018. "An MBSE Methodology to Support Australian Naval Ship Acquisition Projects." In *15th Annual Acquisition Research Symposium*. Naval Postgraduate School, Monterey, CA [31] (Included in Appendix F).

To use MBSE as the foundation of a methodology that could enhance the current Defence acquisition process, work was required to develop an appropriate underlying metamodel. This work included selecting and extending an existing metamodel that could establish and maintain traceability to Defence strategic guidance and enable analysis activities to be managed and executed from within an MBSE tool. The traceability between strategic guidance, which in Australian Defence is provided in documents such as the Defence White Paper, and the systems acquired to deliver the strategy has been an ongoing issue in the strategic planning space [32].

Suitable metamodels for use in the Defence acquisition process are discussed and from amongst these, the Whole-of-System Analytical Framework (WSAF) was selected as a starting point for metamodel development. This decision, which was made in 2011, was based primarily on the WSAF's growing use in Australian Defence acquisition projects at the time. Subsequently, use of the WSAF in Australian Defence has increased, so the decision made in 2011 has proven to be astute.

For the research project, the WSAF was extended to cater for the inclusion of strategic guidance elements in an MBSE model. This inclusion makes explicit the traceability of the requirements, functional architecture and operational domain elements to the Defence strategic guidance documents. The extension was termed the Aligned Process Model (APM), since it aligned the Strategy-to-Task (StT) technique given by Thaler [33] with the frameworks for Australian Defence system development [27]. The key framework for capability planning in Defence at the time, The Strategy Framework 2010 [34], mirrored the StT technique as it discussed 'identifying "ends" and the "ways" and "means" to achieve them' [27]. The Strategy Framework's strategic planning approach for operations was used in the APM, as the steps could be implemented using a scenario-based needs elicitation approach. Later iterations of the MEANS MBSE methodology used capability needs derived by other means, however, the metamodel remained consistent with the one developed as part of the APM research.

The extended WSAF metamodel was implemented to develop a traceable set of operational needs and constraints for an Australian naval ship's organic Unmanned Aerial System (UAS). This implementation demonstrated the extended WSAF metamodel's usefulness for developing operational needs that are traceable to strategic guidance. The MBSE modelling facilitated the identification of operational activities and needs that were repeated across the scenarios [27]. The MBSE model view that showed the traceability from the Defence White Paper through to the operational needs was described as the 'money shot' by one of the Subject Matter Experts (SMEs) as it provided a defensible case for the operational needs. This research was presented in a refereed conference paper with the researcher as the lead author [27] (provided in Appendix A) for which the reviewer feedback included:

- "This paper provides a useful description of the application of a model-based methodology to the traceability of system requirements back to strategic guidance, as well as an example of how requirements might be elicited using a model-based methodology."

At the same time as the APM research was being performed, ‘engineers in the (Australian) Capability Development Group were developing a similarly structured method, albeit paper-based, to make explicit the traceability of high-level capability requirements’ [28: p. 5]. The researcher became involved in amalgamating the methods and during the effort, it became apparent to the team that a well-structured metamodel provided a means to structure not only the MBSE model, but also the analytical activities needed to develop the contents of the model [28]. The team termed these aspects the analysis and outcome threads within the metamodel. The analysis thread comprised the metamodel elements that represent the analytical activities such as stakeholder requirements definition and requirements analysis [28]. The outcome thread comprised the elements that capture the outcomes of these activities such as operational requirements and system functions [28]. These insights were important for the construction of the MEANS MBSE methodology, as they were used to build the methodology process into the MBSE metamodel. This research was presented in a refereed conference paper with the researcher as a co-author [28] for which the reviewer feedback included:

- “The paper presents an interesting topic on MBSE practice, extending traceability “far-left” from system requirements all the way to Government strategic objectives. The paper will be of great interest to the SETE defence audience.”

In subsequent research, the WSAF metamodel was extended further through the inclusion of an analysis domain. The analysis domain was incorporated into the WSAF metamodel to enable the concept and requirements exploration and option evaluation activities to be executed from within an MBSE model. The analysis domain elements are used to manage design data, execute analysis and store the results of analysis within an MBSE model. The structure of the analysis domain elements was refined over three iterations spanning the research project. The key outcome from the research to develop the MBSE metamodel is that the naval ship requirements specified when implementing the MEANS MBSE methodology can be traced to strategic guidance in an MBSE model via a “golden thread”.

1.5.5 Chapter Six - MEANS MBSE Methodology Part 1: Concept and Requirements Exploration

Chapter 6 covers the Australian Defence Risk Mitigation and Requirements Setting Phase between Gate 0 and Gate 1 as shown in Figure 1. The publications upon which chapter 6 is based are:

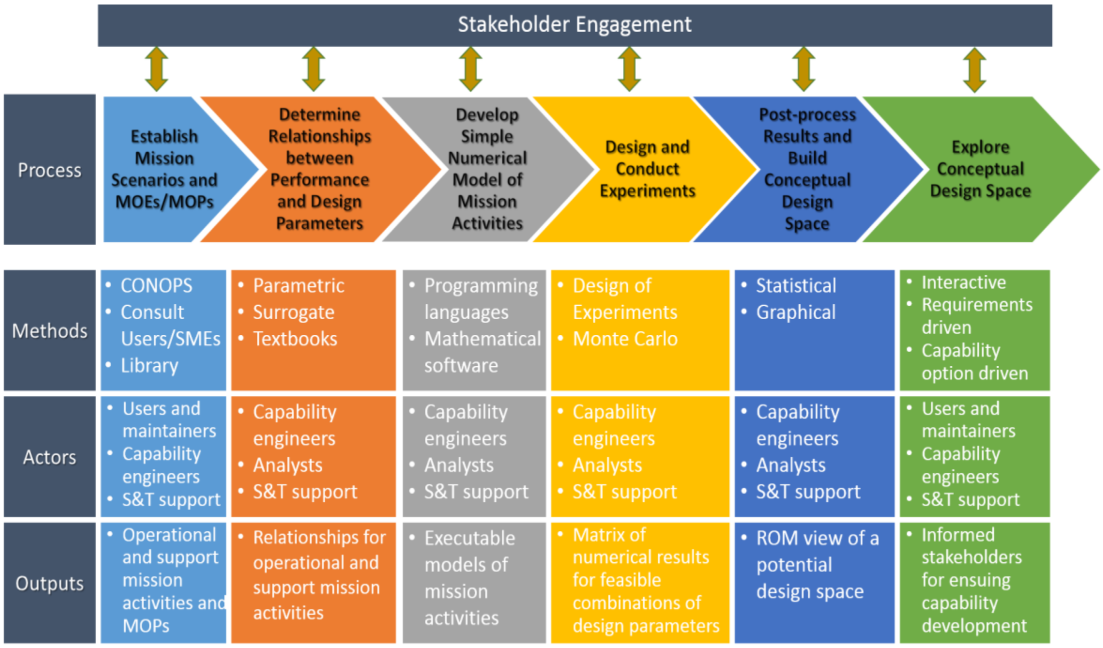
- Morris, B.A., 2014. "Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships." In *SETE2014* Adelaide. [29] (Included in Appendix B).
- Morris, B.A. and Thethy, B.S., 2015. "Towards a Methodology for Naval Capability Concept and Requirements Exploration in an Off-the-Shelf Procurement Environment." In *Pacific 2015 International Maritime Conference*. 2015: Sydney, Australia. [13] (Included in Appendix C)
- Morris, B.A., Cook, S.C., and Cannon, S.M., 2018 "A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions.*"* In *International Journal of Maritime Engineering*, **160** (Part A1 2018): p. 21-40. [17] (Included in Appendix E).
- Morris, B.A., Cook, S.C., Cannon, S.M., and Dwyer, D.M., 2018. "An MBSE Methodology to Support Australian Naval Ship Acquisition Projects." In *15th Annual Acquisition Research Symposium*. Naval Postgraduate School, Monterey, CA [31] (Included in Appendix F).

This first part of the MEANS MBSE methodology is a model-based approach to Design Space Exploration (DSE). In naval ship conceptual design DSE during conceptual design has been termed Concept and Requirements Exploration (C&RE) [13]. The first iteration of the C&RE part of the MEANS MBSE methodology used parametric and surrogate modelling techniques to build Rough Order of Magnitude (ROM) views of an existing ship design space. This ship design space linked ship design parameters to Measures of Performance (MOPs) to give stakeholders an understanding of relationships between combinations of ship design parameters and mission performance attributes. The MOPs were decomposed from capability needs. Executable SysML parametric diagrams were used to conduct and manage the building of the design space from within an MBSE tool. Set-Based Design (SBD) principles were used as a foundation of the methodology constructed in the research as: ‘it provides a means of presenting sets of ship design parameters to build a conceptual design space, rather than a single point conceptual design’ [29: p. 4].

Providing stakeholders with a view of the existing naval ship design space that is linked to appropriate MOPs and Key Performance Parameters (KPPs) enabled trimming of the design space to the region of designs likely to best meet the capability needs. With knowledge of the combinations of design parameters most suited to the KPPs, naval ship acquisition stakeholders can drive the definition of an OTS design by setting requirements accordingly. To generate the design space, Design of Experiments was employed and screening and Monte Carlo experiments conducted. The first iteration included a test implementation for an indicative Anti-Submarine Warfare (ASW) naval ship capability. The work was recorded in a refereed conference paper [29], and is provided in Appendix B. Feedback at the conference was positive, and a suggestion was made to apply the C&RE part of the methodology to an unclassified, or previous naval ship acquisition project. Reviewer feedback included:

- “I like the paper as it is informative and the methodology is sound. It is an easy read and presents how to combine OA, MBSE and conceptual design of naval ships in a logical and straightforward way.”

The first iteration of development of the MEANS MBSE methodology surfaced some issues: lengthy runtimes to execute the simulations from within the MBSE tool, difficulties with the pre- and post-processing of the experiments, and lack of feasibility checks on the combinations of design parameters generated during the experiments. To resolve these issues, the second iteration of development of the C&RE part of the MEANS MBSE methodology utilised a different set of software tools. The software tools used in the second iteration of the research also enabled more readable presentation of the generated results. The second iteration of the C&RE part of the MEANS MBSE methodology also used support scenarios to identify MOPs for the non-materiel components of capability such as personnel, finance and logistics. The second iteration of the C&RE stage of the MEANS MBSE methodology is summarised in Figure 3.



Process	Establish Mission Scenarios and MOEs/MOPs	Determine Relationships between Performance and Design Parameters	Develop Simple Numerical Model of Mission Activities	Design and Conduct Experiments	Post-process Results and Build Conceptual Design Space	Explore Conceptual Design Space
Methods	• CONOPS • Consult Users/SMEs • Library	• Parametric • Surrogate • Textbooks	• Programming languages • Mathematical software	• Design of Experiments • Monte Carlo	• Statistical • Graphical	• Interactive • Requirements driven • Capability option driven
Actors	• Users and maintainers • Capability engineers • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Users and maintainers • Capability engineers • S&T support
Outputs	• Operational and support mission activities and MOPs	• Relationships for operational and support mission activities	• Executable models of mission activities	• Matrix of numerical results for feasible combinations of design parameters	• ROM view of a potential design space	• Informed stakeholders for ensuring capability development

Figure 3: Summary of the second iteration of the C&RE stage of the MEANS MBSE methodology [13].

The second iteration included a test implementation of the MEANS MBSE methodology for an indicative Maritime Security Cutter, Medium (WMSM) capability and was found to be useful for supporting OTS naval ship acquisitions, as the C&RE provided valuable information to stakeholders when making trade-off decisions [13]. The C&RE approach also facilitated the identification of capability risks due to the OTS constraint and could be used to investigate designer performance claims [13]. The second iteration was also delivered as a refereed conference paper [13] (provided in Appendix C) with positive feedback received from the audience. Reviewer feedback included:

- “Paper is directly relevant to the conference audience on a subject of importance.”

The key outcome from the research to construct the C&RE part of the MEANS MBSE methodology is that the requirements defined using the approach will be underpinned by robust analysis and reflective of the ships available in the OTS marketplace. Furthermore, this part of the MEANS MBSE methodology facilitates the identification of capability risks associated with OTS ship designs.

1.5.6 Chapter Seven - MEANS MBSE Methodology Part 2: Off-the-Shelf Naval Ship Option Evaluation

Chapter 7 covers the Risk Mitigation and Requirements Setting phase between Gate 1 and Gate 2 as shown in Figure 1. The chapter provides a brief introduction to the researcher's publications:

- Morris, B.A. and Cook, S.C., 2017. "A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms." In *INCOSE International Symposium*, Vol. 27, No. 1, pp. 688-703. [30] (Included in Appendix D)
- Morris, B.A. and Tait S., 2018. *Progress Report on an Option Evaluation Method for RAN Surface Ship Acquisitions during Risk Mitigation and Requirements Setting.* (FOUO) Defence Science and Technology Group, Department of Defence (In publication). [35]

These publications cover the construction of the OTS ship design option evaluation component of the MEANS MBSE methodology to support OTS naval ship acquisitions. This part of the methodology supports the **options refinement** activities undertaken by above-the-line stakeholders. It also supports the selection of a preferred design from either those designs shortlisted during C&RE, or those received from designers in response to a Request for Tender (RFT).

Three key techniques were incorporated into the model-based OTS naval ship design option evaluation method: MBSE, Multi-Criteria Decision Making (MCDM) and Pattern-Based Systems Engineering (PBSE) [30]. The model-based design option evaluation method part of the MEANS MBSE methodology facilitates the development of traceable evaluation criteria, as well as providing for a range of evaluation criteria categories. A summary of the model-based option evaluation stage is provided in Figure 4.

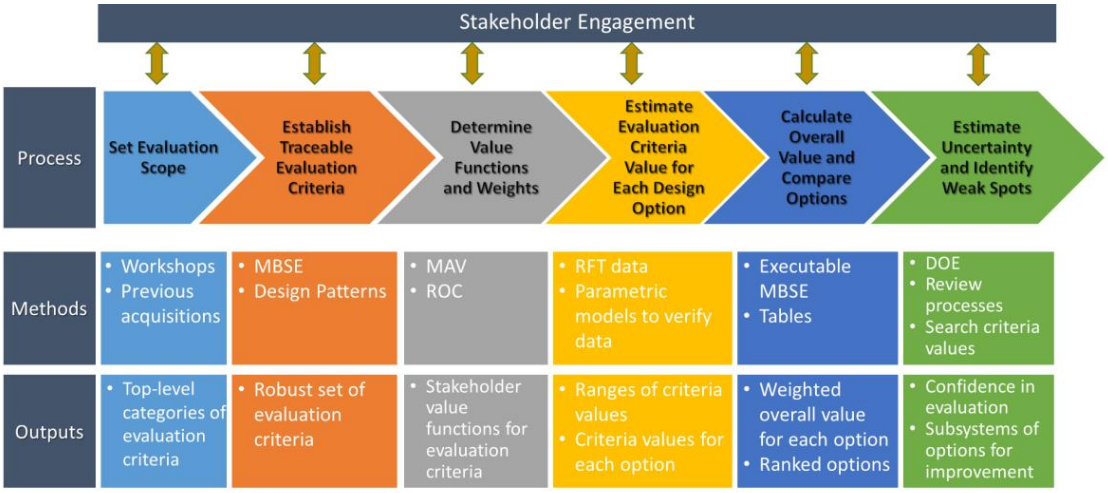


Figure 4: Summary of the design option evaluation stage of the MEANS MBSE methodology [30].

The OTS design option evaluation part of the methodology was tested and found to be useful ‘as a means of managing the evaluation criteria traceability, maintaining design data and identifying weak spots in OTS design options’ [30: p. 14]. Weak spots in an OTS design are identified by below average values for a particular evaluation criterion [36: p. 123]. Being able to identify any weak spots in an OTS design and quantify their impact is a useful feature of this part of the MEANS MBSE methodology. This is particularly true for the mission performance evaluation criteria, which are the KPPs. The MBSE model built while implementing the MEANS MBSE methodology allows the traceability from the KPPs back to the capability needs to be clearly communicated. Therefore, the impact of a weak spot in an OTS design option’s mission performance evaluation criteria on the capability can be demonstrated. Nonetheless, while technically violating the OTS acquisition strategy, design changes can be made to an OTS ship design option relatively easily at this stage of the lifecycle in order to lessen the impact of any deficiencies inherent in a design.

A refereed conference paper covering the construction of the design option evaluation stage of the methodology was presented to the INCOSE 2017 International Symposium (provided in Appendix E) and received reviewer feedback that included:

- “Nice example of leveraging MBSE to drive robust SE execution.”
- “This topic is completely in line with the direction Systems Engineering is heading and presents a contemporary approach to making decisions by reuse of data and models in a more integrated and traceable environment. This is the type

> of work, paper and talk that the community needs to be exposed to. It will help to push the state of practice forward.”

The refereed conference paper [30] also continued the test implementation that used an unclassified Concept of Operations for a United States Coast Guard Medium Security Cutter to test the model-based option evaluation method.

1.5.7 Chapter Eight - Bringing it all Together: The MEANS MBSE Methodology to Support Early Phase Australian Off-the-Shelf Naval Ship Acquisitions

Chapter 8 combines the research and lessons learned from chapters five, six and seven into the overall MEANS MBSE methodology that covers the Defence Risk Mitigation and Requirements Setting Phase. The chapter is based on the publications:

- Morris, B.A., Cook, S.C., and Cannon, S.M., 2018 “A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions.*”* In *International Journal of Maritime Engineering*, **160** (Part A1 2018): p. 21-40. [17] (Included in Appendix E).
- Morris, B.A., Cook, S.C., Cannon, S.M., and Dwyer, D.M., 2018. “An MBSE Methodology to Support Australian Naval Ship Acquisition Projects.” In *15th Annual Acquisition Research Symposium*. Naval Postgraduate School, Monterey, CA. [31] (Included in Appendix F).

This chapter covers the final updates to the MEANS MBSE methodology and provides a worked example of the overall MEANS MBSE methodology. A final iteration of development of the C&RE approach was completed at the end of the researcher’s candidature. This research was presented at the US Naval Postgraduate School’s 15th Annual Acquisition Research Symposium and published in [31] (provided in Appendix F). This iteration again used the model integration software above, combined with a new ship performance M&S framework co-developed by the researcher, which leverages higher fidelity naval architecture simulation tools [37]. The final iteration of the C&RE approach is summarised in Figure 5.

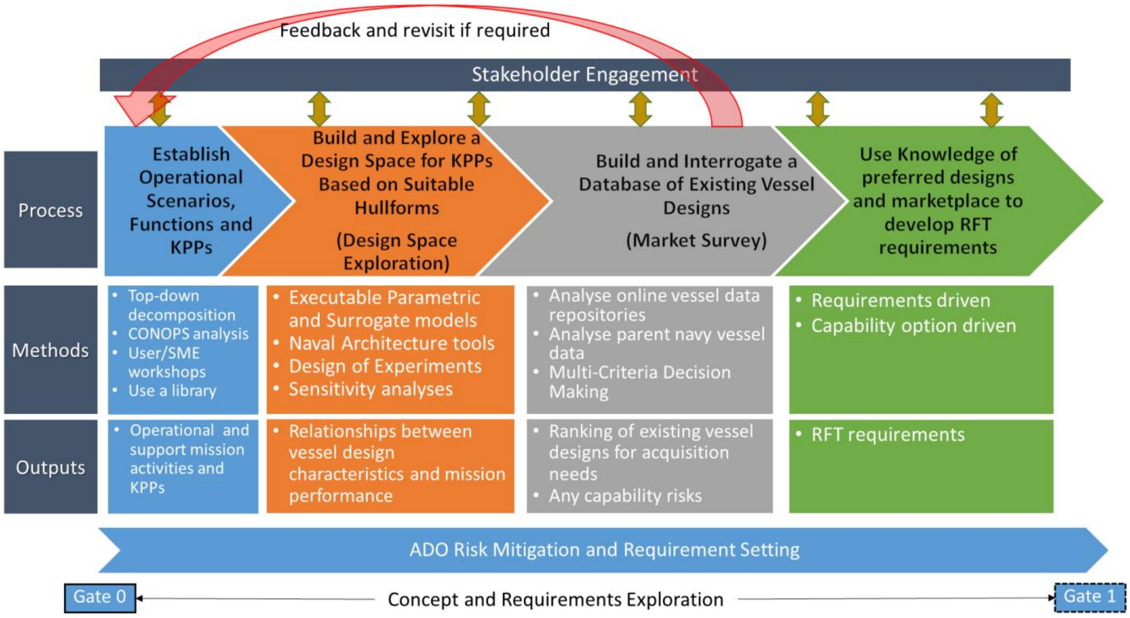
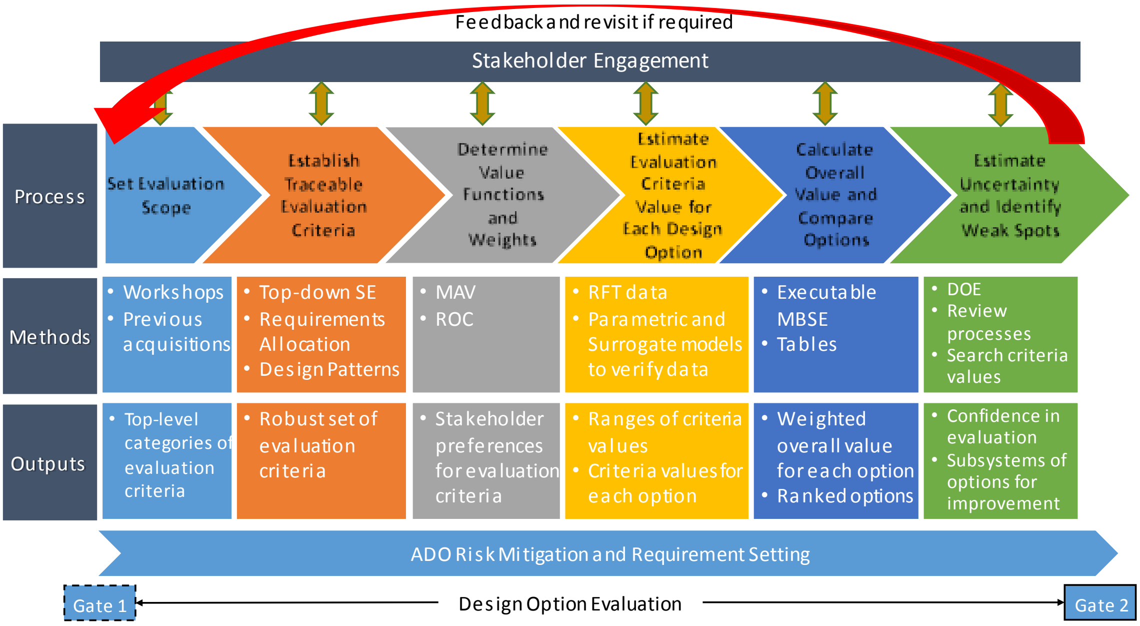


Figure 5: Final iteration of the C&RE approach [31].

A key refinement in this iteration of the C&RE approach’s development was the introduction of an explicit market survey activity as the third step in the process (shown in the grey elements in Figure 5).

The option evaluation part of the methodology was also updated to include a feedback mechanism to account for the evolution of OTS designs as final design changes are made between Gate 1 and Gate 2 in the Defence lifecycle. A summary of the updated methodology for the option evaluation stage is shown in Figure 6.



Process	Set Evaluation Scope	Establish Traceable Evaluation Criteria	Determine Value Functions and Weights	Estimate Evaluation Criteria Value for Each Design Option	Calculate Overall Value and Compare Options	Estimate Uncertainty and Identify Weak Spots
Methods	• Workshops • Previous acquisitions	• Top-down SE • Requirements Allocation • Design Patterns	• MAV • ROC	• RFT data • Parametric and Surrogate models to verify data	• Executable MBSE • Tables	• DOE • Review processes • Search criteria values
Outputs	• Top-level categories of evaluation criteria	• Robust set of evaluation criteria	• Stakeholder preferences for evaluation criteria	• Ranges of criteria values • Criteria values for each option	• Weighted overall value for each option • Ranked options	• Confidence in evaluation • Subsystems of options for improvement

Figure 6: Summary of the final MBSE methodology for the Option Evaluation stage.

During this late stage of the research, the author also crystallised the view that many activities performed while implementing the methodology were design activities. This highlighted the somewhat counterintuitive importance of design in the early phases of OTS naval ship acquisitions due to the need for the acquirer to be informed of the most suitable region of the design space for the capability needs. Being an informed acquirer will allow the development of a specification for a Request for Tender that constrains responses to designs from within the suitable region of the design space [17]. The need to build knowledge of the OTS design space was reinforced to the researcher over the course of the research project and is highlighted in the journal paper that is part of the basis of this chapter (provided in Appendix E) with [17: p. 2]:

> ‘The OTS acquisition strategy for naval ships appears to be analogous to the ‘repeat’, or ‘modified-repeat’ naval ship design approach, since they both rely on adopting 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 [38]. This is similar to many OTS naval ship 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 ship capability acquisition

> programs (Saunders [14] and Keane Jr and Tibbitts [38]). 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 [39]. Furthermore, to maximise the potential of these approaches the existing ship design will ideally still be in production, since evolving legislative requirements can necessitate significant design changes for older parent ships [39]. Hence, to realise the benefits of lower acquisition cost and schedule risks in OTS naval ship 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 ship 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.'

Chapter 8 also provides a walk-through of an example implementation of the methodology. The example uses an unclassified United States Coast Guard Medium Security Cutter Concept of Operations and demonstrates how each step of the methodology process can be performed.

The thesis is concluded in chapter nine with a discussion on the novelty and contribution of the research, as well as topics for future work. The appendices contain copies of the (unclassified) publications upon which that the thesis is built.

1.6 Contribution to Knowledge

Overall, the research provides an exemplar MBSE methodology and a body of work on how early stage ship design activities could be more broadly adopted and embedded into Australian Defence OTS naval ship acquisition. The MEANS MBSE methodology also provides an approach to conducting middle-out SE in a model-based manner that supports and enhances traceability between strategy and materiel.

The research to construct the MEANS MBSE methodology identified the unique nature of OTS naval ship acquisitions. It extended the use of MBSE to establish, manage and guide early stage design and analysis activities, whilst simultaneously maintaining traceability to strategic guidance and capability needs. This extension will allow capability development stakeholders to demonstrate the links between strategy, design activities and requirements definition, thereby building in ‘contestability’ and SE rigour to the specification of the required naval ship. The novelty of the research arises from the bespoke synthesis of several different proven methods for robust systems development into a MBSE based methodology. Constructing the methodology upon an MBSE foundation provides advantages over traditional SE approaches including enhanced communication, clearer understanding of the problem space and system dependencies [20], [23]. The traceability that has been set up in the methodology also allows for rapid investigation of the impact on requirement changes. Reversing the traceability path allows for an assessment of the impact on requirements, of ship design changes. These contributions should result in better outcomes for naval ship acquisitions that implement the methodology.

Including design patterns in the methodology enables reuse of MBSE models and domain knowledge in subsequent naval ship acquisition projects. This will reduce the level of effort and resources required to conduct acquirer acquisition activities. The MBSE models could be exploited in subsequent acquisition efforts to rapidly trace through from naval missions to operational activities and their MOPs and KPPs, provided of course that the KPPs remain suitable. The MBSE models essentially become a pattern of design patterns. Furthermore, reuse of knowledge from previous projects could also inform acquisition stakeholders of previous sources of risks and opportunities during early lifecycle activities [30]. The test implementations performed for this research (the United States Coast Guard Maritime Security Cutter example (covered in [13, 17, 30]), an Anti-Submarine Warfare Ship implementation (covered in [29]) and a Hydrographic Survey capability (covered in [31])) provide a starting point for knowledge building from the MBSE models that were developed.

A final key contribution from the research is that the MEANS MBSE methodology is relatively easy to implement when compared to similar methods that have been developed. The methodology utilises off-the-shelf software tools and has the ability to use multi-fidelity models to build the OTS design space for C&RE thus greatly reducing the level of effort required compared to developing complex, bespoke mission simulation tools. These aspects, particularly when combined with the reuse aspects associated with pattern-based methods outlined above, make the MBSE methodology ideally suited to acquisition environments with constrained resources.

1.7 Chapter One Summary

This chapter introduces the research project. The research problem, research questions and guiding principles used in the research are stated, and this is followed by a brief overview of the selection of the Constructive Research Approach as the research methodology. The chapter concludes with a summary of the thesis and an outline of the publications upon which this combined conventional and publications thesis is based. Finally, the novelty and contributions to knowledge arising from the research are stated.

Chapter 2: Literature Review 1: Defence Acquisition Manuals and Off-the-Shelf Acquisition

2.1 Introduction

This chapter provides a literature review of acquisition manuals and standards relevant to the first research sub-question that was given in Section 1.2:

- *How are the activities between Gate 0 and Gate 2 presently performed? What processes and tools are currently employed to support this class of activity?*

The lifecycle phase that spans the activities between Gate 0 and Gate 2 in the Australian Defence lifecycle is the Risk Mitigation and Requirements Setting Phase. This phase ‘involves the development and progression of capability options through the investment approval process leading to a government decision to proceed to acquisition’ [4: p. 26]. The approximate alignment of the Defence Risk Mitigation and Requirements Setting Phase with the equivalent phases of several other system lifecycles is shown in Figure 7.

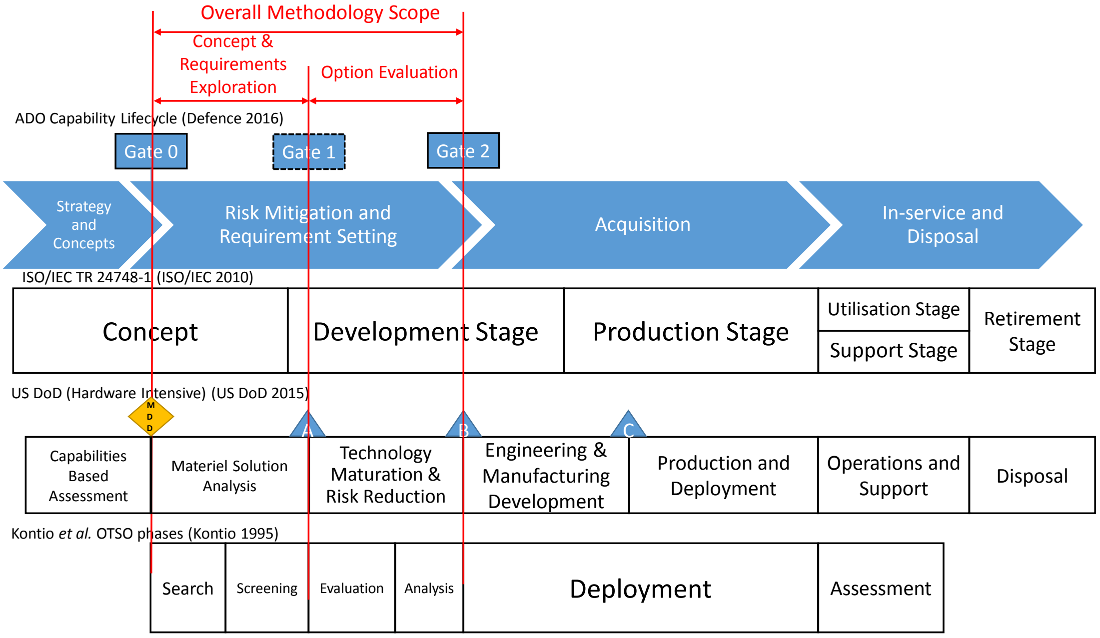


Figure 7: Various system lifecycles and the phases of interest for the research project.

The key activities related to the specification of the materiel system during the Defence Risk Mitigation and Requirements Setting phase are: **requirements definition**, **requirements setting** and **options refinement**. In the United States (US) of America Department of Defense (DoD) lifecycle, described in DoDI 5000.02 [40], the Technology Maturation and Risk Reduction Phase overlaps with the first part of the Defence Risk Mitigation and Requirements setting Phase as shown in Figure 7. This overlap is due to the common focus of reducing the various risks associated with the acquisition, along with the development and trade-off of designs and requirements. The Materiel Development Decision (MDD) milestone in the DoD lifecycle is aligned with the Defence Gate 0 milestone since a decision to proceed at this milestone endorses the need for a new product.

The approximate alignment of the Defence lifecycle with the ISO/IEC TR 24748-1:2010 [41] lifecycle shown in Figure 7 is due to the similar purposes of these phases in the lifecycles. In the ISO/IEC TR 24748-1:2010 lifecycle, the principle purposes of the relevant parts of the Concept and Development phases include: concept exploration, refinement of the system requirements, and creation of the solution description [41: p. 14]. Similarly, a fundamental purpose of the Defence Risk Mitigation and Requirements Setting Phase is to refine the Joint Capability Needs Statement into a contractible set of system requirements [4: p. 28].

The Off-the-Shelf Option (OTSO) method proposed by Kontio *et al.* [42], while initially intended for OTS software development projects, is included in Figure 7 to compare an OTS approach with the other lifecycles, which are focused on bespoke system development. The alignment of the OTSO search and screening stages with the first part of the Defence Risk mitigation and Requirements Setting Phase is due to the OTSO activities being used to inform changes to requirements [42]. The alignment of the evaluation of the shortlisted alternatives and analysis of the evaluation in the OTSO method with the second part of the Defence Risk Mitigation and Requirements Setting Phase arises as the OTSO evaluation stage ‘produces data on how well each alternative (option) meets the criteria defined’ [42: p. 8]. Kontio *et al.* [42], also note the selection of OTS options is ‘…an important activity in the project, with a high potential impact on the product and project objectives’ [42: p. 2].

The following sections in this chapter cover a review of the Australian, US and United Kingdom (UK) defence acquisition manuals and guides to identify and compare the key early-phase approaches and activities. The final section of the chapter reviews literature covering the OTS acquisition strategy to investigate whether it has an impact on the activities performed during acquisition.

2.2 Current Guidance for Early-Phase Defence Acquisitions

2.2.1 Australian Defence Acquisition

In 2015, Australian Defence underwent a wide ranging review, the First Principles Review (FPR) [2]. Following the FPR, a new approach (which remains current at the time of writing in 2018) for Defence acquisition was set out in the Interim Capability Life Cycle Manual (ICLCM) [4]. The ICLCM provides a set of principles that underpin the design of the Capability Life Cycle (CLC). These principles include [4: p. 3]:

- ‘The focus is on a joint and integrated approach to the development of future Defence capability and ensuring that capability options are aligned with strategic and resource guidance’
- ‘Integrated project planning across all the Fundamental Inputs to Capability (FICs) will be undertaken for all projects to ensure that critical enablers … are accorded appropriate priority in investment decisions’
- ‘Effective arms-length contestability is an integral and vital part, which supports rather than undermines accountability’
- ‘Industry is engaged earlier and is a key partner in the delivery of Defence capability’

The phases of the Defence CLC set out in the ICLCM [4] as shown in the uppermost lifecycle in Figure 7 are [4: p .4]:

- Strategy and Concepts
- Risk Mitigation and Requirements Setting
- Acquisition
- In Service and Disposal

The phase of interest for the research project is the Risk Mitigation and Requirements Setting Phase. This phase of the CLC [4: p. 28]:

> ‘...involves the development and progression of capability options through the investment approval process leading to a government decision to proceed to acquisition.’

A key focus during this phase is the development by the capability manager of [4: p. 28]:

> ‘…a requirement statement which can be issued to industry, based on the agreed statement of military need and inclusive of all fundamental inputs to capability.’

The Fundamental Inputs to Capability (FICs) are defined as [4: p. 13]:

- Organisation
- Command and Management
- Personnel
- Collective Training
- Major Systems
- Facilities and Training Areas
- Supplies
- Support
- Industry

It is notable that industry is a standalone FIC in the ICLCM [4], as it was described as ‘an element of the support FIC’ in the previous version of the Defence acquisition manual [43: p. 2]. The role that industry could play in the early phases of the CLC where Defence is developing the future force structure and undertaking initial capability design activities to elucidate capability requirements is unclear. It could be advantageous for Defence to conduct these activities ‘above-the-line’ to avoid any possible commercial interference during these crucial early phases. Once clarity of the force and individual capability design has been achieved and specified in some form of requirement statement, industry could be invited into projects via a request for information (RFI), or request for tender (RFT) mechanism.

The fundamental activities during the Risk Mitigation and Requirements Setting stage are [4: p. 28]:

- ‘Converting the Joint Capability Needs Statement into a contractible requirement statement and preparing for release of tender documentation;
- Mitigating key risks identified in the risk profile;
- Securing Government approval to proceed with acquisition, and;
- Developing plans to deliver the full scope, including the FICs, identifying any risks and ensuring budgets, resources and timescales are properly aligned.’

The ICLCM states that these activities [4: p. 28] ‘…allow the launch of a competitive tendering process (if required) or initiation of sole-source solicitation.’

The ICLCM includes guidance on the need to develop traceable requirements, a strength of applying MBSE during the early phases of a system’s lifecycle [23], with the following [4: p. 6]:

> ‘It is essential the CLC maintains the integrity of the plans in the White Paper and the Integrated Investment Program to deliver the agreed program of future investment in Defence capability…The Defence Planning Guidance (DPG), derived from the Defence White Paper, presents a classified summary of Defence strategic guidance, including Defence missions and essential force attributes.’

This infers that all requirements developed and released to industry during the Risk Mitigation and Requirements Setting phase of the CLC should therefore be traceable to the missions and force attributes given in the DPG. This is emphasised within the ICLCM with [4: p. 7]

> ‘The CLC process seeks to align strategy, capability and resources to provide options for government on the design of future Defence capability, in particular the future force structure.’

While there are several mentions of the need to align investment and strategic priorities for Defence capability in the ICLCM [4], there are no explicit activities or methods outlined to ensure this alignment. However, a new 'contestability' function has been established following the FPR to [4: p. 7]:

> '…improve the quality of advice (to government) by ensuring the right questions are asked at the right time. It is essential to achieve increased confidence in Defence's management of force and capability design.'

While this is a good intention, it is not clear whether asking the 'right questions', whatever they may be, 'at the right time' will achieve the desired increased level of confidence in Defence's advice to government. However, if the team responsible for undertaking the early CLC phases can be supported to maintain traceability between strategy and the acquisition, or capability design activities, this should help build the necessary confidence and answer any questions arising from the contestability function. The ICLCM goes on to further describe the contestability function with [4: p. 7]:

> 'Contestability…provides a source of assurance to the Vice Chief of the Defence Force, as chair of the Investment Committee, the Secretary and Chief of the Defence Force, the central agencies; the Minister and government that Defence's capability needs and requirements are aligned with strategy and resources and can be delivered in accordance with government direction.'

It appears as though this assurance will be generated by the contestability function delivering [4: p. 8]:

- **Strategic contestability** – occurring in parallel with the force design function, this will ensure delivery of strategic needs at the portfolio and project levels.
- **Program, Product, or project assurance** – associated with the implementation of governance at the various levels.
- **Standards and models** – 'the contestability function has a leading role in identifying systemic, recurring issues for resolution, and in developing standards, tools and models to support contestability.'

The third point above implies any methods, tools, processes, or methodologies to support Projects to provide a 'contestable' business case at the decision gates should be developed, or endorsed, by the contestability function if they are to be used in Defence acquisition projects. (The business case is the decision document provided by Defence to the Government at the CLC gates [4]. The content of the business case depends on the decision gate.)

Returning to the fundamental activities within the Risk Mitigation and Requirements Setting Phase, **Requirements definition** is undertaken to support the development of the Gate 1 business case (although Gate 1 is only required for 'complex and high risk' category projects). Requirements definition [4: p. 30]:

> '…focuses on converting the Joint Capability Needs Statement into a contractible requirement statement and preparing for the release of tender documentation (for competition or sole source). Requirements need to be standardised, fit for purpose, complete, and account for all FIC.'

If a project receives government approval to continue to Gate 2, the activities that need to be undertaken include [4: p. 33-34]:

- **Requirements setting** – where the Integrated Project Team finalises requirements analysis informed by industry solicitation. 'The level of detail in the requirements … will be sufficient to allow direct comparison (such as cost and capability trade-offs) between options and identification of the Key Performance Parameters (KPPs)[3] for each requirement.'
- **Options refinement** – at this stage of the CLC, the options are specific capability solutions, typically provided by industry in response to an RFT. 'Each option is assessed to confirm feasibility, acceptability and suitability.'

Again, the ICLCM [4] provides no guidance on how to perform these activities in a manner that will satisfy the contestability function, suggesting this is presently a knowledge gap that would be beneficial to fill for project stakeholders. The ICLCM goes on to provide an overview of the design, integration, and test and evaluation of the

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[3] The ICLCM interpretation of KPP appears to differ from the more widely used definition given in the JCIDS Manual and the INCOSE Technical Measurement Guide; i.e. that KPPs are the critical or essential performance attributes of a system. This means there is unlikely to be a KPP for each requirement.

Defence capability to be delivered. It provides an indication of how acquisition projects could be supported by modelling, analytical methods and tools with [4: p. 45]:

> ‘An effective joint force is the result of the translation of strategic policy, supported by early, evidence-based and transparent analysis to provide decision makers with the necessary information to make difficult but informed capability trade-off decisions across the portfolio.’

This work flow is summarised in Figure 8.

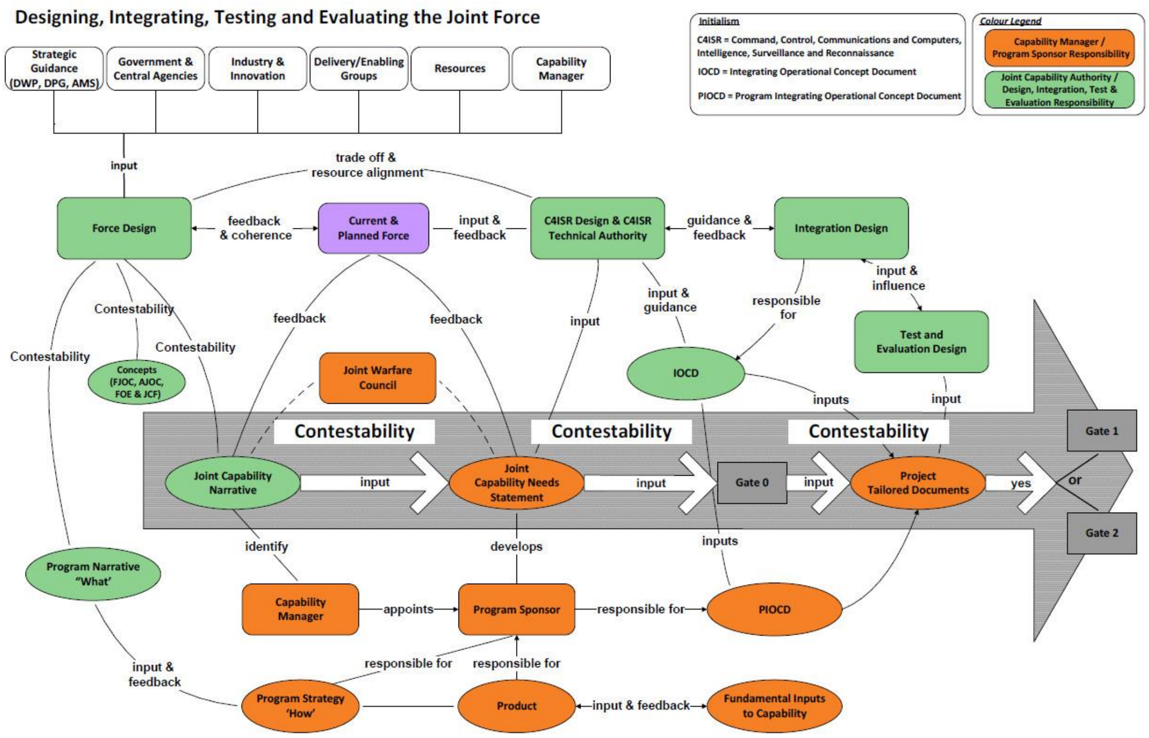


Figure 8: The ICLCM design pathway [4].

The principles that apply to these design, integration, test and evaluation activities include [4: p. 45]:

- ‘capability decisions based on purposeful evidence-based analysis aligned to strategic intent; and
- robust information management that is underpinned by contestability functions, transparent options development and prioritisation activities, decision support and advice to government.’

The ICLCM [4] has an increased focus on the Joint, or force level of defence capability compared to the previous editions of Defence acquisition guides. Force design is specifically mentioned in a large number of instances and there is an emphasis on ensuring consistency between the portfolio, program, and project levels of capability development. However, guidance on how to demonstrate, or ensure consistency between the different levels is mostly in the form of the principles given above and, therefore, lacking detail. There is a risk that the program and project managers will implement their own approaches, which could lead to inconsistences across capability domains and projects.

No specific mention is made in the ICLCM of how the Joint Capability Needs Statement should be translated at the project level into a specification of the physical systems that will address the needs. This lack of detail is highlighted in the project level section of the ICLCM where the core functions of the project are described, which include [4: p. 80]:

- **Requirements development** – where ‘requirements are developed from capability gaps identified in the Joint Capability Needs Statement and are informed by existing architectures and concepts and developed only to the level of detail that is sufficient for the purposes of Project decision making, solicitation and acceptance.’

This suggests that approaches such as the use of design patterns of existing architectures are suitable for use in the ‘smart buyer’ approach (i.e. using the FPR definition [2: p. 33] that a smart buyer can accurately define the product they are purchasing) to support requirements development within projects.

Late in the research project (mid-2018), the researcher became aware of a new release of an Australian Defence Functional Handbook relevant to the early phases of acquisition, the Capability Definition Documents (CDD) Guide [44]. The CDD Guide provides guidance for the preparation of the set of CDD that [44: p. 6]:

- ‘Describe the operational needs and technical requirements for a capability;
- Address the full set of FIC
- Are necessary for Defence to realise the proposed Capability.’

The three CDD are [44]:

- The Operational Concept Document (OCD) – the capstone document that captures the operational concept of the capability system.
- The Function and Performance Specification (FPS) – the formal system requirements specification of the materiel system.
- The Test and Evaluation Master Plan (TEMP) – that documents the Verification and Validation (V&V) and Test and Evaluation (T&E) activities needed to accept (and characterise) the capability being acquired.

The CDD Guide [44] gives acquisition stakeholders much more detail on the types of activities that need to be performed in order to define capability than the ICLCM [4]. However, the document is not widely distributed and could not be located by the researcher on the public internet. This reflects the content of the ICLCM [4], which contains no mention of the CDD Guide. The ICLCM [4] only requires the TEMP to be included in the business cases at the decision gates. Nonetheless, the processes given in the CDD Guide [44] are well aligned with several of the Systems Engineering (SE) processes given in the SE standard, ISO/IEC/IEEE 15288 [18].

The purpose of this latest CDD Guide is '…to describe a process for ensuring that the scope of the project to realise or update a capability is fully captured, properly defined and is traceable to government direction' [44: p. 6]. The CDD Guide provides a high-level overview of how the CDD should be traceable to government direction as shown in Figure 9.

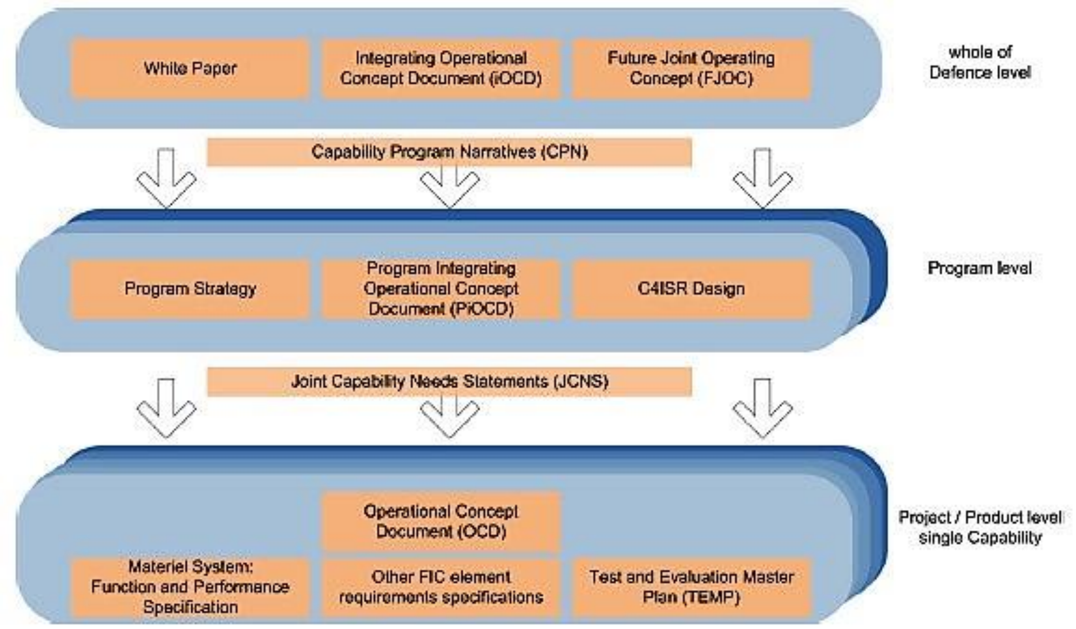


Figure 9: Overview of CDD traceability to government direction [44].

The CDD Guide [44] gives a high-level overview of the process for developing Defence CDD as shown in Figure 10.

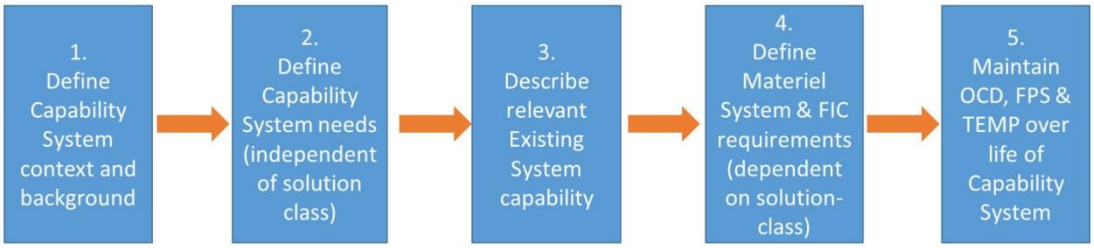


Figure 10: High-level process for developing the CDD[44].

The CDD Guide [44] provides further details on the sub-processes for each of these steps in the high-level process, however, these sub-processes are not warfare domain specific and independent of the acquisition strategy. For example, the “define materiel system & FIC requirements” (step 4 in Figure 10) sub-process shown in Figure 11 does not appear to account for the ability of OTS systems to satisfy the requirements that are defined. Rather, the CDD Guide processes appear to be requirements-driven, which may not be suitable for OTS acquisitions. This is discussed further in Section 2.3.

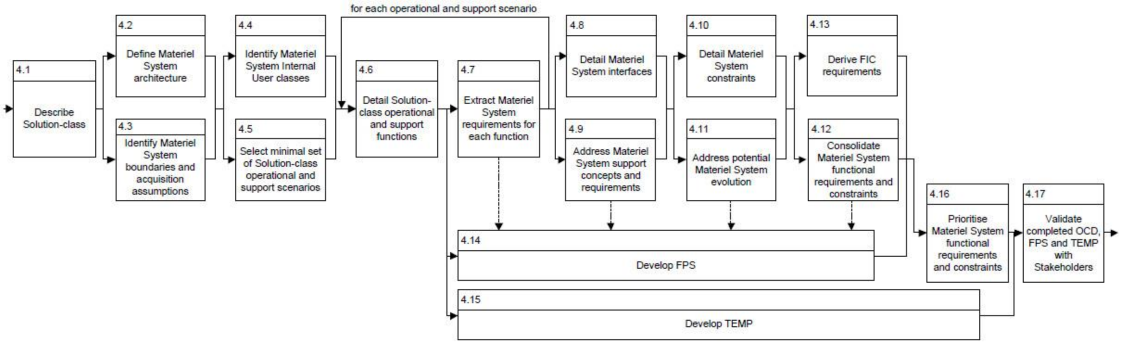


Figure 11: The CDD Guide define materiel system requirements process[44].

Interestingly, whilst not mandating the use of MBSE to support the requirements development process for Australian Defence capability, the CDD Guide notes its usefulness with [44: p. 17]:

> ‘The CDD Guide also recognises that architectural views can assist with representing a capability system, its components, their relationships to each other and the environment, and the principles guiding its design and evolution … The OCD is not intended to be the repository for all of the architecture products which are relevant to the capability system … This information should be retained in the tools used to capture the architectures … and the applicable architectural products and information should be included in the OCD.’

This implies that if any MBSE methodology constructed during the research project adheres to established SE processes and architecture frameworks, it will be aligned with the intent and processes in the CDD Guide [44].

While the authority and some of the processes in the CDD Guide [44] are debatable, an OCD will be useful as a basis for the analysis and evaluation activities that should underpin requirements development and option evaluation during the Risk Mitigation and Requirements Setting Phase. This will be particularly true if the operational scenarios in the document are traceable to the capability needs. This aspect is noted in the CDD Guide with [44: p. 22]:

> ‘The CDD define the technical scope of each of the solution-classes for each option being investigated and, therefore, provide one of the primary

> inputs into the analysis of the options that underpin the required business case(s).'

2.2.1.1 Early-Phase Australian Defence Acquisition Summary

The ICLCM [4] has been developed in response to the recommendations provided in the 2015 FPR [2]. The ICLCM has a higher focus on the Joint Force and how projects to acquire capability products fit into the system-of-systems (SoS) than the previous capability development handbook [43], which was focused on project level capability acquisition.

A criticism in the FPR [2] was the 'processes in the current (i.e. previous) capability development lifecycle are cumbersome, excessively bureaucratic and inefficient' [2: p. 33]. In response, the Defence ICLCM [4] appears to have swung the pendulum too far in the opposite direction. The Defence ICLCM [4] lacks specific guidance, such as processes or methods, on how to develop, capture and engineer traceable requirements from the Joint Capability Needs Statement, the trigger for a project at Gate 0, and undertake capability design activities. This appears to be a gap in knowledge that is left up to the project manager to address in each acquisition. Filling this knowledge gap is addressed in part by the CDD Guide [44], however, this document is not widely distributed or consistently used within Defence acquisitions. This lack of widespread direction may lead to inconsistent approaches and inconsistent outcomes. At the same time, any approach developed to provide support in the new CLC needs to be flexible, or tailorable enough to account for the range of acquisition approaches that can be implemented under the new lifecycle.

Previously introduced in Chapter 1, model-based techniques appear to be well suited as a basis for an approach to support Defence project-level capability development activities. While there are some brief comments in the CDD Guide [44] on the use of Functional Flow Block Diagrams to model concepts of operations, as well as an overview of Defence Architecture Framework views that can potentially be included in an OCD, model-based approaches are neither encouraged or discouraged in the Defence acquisition documents. It is possible model-based approaches to assist capability design and requirements elucidation activities could be developed within domains (i.e. land, maritime, air and joint) due to the aforementioned 'use of existing architectures and concepts' [4: p. 80]. The architecture of maritime platforms, for example, could utilise existing structures such as the Extended Ship Work Breakdown Structure (ESWBS) [45]. Any approach developed to support Defence capability acquisition will also need to adhere to the ICLCM principles, including supporting the 'smart buyer' concept.

2.2.2 United States of America Department of Defense

The United States of America (US) Department of Defense Instruction (DoDI) 5000.02 was updated in early 2017 [40]. It provides '…established policy for the management of all (US) acquisition programs…' [40: p. 1]. As such, it is the US equivalent of the Australian Defence ICLCM. The DoDI 5000.02 provides a generic acquisition, or capability lifecycle model, along with six DoD specific models that can be applied according to the type of system being developed. The six models are [40]:

i. Hardware intensive program (e.g. major weapon platform)
ii. Defense unique software intensive program (e.g. military unique Command and Control (C2) systems)
iii. Incrementally deployed software intensive program (e.g. business systems, C2 upgrades)
iv. Accelerated acquisition program (where schedule considerations dominate)
v. Hybrid acquisition program A (combination of hardware and software where hardware dominates)
vi. Hybrid acquisition program B (combination of hardware and software where software dominates)

A naval ship, which can be considered a major weapon platform, will typically use the hardware-intensive program lifecycle. It is worth noting that a US DoD 'program' is the equivalent of an Australian Defence 'project' because they both acquire a product [40].

Like the Defence ICLCM, the DoDI 5000.02 [40] also provides scope for differing levels of rigour in the analysis and capability definition documents (CDD) required for different classes of acquisition with: 'tailoring is always appropriate when it will produce a more efficient and effective acquisition approach for the specific product'

[40: p. 18]. It also covers the activities that should be conducted when faced with an urgent defence need and terms these ‘Rapid (changed to ‘Urgent’ in the 2017 update) acquisition activities’ [40].

As shown in Figure 7, the corresponding capability lifecycle phases for the Risk Mitigation and Requirements Setting Phase of the ICLCM in DoDI 5000.02 are roughly the Materiel Solution Analysis Phase and the Technology Maturation and Risk Reduction Phase. The US DoD equivalent of the Defence Gate 0 milestone is the Material Development Decision (MDD) since [40: p. 18]:

> ‘This decision point is the entry point into the acquisition process for all defense acquisition products…’

If a program is approved at the MDD, it enters the Materiel Solution Analysis Phase of the US DoD lifecycle. The purpose of the Materiel Solution Analysis Phase is [40: p. 18]:

> ‘…to conduct the analysis and other activities needed to choose the concept for the product that will be acquired, to begin translating validated capability gaps into system-specific requirements including the Key Performance Parameters (KPPs) and Key System Attributes (KSAs), and to conduct planning to support a decision on the acquisition strategy for the product. Analysis of Alternative solutions, key trades among cost schedule and performance, affordability analysis, and planning for risk mitigation are key activities in this phase.’

At the end of the Materiel Solution Analysis Phase, Milestone A ‘approves program entry into the Technology Maturation and Risk Reduction Phase’ [40: p. 20]. Importantly, the activities within this phase may be performed either within the DoD or contracted out [40: p. 20]. The Technology Maturation and Risk Reduction Phase [40: p. 21]:

> ‘…should include a mix of activities intended to reduce the specific risks associated with the product to be developed. This includes additional design trades and requirements trades necessary to ensure an affordable product and executable development and production programs. Capability

> requirements are matured and validated, and affordability caps are finalized during this phase.'

In a similar manner to the ICLCM [4], the DoDI 5000.02 provides high-level guidance on the need to conduct these early acquisition phases with consideration of all stakeholders when it notes [40: p. 21]:

> 'The Technology Maturation and Risk Reduction Phase requires continuous and close collaboration between the program office and the requirements communities and authorities.'

The US acquisition guidance provides much more detailed guidance than the Australian ICLCM [4] and explicitly call for design work and systems engineering analysis, with the DoDI 5000.02 noting [40: p. 22]:

> 'During this phase, and timed to support Capability Development Document validation, the Program Manager will conduct a systems engineering trade-off analysis showing how cost and capability vary as a function of the major design parameters. The analysis will support the assessment if refined KPPs/KSAs in the Capability Development Document.'

Milestone B roughly aligns with Gate 2 in the Defence capability lifecycle as shown in Figure 7. Milestone B is 'normally the formal initiation of an acquisition program' [40: p. 27] and is the milestone at which the contract is awarded for development and production of the major system.

While DoDI 5000.02 provides the '…policy for the management of all acquisition programs…' [40: p. 1], the activities for the '…identification of capability requirements and associated capability gaps (as well as the) development of capability requirement documents' [46: p. 1] are covered in the Joint Capabilities Integration and Development System (JCIDS) [46].

Similar to DoDI 5000.02 [40], the activities described in the JCIDS manual [46] are given in a more prescribed and structured manner compared to the Defence ICLCM [4].

In contrast to the Defence ICLCM [4], which does not touch on the skills required to develop and acquire defence capability, the JCIDS manual [46] sets out levels of training that people involved in the requirement development process are required to undertake [46]. While different in the level of detail provided in the processes to be performed during requirements development, the JCIDS manual [46], like the Defence ICLCM [4], takes a Joint Force, or SoS view of defence capability. Both manuals stress the need for programs and projects to align with the capability needs identified from Force Design type activities, which are termed Capability Gap Analysis in the JCIDS manual [46].

The JCIDS manual, in a similar manner to the Defence ICLCM [4] Fundamental Inputs to Capability (FIC), describes a capability in terms of 'DOTmLPF-P' where [46]:

- D = Joint Doctrine
- O = Organisation
- T = Training
- m = materiel
- L = Leadership and Education
- P = Personnel
- F = Facilities
- P = Policy

In contrast to the Defence ICLCM [4], the JCIDS manual explicitly provides a range of methods to address an identified capability gap and highlights a preference for addressing them through changes to the non-materiel elements of capability with the statement [46: p. D-14]:

> 'When conducting analyses and drafting capability requirement documents, Sponsors will consider both non-materiel and materiel solutions and to the maximum extent possible, recommend approaches in the order listed below…:
>
> i. DOTmLPF-P changes
> ii. Procurement or modification of off-the-shelf products, services and technologies

iii. Additional production or modification of previously developed US and/or allied/partner nation…systems or equipment

iv. Cooperative development program with one or more allied nations

v. A new joint DoD component

vi. A new DoD Component unique development program’

The JCIDS manual [46] uses a Capability-Mission Lattice to provide ‘an integrating construct for articulating the dependencies between capability requirements as well as the traceability between related processes and activities…’ [46: p. B-4]. The Capability-Mission Lattice is shown in Figure 12.

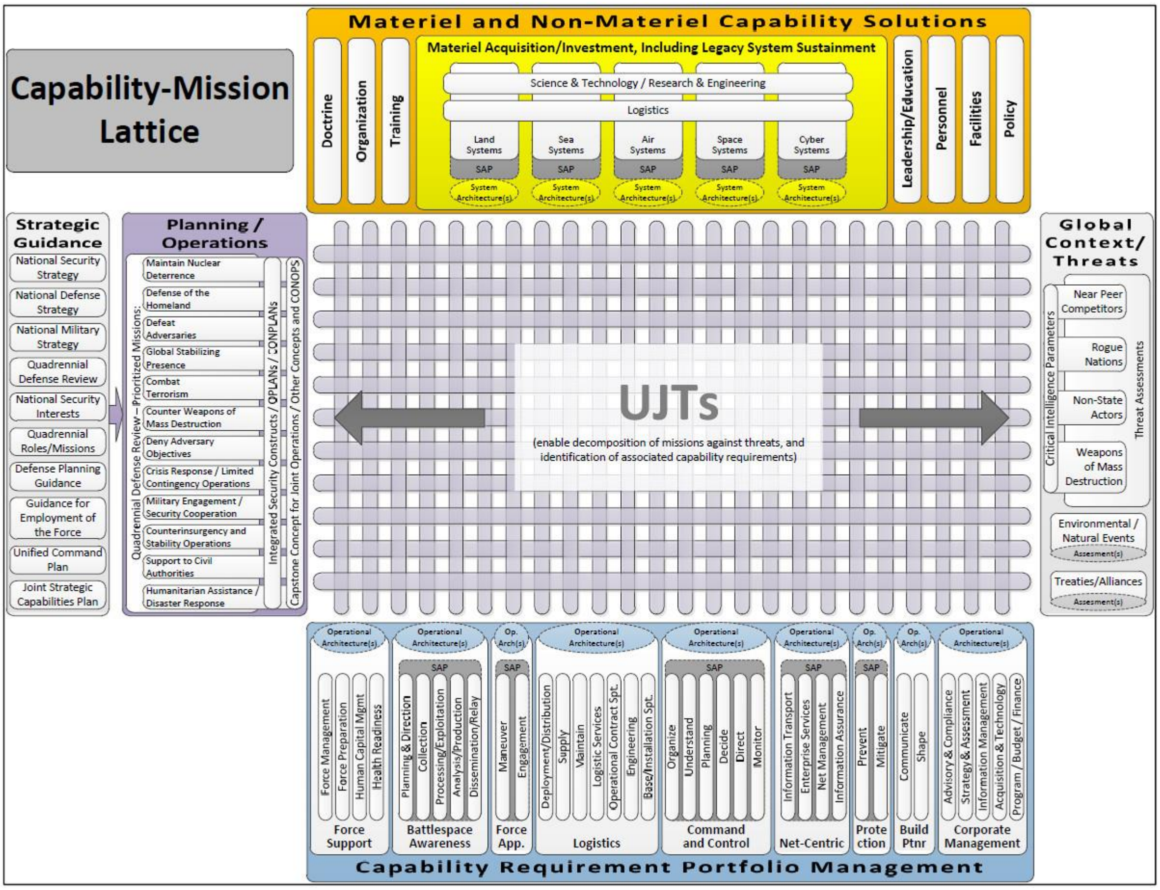


Figure 12: JCIDS Capability-Mission Lattice. UJTs = Universal Joint Tasks [46].

The Capability-Mission Lattice provides a useful framework for ensuring requirements are traceable from strategic guidance, through operations and activities to the US FIC equivalent. This is a similar framework to the ‘Strategy-to-Task’ framework by Thaler

[33] that links 'means' to 'ends'. It is also noteworthy the Universal Joint Tasks represent a design pattern of military operational activities, which are provided in documents such as the Universal Naval Task List (UNTL) [47]. Furthermore, it appears as though by design, the Capability-Mission Lattice reflects the US DoD Architecture Framework (DoDAF) Version 2.02 metamodel [48] released by the US DoD Chief Information Officer. A high-level conceptual overview of the DoDAF Version 2.02 metamodel is shown in Figure 13.

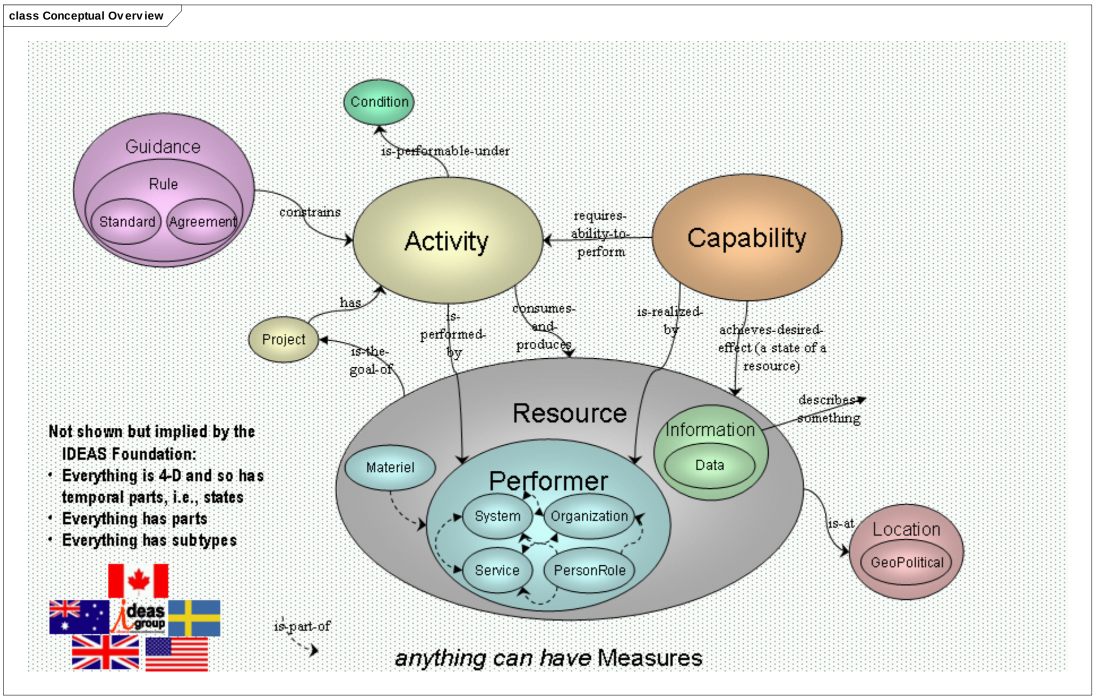


Figure 13: US DoDAF Version 2.02 metamodel conceptual overview [48].

When discussing the decomposition from strategic guidance to operations, the JCIDS Manual seems to encourage the use of operational design patterns by stating [46: p. B-7]:

> 'An organisations operations, roles, missions, or functions can be organised in terms of the Department's top-level mission areas. Service and joint concept(s) or CONOPS will articulate how the organisation plans to accomplish its roles, missions, or functions, which may be further decomposed into lower levels of the Universal Joint Task List (UJTL).'

While no specific mention of Model-Based Systems Engineering (MBSE) tools is made, the use of 'tools' to capture this high-level requirements traceability is mentioned in the JCIDS manual with [46: p. B-9]:

> ‘Tools which leverage the Capability-Mission Lattice…and integrate data available from applicable databases are being developed by the Joint Staff for use by the Functional Capabilities Boards and other capability requirement stakeholders.’

These tools appeared to be in the prototype stage at the time of the JCIDS Manual release in 2015, with the manual stating [46: p. B-10]:

> ‘The portfolio tools in development specifically allow queries against and integrate information related to:’
>
> - Mapping defense planning scenarios to Universal Joint Tasks
> - Mapping Universal Joint Tasks to Joint Capability Areas
> - Mapping validated capability requirements to Joint Capability Areas. This data is provided by Sponsors in their capability requirements documents and associated DoDAF views.
> - Mapping current and recently completed Science and Technology efforts to Joint Capability Areas
> - Mapping validated capability requirements to acquisition programs.
> - Mapping acquisition programs to budget data.

An internet and open literature search for these tools at the time of writing (2018) was unsuccessful in locating information on such tools. However, the reference to DoDAF views above, as well as the discussion in previous paragraphs implies that most MBSE tools should be capable of performing the role of such a tool.

There is a focus on producing documents to define and specify US DoD capability at the various milestones in the DoDI 5000.02 lifecycle, which suggests that there is not a great deal of Model-Based Conceptual Design being undertaken in the US DoD at the present time. However, the DoDAF, which can be used as a means of viewing MBSE models, is prescribed as a means of documenting the data generated from a Capability-Based Assessment (CBA) in the JCIDS Manual [46]. There is also a Digital Engineering initiative in the US DoD that is driving the use of model-based approaches in acquisitions, which is discussed further in Chapter 3. The CBA approach appears to align with the Strategy and Concepts Phase in the Defence ICLCM [4], since the CBA [46: p. C-B-1]:

> '…provides a robust assessment of a specific mission area, or similar bounded set of activities, to assess the capability and capacity of the joint force to successfully complete the mission or activities.'

JCIDS provides the guidance in Figure 14 for the use of DoDAF views to capture CBA data, which 'often leads to the identification of new or modified capability requirements and associated capability gaps' [46: p. C-B-1], in capability definition documents. When discussing the DoDAF views generated during a CBA as shown in Figure 14, the JCIDS manual states [46: p. C-B-4]:

> 'The DoDAF Operational Views and Capability Views illustrated…should be generated during the CBA, as leveraging these DoDAF views and associated data can significantly improve efficiency, saving time and resources later in the JCIDS and Defense Acquisition System processes.'

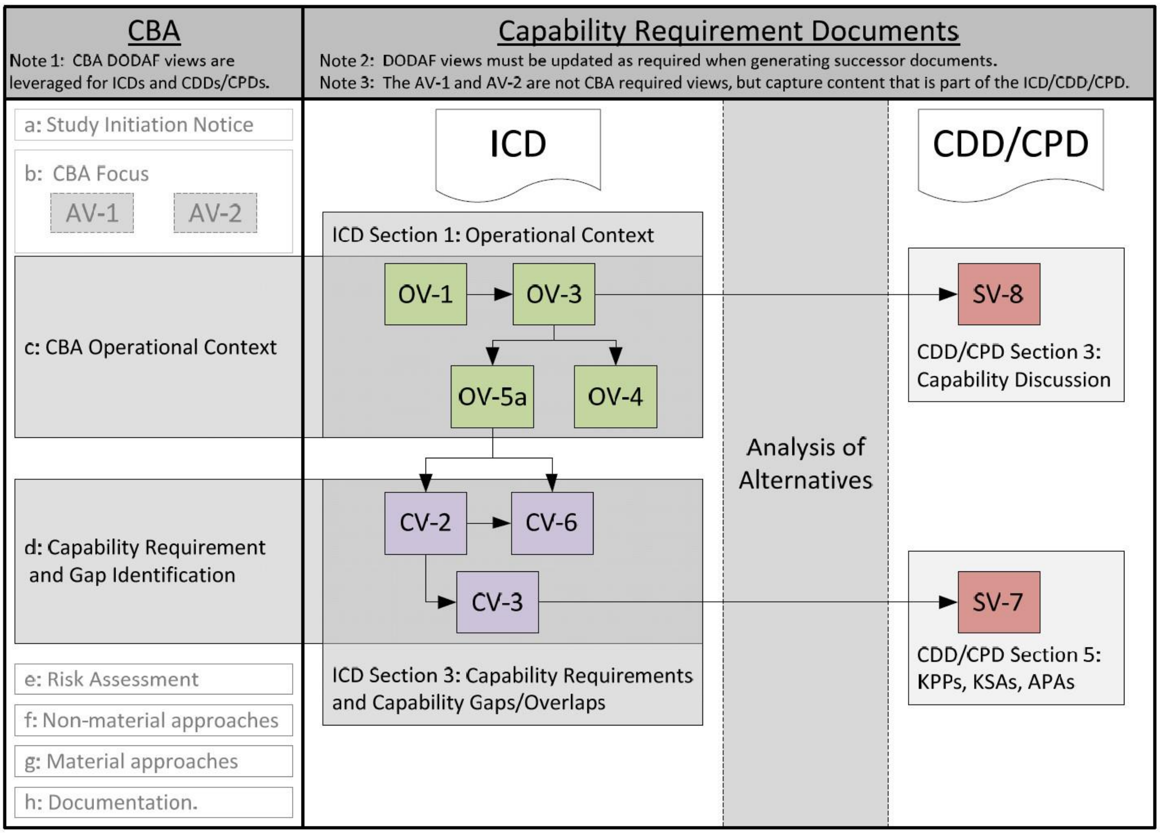
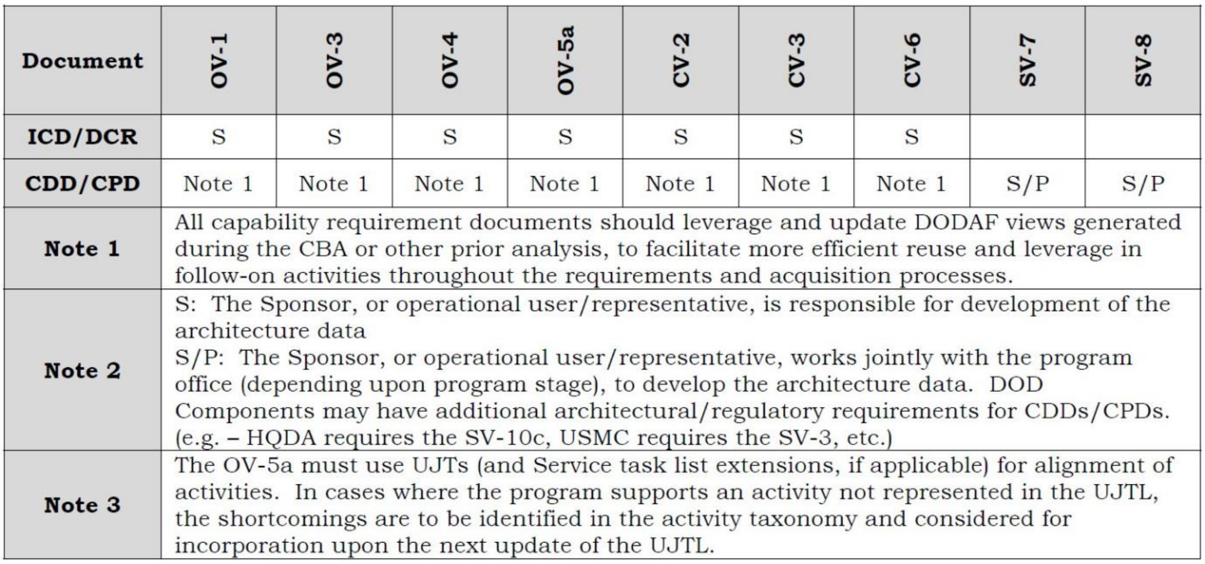


Figure 14: DODAF Views to represent CBA data in US DoD capability definition documents. ICD = Initial capability description, CDD = Capability Definition Document, CPD = Capability Production Documents [46].

However, somewhat counterintuitive to the preceding paragraph quoted above, which highlights the efficiencies of generating DoDAF views, the JCIDS Manual states in the next paragraph [46: p. C-B-4]:

> ‘Note that the level of detail in DoDAF views generated during a CBA does not require the use of sophisticated architecture tools and associated personnel unless directed by the sponsor. The data required for most of the views can be structured as tables using…spreadsheet programs, and used in that form for the purposes of generating capability requirements documents and submitting associated DoDAF views for review. The data must be submitted in such a form that it may be efficiently imported into architecture tools for follow on efforts…’

This begs the question: ‘why not just develop an MBSE, or architecture model to begin with?’ Furthermore, several DoDAF views are required to be included in the US DoD capability requirements documents as shown in Table 1. The JCIDS Manual notes ‘data for DoDAF views should be captured to the greatest extent possible during Capability-Based Assessments to reduce workload when generating capability requirement documents and performing follow-on efforts’ [46: p. D-15]. Using an MBSE model to capture the CBA results and generate DoDAF views for US DoD capability requirement documents would reduce workload even further, particularly if requirements change throughout these early lifecycle phases as they frequently do. A more detailed discussion on the use of MBSE and other model-based approaches to support Defence acquisition is provided in Chapter 3.



Document	**OV-1**	**OV-3**	**OV-4**	**OV-5a**	**CV-2**	**CV-3**	**CV-6**	**SV-7**	**SV-8**
ICD/DCR	S	S	S	S	S	S	S		
CDD/CPD	Note 1	Note 1	Note 1	Note 1	Note 1	Note 1	Note 1	S/P	S/P
Note 1	All capability requirement documents should leverage and update DODAF views generated during the CBA or other prior analysis, to facilitate more efficient reuse and leverage in follow-on activities throughout the requirements and acquisition processes.								
Note 2	S: The Sponsor, or operational user/representative, is responsible for development of the architecture data S/P: The Sponsor, or operational user/representative, works jointly with the program office (depending upon program stage), to develop the architecture data. DOD Components may have additional architectural/regulatory requirements for CDDs/CPDs. (e.g. – HQDA requires the SV-10c, USMC requires the SV-3, etc.)								
Note 3	The OV-5a must use UJTs (and Service task list extensions, if applicable) for alignment of activities. In cases where the program supports an activity not represented in the UJTL, the shortcomings are to be identified in the activity taxonomy and considered for incorporation upon the next update of the UJTL.								

Table 1: DODAF views required for US DoD capability requirements documents [43].

For naval ship acquisition programs, the US DoD capability lifecycle would follow the phases shown in Figure 7 and use the Initial Capabilities Document (much more detailed than the Australian Defence Joint Capability Needs Statement), Capability Development Document (no equivalent in the Defence ICLCM [4]), and the Capability Production Document (only a 'contractible requirement statement' is mentioned in the Defence ICLCM [4]) to define the capability requirements. The JCIDS Manual states [46: p. D-5]:

> 'For shipbuilding programs, program initiation occurs at Milestone A and the validated Capability Development Document is required prior to the earlier of Milestone A or the request for proposals release for activities to be executed during the Technology Maturation and Risk Reduction Phase of acquisition.'

The JCIDS Manual notes the need for 'requirements elucidation', or Concept and Requirements Exploration in the early phases of the capability lifecycle with [46: p. D-5]:

> 'Incorporating knowledge gained from activities completed during the Technology Maturation and Risk Reduction phase of acquisition into the development KPPs, KSAs and APAs of the Capability Definition Document, ... is essential to having stable requirements and a technically

> feasible program delivering an effective capability solution to the warfighter.'

There is also acknowledgement within the JCIDS Manual that a range of sequences, such as concurrent phases, may be used during acquisitions as 'capability requirement document sequences do not have to follow a purely linear progression' [46: p. D-7].

Interestingly, whilst the Australian Defence ICLCM [4] makes no specific reference to SE (although the CDD Guide notes that an Integrated Project Team should include 'at least one experienced Systems Engineer' [44: p. 6]), the DoDI 5000.02 [40] devotes an enclosure (enclosure 3) to applying SE discipline across the entire acquisition lifecycle. It calls for a SE plan to be prepared for each phase of the system lifecycle, along with technical reviews of program progress conducted by subject matter experts [40]. The systems engineering enclosure also points out the need to conduct modelling and simulation (M&S) with [40: p. 97]:

> 'The Program Manager will integrate modelling and simulation activities into program planning and engineering efforts. These activities will support consistent analyses and decisions throughout the program's lifecycle.'

2.2.2.1 US DoD Acquisition Summary

The overall theme of the DoDI 5000.02 [40] and JCIDS [46] documents appears to be of a more structured approach to acquisition than the equivalent Australian acquisition documents. This increased level of structure in acquisition correlates with the increased level of resources available in the US DoD, however, this does not account for the increase entirely. The focus on SE during an acquisition aligns the US practice more closely to the standard processes set out in ISO/IEC/IEEE 15288:2015 [18] for complex, technical system acquisition than the present Australian acquisition guidance.

A key difference between the Australian Defence and US DoD approaches is the importance placed on the training and certification of the people involved in US DoD acquisitions. While the US DoD requires acquisition staff to have demonstrated competencies instilled through substantial training at the Defense Acquisition

University and substantial, relevant, on-the-job experience of more than eight years to reach the top level of certification, there is no such requirement in the Defence ICLCM [4]. Not having a formal training and certification program increases the risk of Defence acquisition staff veering from best acquisition practice.

Another key difference between the US DoD and Australian Defence acquisition manuals that could result in inconsistent outcomes for Defence acquisition projects is the lack of detail on acquisition activities in the ICLCM [4]. There is a higher level of detail in both the DoDI 5000.02 [40] and JCIDS manual [46] on developing traceable performance measures and requirements. There is also greater detail in the US documents on the types and contents of capability description documents used in acquisitions, as well as the activities that should be performed during the various phases of the capability lifecycle. While greater detail on the type and content of Defence capability definition documents is given in the CDD Guide [44], there is no clear linkage between its contents and the processes given in the Defence ICLCM [4].

While model-based approaches are not specified within the US DoD acquisition documents, there is sufficient guidance around the use of DoDAF views to suggest that MBSE is used to support the acquisition activities. Further backing for the use of model-based approaches during the early phases of Defence acquisition is provided in DoDI 5000.02 [40] through its highlighting of M&S to support analyses and decision making. Additionally, it is worth noting the DoDI 5000.02 points out that [40: p. 97]:

> ‘Models, data, and artefacts will be integrated, managed and controlled to ensure that the products maintain consistency with the system and external program dependencies, provide a comprehensive view of the program, and increase efficiency and confidence throughout the program’s lifecycle.’

Finally, after identifying the level of training and detail of guidance as the key differences between the Australian Defence and US DoD acquisition manuals, some thoughts: without well-established processes, methods, tools and training in rigorous requirements development, there is a risk that the content of capability development documents could be effectively ‘copied and pasted’ from previous documents without proper consideration of the capability needs. This increases the risk of poor acquisition project outcomes and suggests that acquisition staff need more support on the types of activities that should be performed, not less, from acquisition manuals, as well as methods, tools and training.

2.2.3 United Kingdom Ministry of Defence

The United Kingdom (UK) Ministry of Defence (MoD) has recently (1st April 2016) released a new Acquisition System Handbook (ASH) [49] following a Defence reform review conducted in 2010. The UK ASH is based on the principles set out in the Acquisition System Operating Model (ASOM) [50]. There is also an Acquisition System Guidance Website that provides a 'new single area for all acquisition guidance' [51]. Like the US DoD, the UK MoD has more than one lifecycle model and uses two basic models [51]:

1. CADMID, which comprises the phases:
    - Concept
    - Assessment
    - Demonstration
    - Manufacture
    - In-service
    - Disposal

2. CADMIT, which comprises the phases:
    - Concept
    - Assessment
    - Demonstration
    - Migration
    - In-service
    - Termination

The key difference between the two is 'in the CADMIT lifecycle the approval points occur later, in order to manage the risks better' [51]. Alongside these lifecycle models, the UK MoD Acquisition Guidance also uses four lifecycle variants for acquisitions [51]:

- Sequential
- Incremental
- Evolutionary
- Combination

The phases of the UK MoD lifecycle models that align with the Australian Defence Risk Mitigation and Requirements Setting Phase that is the focus of this research project, appear to be the Concept phase and part of the Assessment phase. This is due to some of the activities undertaken within these phases, such as the production of a System Requirements Document (SRD), being aligned with those in the Defence ICLCM [4] Risk Reduction and Requirements Setting Phase, such as requirements development. The ASH also references requirements setting, which has a similar definition to the Defence ICLCM [4] requirements definition activity given in Section 2.2.1 with [49: p. 22]:

> ‘It underpins the tasking of the Delivery Agent by translating Customer Capability Planning outputs into specific goods and services requirements…’

In a similar manner to the Defence ICLCM describing capability in terms of the FIC and the US DoD DOTmLPF-P description of capability, the UK MoD describes the concept of capability in terms of the Defence Lines of Development (DLoDs) [51]:

- Training
- Equipment
- Personnel
- Information
- Doctrine and concepts
- Organisation
- Infrastructure
- Logistics
- Interoperability

The ASH also notes a preference for implementing SE within acquisition projects to assist with force design with [49: p. 25]:

> ‘The use of Systems Engineering principles will also ensure that solutions can be integrated with minimum cost, technical risk managed and the systems are interoperable.’

Like the US DoD JCIDS manual [46], the UK MoD Acquisition System Guidance [51] highlights the need for staff involved in Defence acquisitions to hold appropriate competencies for their job functions. As noted previously, acquirer competency is not addressed in the Defence ICLCM [4].

In a 2013 article on chronic challenges in UK defence acquisition, Hambleton *et al.* [52] note two of the challenges as:

- Developing intelligent customers – in a manner similar to the Australian Defence ‘smart buyer’ approach.
- Translating capability to specification.

Hambleton *et al.* [52: p. 366] note:

> ‘It is difficult to translate from a desired military capability to a requirement statement and on to a detailed technical specification without potentially-disruptive misunderstandings.’

The UK MoD ASH appears to be acutely aware of the traceability issue as it highlights the importance of tracing from strategic guidance contained in Defence plans, through the Command plans, into the Command Acquisition Support Plans and the User Requirements Document and Systems Requirements Document. The UK MOD term this traceability the “**golden thread**” and define it as [49: p. 22]:

> ‘The unbroken, top-down linkage of requirements from Defence policy to DLoD outputs, that provides the direction for investment plans and ensures that the capabilities generated are coherent and consistent with MoD’s strategic investment.’

The ASH hints at the possibility of using MBSE within acquisition programs, as the requirements management tool DOORS® is referenced as an approach to maintaining evidence of the "golden thread" with [49: p. 24]:

> 'The use of DOORS for capturing and managing all User and Systems Requirements to a common minimum standard should be considered, to ensure an effective audit trail…'

2.2.3.1 UK MoD Summary

In a similar manner to the Defence ICLCM [4], the UK MoD acquisition guidance provides less prescriptive detail on the processes that should be used in Defence acquisitions and contains mostly high-level guidance in their latest acquisition manuals. As for Australian Defence, this could result in inconsistent acquisition project outcomes.

The UK MoD acquisition manuals do place an emphasis on developing traceable requirements. The desire to create a golden thread links to an issue that has been identified in Australian capability acquisition, where authors such as Baker [53], back in 2000, and more recently Hodge [32], have identified a 'gap in explanation' between strategy and force structure options. This issue reinforces the importance of traceability in requirements definition and indicates that traceability should be part of the foundation of any methodology intended to support defence acquisitions. Nonetheless, unlike the JCIDS manual [46], which uses the Capability-Mission Lattice framework for requirements traceability, the ASH [49] does not provide extensive guidance on how to trace from strategic guidance to capability requirements.

2.3 Off-The-Shelf Acquisition

Increasingly, Defence system acquisition projects generally, and naval ship acquisition projects in particular, are adopting an Off-the-Shelf (OTS) acquisition strategy. This section covers a brief review of the implications of adopting the OTS strategy and investigates whether the processes from the acquisition manuals reviewed above remain suitable for this strategy. The perceived benefits of the OTS acquisition strategy are associated with a reduction to program schedule and cost risks [14: p. 3]. If suitable requirements are to be defined for the capability needs in the early phases of OTS acquisitions, it is necessary to understand the OTS solution space. This is reflected in the lessons learned from the procurement of a OTS helicopter by the US DoD with ‘once the decision was made to go with a Commercial Off-the-Shelf (COTS) aircraft, the requirements had to reflect aircraft that were currently being produced’ [54: p. 33]. This implies that firstly, the specification must be reflective of the commercial marketplace, and secondly, to achieve this, the OTS design space must be understood.

Another aspect to consider with OTS acquisitions is that while the strategy can reduce cost and schedule risks, it may result in the capability option selected: (1) not fully meeting all of the user’s operational needs, (2) not fully integrating with other in-service capabilities, and (3) not fully suiting the local geographic and strategic circumstances [15]. This implies there is also a need to understand any capability risks presented by the OTS constraint. This is reflected in Lebron *et al.* [55: p. 7-2] who state:

> ‘The impetus for greater application of COTS technology creates a new systems engineering challenge – to cost-effectively assess and integrate commercial technologies prone to continuous change …. The overall goal is to meet mission requirements while ensuring cost, schedule, and performance throughout the weapon system life cycle. This goal can be compromised by poorly estimating the risks involved with COTS technology insertion.’

Further, Lebron *et al.* [55: p. 7-3] state:

> ‘The first step in meeting this objective is to assess the viability of the commercial technology in the context of performance, complexity, criticality, supportability, and life cycle cost factors.’

Another key difference related to the SE approach used in OTS and developmental acquisition is that for developmental acquisition, where a system can be designed to meet the specification to the extent allowed by financial and other constraints, the ‘top-down’ SE approach to conceptual design (decomposition) is suitable. OTS acquisition, with its need to understand the marketplace appears to require more ‘bottom-up’ Systems Integration effort. The researcher has previously noted [17: p. 2]:

> ‘OTS strategies change the nature of defence acquisition projects from the traditional top-down requirements-driven approach to a middle-out approach.’

Hitchins [56] proposes an OTS procurement life cycle that does not contain a conceptual design stage. He proposes a ‘Total systems acquisition (TSA)’ paradigm that relies on industry to anticipate the defence market’s needs and then for nations to ‘procure defence equipment like we procure everything else – go out and shop for it in the international defence marketplace’ [56: p. 285]. Hitchins admits that TSA is somewhat idealistic and suggests that for it to be effective a robust defence marketplace is needed, which already exists in technology areas such as sensors, processors, weapons and communications [56: 287]. He goes on to note that ‘the defence market is less robust, however, at platform level. There is limited choice of advanced fighter, ship and tank platforms, for instance’ [56: p 287].

In the case of OTS naval ship acquisitions, the researcher has noted [17: p. 2]:

> ‘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 adopting 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 [38]. This is similar to many OTS naval vessel acquisitions, where the OTS design (the parent) is modified (to varying degrees) into a supposedly 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 ([14] and [38]).’

The need for design activities to support requirements development in OTS naval acquisitions does not dissipate, since as noted by the researcher [17: p. 2]:

> ‘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 [39]. Furthermore, the existing vessel design will ideally still be in production, since evolving legislative requirements may necessitate significant design changes for older parent vessels [39]. Hence, to realise the benefits of lower acquisition cost and schedule risks in OTS naval vessel acquisitions, the project will need to aim to identify existing OTS designs, or a region in the OTS design space, with very similar operational and legislative requirements to those developed from the project's capability needs, then specify tender requirements accordingly. Unlike the navy undertaking a modified-repeat design approach to address a capability gap however, the OTS acquirer will not have knowledge of the parent design's requirements and design data.'

Authors such as Kontio *et al*. [42] and Constantine and Solak [57] have identified the unique nature of OTS acquisition and have identified the need to perform OTS option selection, or option analysis during conceptual design in an OTS acquisition process. Constantine and Solak [57] highlight the need to search for OTS options that accurately reflect the stakeholder requirements during conceptual design. It follows that in the early phases of an OTS acquisition, requirements definition, developing option evaluation criteria for options analysis and searching for OTS solution candidates needs to be performed concurrently. This aligns with Saunders' [14] approach of conducting system architecture definition and technology/market studies concurrently during OTS projects. Several structured approaches to performing option analysis, which could conceivably be implemented in MBCD, can be found in the open literature, such as Pahl and Bietz [36], Kontio *et al*. [42] and as Julian *et al.* [58]. Techniques for performing option evaluation are explored further in Chapter 3.

The open literature covering the OTS acquisition strategy reviewed for this sub-section indicates that the processes given in the defence acquisition manuals remain appropriate in acquisition projects that adopt this strategy. However, it is prudent to understand the impact on the solution space the OTS strategy imposes. This means the acquisition project activities may need to be sequenced differently to a developmental acquisition project. Furthermore, a market survey, or exploration of the existing solution space should be undertaken to understand the ability of OTS solutions to meet the acquisition project capability needs.

2.5 Chapter Summary

This chapter covered a review of the acquisition manuals of the Australian, United States of America's and United Kingdom's Defence organisations to gain an understanding of current defence acquisition practice. This review was undertaken to address the first sub-question for the research covered in this thesis:

> *How are the activities between Gate 0 and Gate 2 presently performed? What processes and tools are currently employed to support this class of activity?*

This chapter also covered a brief review of literature covering the acquisition strategy of interest for the research covered in this thesis; Off-the-Shelf acquisition, to gain an understanding of whether the processes and methods from the manuals remain applicable.

The three key activities related to the specification of the capability system within the Risk Mitigation and Requirements Setting Phase of the Defence CLC are: **requirements definition**, **requirements setting** and **options refinement**. The Defence ICLCM [4] only provides high-level guidance on what these activities involve and how they should be performed. This lack of specific guidance, such as processes or methods, is a recurring theme of the Defence ICLCM [4]. Specifically, there is little guidance on how to develop, capture and engineer traceable requirements from the Joint Capability Needs Statement, the trigger for a project at Gate 0, and undertake project activities up to deciding on the preferred tender at Gate 2.

The Defence CDD Guide [44] gives acquisition stakeholders much more detail on how to define capability in a traceable and robust manner than the ICLCM [4]. However, the document is not widely distributed and appears to lack authority. This reflects the content of the ICLCM [4], which contains no mention of the CDD Guide [44]. This inconsistency across the Australian Defence acquisition guidance and practice indicates there is a need for tools and methods to support the processes in the acquisition manuals as well as capture the 'golden thread'.

The US DoD acquisition manuals, DoDI 5000.02 [40] and JCIDS [46], provide a far more structured approach to acquisition, through the application of SE approaches, than the equivalent Defence ICLCM [4] and CDD Guide [44]. This focus on SE during an acquisition aligns the US practice more closely to the standard practice of complex, technical system SE set out in ISO/IEC/IEEE 15288:2015 [18] than the present Australian practice. Two key differences between the Defence and US DoD manuals were found. Firstly, the level of detail on the activities that need to be performed in the equivalent US DoD lifecycle phases between the Australian Defence Gate 0 and Gate 2 is higher. Secondly, there is a requirement for US DoD acquisition staff to undergo training and competency assessment, which is not covered in the Australian Defence acquisition manuals.

The UK MoD acquisition guidance provides less prescriptive detail on the processes that should be used in Defence acquisitions than the US DoD acquisition manuals and contains mostly high-level guidance. As for Defence, this could result in inconsistent acquisition project outcomes. The UK MoD acquisition manuals do place an emphasis on developing traceable requirements in order to create a golden thread from strategic guidance through the systems acquired.

The Australian Defence, US DoD, and UK MoD acquisition manuals do not specifically mention MBSE. However, they contain numerous statements suggesting MBSE and other model-based approaches can usefully support the early-phase activities of acquisition programs. This is particularly relevant for the guidance to develop DoDAF views during US DoD and Australian Defence acquisitions. Furthermore, the emphasis on developing or acquiring systems that are traceable via a golden thread back through the requirements to the initiating needs in all of the acquisition manuals, suggests MBSE is highly applicable to supporting most of the lifecycle processes. The suitability of several model-based approaches for supporting early-phase acquisition processes is covered in more detail in Chapter 3.

From the literature covering the OTS acquisition strategy reviewed in this chapter, it appears the processes, tools and methods given in the acquisition manuals above remain suitable when the OTS strategy is adopted for a defence acquisition. However, adjustments should be made in the sequencing of the activities, due to the need to understand the constraint the OTS strategy places on the solution space. This means a market survey activity, or an exploration of the existing design space, needs to be performed concurrently with requirements definition activities.

Chapter 3 – Literature Review 2: Concept Design and Approaches to Support Early Stage Off-the-Shelf Naval Ship Acquisition

3.1 Introduction

Two key themes were identified in the first literature review: the Australian Defence acquisition manuals provided a relatively low level of detail on the processes, methods and tools that could be used to support naval ship acquisitions, and the widespread adoption of Off-the-Shelf (OTS) strategies. These themes suggest Defence acquisition personnel could benefit from methods and tools that support them to implement the acquisition processes in a robust and traceable manner. This chapter covers a review of the conceptual design and Model-Based Conceptual Design (MBCD) open literature that was undertaken to identify approaches that have been or could be used to support Defence naval ship acquisitions. Conceptual design literature is included in the review as there is a growing understanding within the Systems Engineering (SE) discipline that the process of requirements definition should include design activities. This understanding is evidenced by the statement by Crowder, Carbone *et al.* [7: 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.’

This part of the literature review informs the research to construct an MBSE methodology to support OTS naval ship acquisition by seeking perspectives beyond the prescribed approaches within defence acquisitions manuals and standards. Model-based approaches are a focus as they can support early stage acquisition activities and still adhere to best practice, as well as generate the necessary acquisition products. This literature review also identifies the features, elements, or approaches that have been used during the early phases of naval ship acquisition, as well as in other domains. These elements are scrutinised for their utility to support and enhance the early phases of naval ship acquisition projects in line with the second sub-question for the research project:

> *What approaches can be used to support the early phases of naval ship acquisitions that can enable and enhance rigour and traceability between strategic objectives and capability development?*

From earlier, the three guiding principles used to identify approaches that may be suitable were:

1. Maintain traceability to the original, strategic intent of the ship 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.

The following subsections describe several approaches identified from a review of the open literature that could be used during the early phases of naval ship design and acquisition that adhere to these guiding principles. The approaches that were identified fall into three main categories: conceptual design processes, model-based methods, and decision support methods.

3.2 Conceptual Design Processes

Conceptual design, or *requirements definition* is a key phase of the system development lifecycle (SDLC) [59: p. 54-55]. It is a process comprising activities to transition, or elaborate a stated need into a system specification for a solution concept ([59: p. 54-55], [36: p. 159] and [60: p. 166]). In a "top-down" SE approach, these activities typically take the form of a functional decomposition and subsequent morphological analysis to explore possible solutions [60: p. 166].

While noting that there are a multitude of SDLCs that 'vary according to the nature, purpose, use and prevailing circumstances of the system' [18: p. 14], ISO/IEC/IEEE 15288 [18] refers to the generic lifecycle phases given in ISO/IEC TR 24748-1 [41]: Concept, Development, Production, Utilisation, Support, and Retirement. The processes that appear to cover the conceptual design stage within ISO/IEC/IEEE 15288 [18] are the technical processes of Business or Mission Analysis, Stakeholder Needs and Requirements Definition, System Requirements Definition and Architectural Definition, along with System Analysis.

Conceptual design is important for system success. Yaroker *et al.* state: ‘One of the most influencing factors determining the success and longevity of any developed system is the quality of its underlying conceptual design’ [11: p. 381]. While discussing the concept stage of the ISO/IEC/IEEE 15288 generic lifecycle, the INCOSE SE Handbook notes that ‘if the work is done properly in the early phases of the lifecycle, it is possible to avoid recalls and rework in later stages’ [6: p. 29]. Simultaneously, ‘the designer is faced with a lack of relevant knowledge and data regarding the problem, its requirements, its constraints, the technologies to be infused, the analytical tools and models to be selected, etc.’ [61: p. 3]. Finally, Blanchard and Fabrycky [59: p. 54] state that ‘conceptual design is the first and most important phase of the system design and development process.’ A key feature from the literature on early stage design that is applicable to naval ships is a thrust to develop resilient systems.

3.2.1 Engineering Resilient Systems

According to Jackson and Ferris, ‘the resilience of engineered systems is an emerging field’ [62: p. 153]. The literature from which the feature of resilient systems emerges comes from the both the general SE field and the US Defence field in particular. The two different fields appear to have taken two slightly different, yet linked interpretations of ‘resilient systems’ when it comes to the engineering of systems. Firstly, there is the interpretation found in general SE literature that ‘resilience in engineered systems involves a wide range of potential threats and system responses, both pre-emptive and post-event.’ [62: p. 153].

The second interpretation is tied to literature covering the US Department of Defense (DoD) and is associated with the resilience of Defence materiel to changes in operating requirements. This interpretation has been termed Engineered Resilient Systems (ERS) and the US DoD has announced ERS as an S&T priority area. Spero *et al* [63: p. 763] succinctly describe resilience in the context of the US DoD ERS thrust as:

> ‘Resilience in the context of ERS is more than robustness; resilience implies that when the system is placed in an environment in which it was not originally intended to operate, after some degradation in performance, the system can be adapted or reconfigured to perform at its intended levels.’

Interestingly, a presentation by Holland [64] notes that a range of capabilities need to be developed and demonstrated in order to deliver ERS techniques for the US DoD, which include:

- The integration of M&S, collaborative tools, tradespace analysis, engineering design processes into a single architecture, which could result in a 100-fold increase in the number of operational scenarios considered during conceptual design.
- Set Based Design (SBD) for tradespace exploration.

The first point is highly relevant for this research project as it suggests the implementation of robust design and analysis approaches in defence acquisitions could have a flow-on benefit though the acquisition of more resilient systems.

The two (i.e. non-US DoD and US DoD ERS) interpretations of resilience appear to be compatible, where the ‘potential threat’ to the system from the first interpretation is the change in operational requirement in the US DoD ERS interpretation. Although the authors appear to use yet another slightly different interpretation of ‘resilience’ (where the authors define resilience being associated with internal system variations and ‘robustness’ being associated with variations in the external environment) Ryan and Rehman [65: p. 4] provide some interesting thoughts on designing for uncertainty.

> ‘If the system is to be robust and resilient, it must survive the uncertainty in its environment, any given solution must be a sufficient solution in the presence of that uncertainty. Since the exact variation in parameters at an instant can never be known *a priori* … the designer allows for some tolerance in the nominal requirement and consequently the solution space must be broadened to accommodate those extended requirements.’

Ryan and Rehman [65: p. 5] provide a conceptual view of these thoughts in Figure 15, with the explanation:

> ‘As illustrated in Figure 15, if a solution (S_i) is a minimum sufficient solution to the nominal system requirements (R) (which did not include the requirement to be robust), then any robustness required in the solution (Δs) to accommodate uncertainty (Δr) will require one or more additional solution elements, such that the solution (S_i) will no longer be a sufficient solution.’

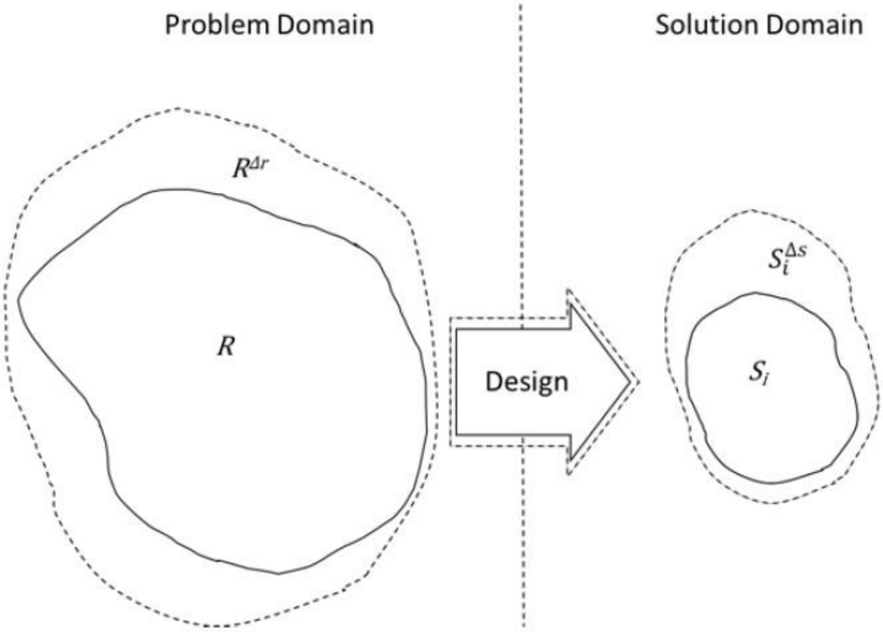


Figure 15: The inclusion of robustness requirements to accommodate uncertainty in the problem domain requires additional solution elements in the solution domain [65].

While there are slightly different yet compatible interpretations of ‘resilience’ present in the open literature, they all relate to the ability of a system to absorb changes in the system’s operating scope. These changes can be due to changes in the system requirements, operating environment, or disruptive events.

3.2.1.1 Resilient Systems in Naval Ship Conceptual Design

Incorporating resilience into naval ships through the implementation of Set-Based Design (SBD) principles has been described in the open literature since the late 1990’s. Singer *et al*. [66: p. 1] state that ‘traditional design process or methods have often failed due to the inherent complexity of large-scale product design.’ They go on to say 'designing large complex systems, such as naval ships … requires a new approach to design'. Singer *et al.* noted [66: p. 10]: 'In an academic environment SBD produced better solutions faster, when compared to optimisation methods, non-collocated engineering teams, and point-based approaches'. Stemming from a study of Toyota's design approach for automobiles in the mid 1990's, the features of the SBD design process have been identified as [67]: 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.

Hannapel [68] notes two main advantages of SBD over the traditional point-based naval ship design approach. 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 with more information available as the decisions are purposely delayed in the SBD approach.

SBD in naval ship design appears to build upon a proposal to use 'concurrent engineering design' in the early 1990s, since they share similar themes regarding the need for more information on which to base design decisions. Mistree *et al* state [69: p. 567]: 'A product of and a clear motivation for concurrent engineering is to "drag" the knowledge curve to the left, thereby increasing the ratio of hard to soft information that is available in the early stages of design.'

In the literature covering naval vessel conceptual design by a prominent British author, the principle of '*requirements elucidation*', rather than requirements engineering [70], emerges. In this approach, which is synonymous with Concept and Requirements Exploration (C&RE) as discussed in Section 3.4.1, '…the initial design phase is characterised by the need to elucidate what the requirements should be…' [71: p. 895]. Andrews [71: 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, based on Toyota's Product Development System and recently introduced into US Navy ship procurement.'

An issue with SBD as a means of incorporating resilience into naval platforms noted by Fox [72: p. 7], is that SBD still appears to be a 'descriptive' design approach, which are typically of less utility to design engineers than prescriptive approaches [69]. Nonetheless, SBD was identified as suitable for the early phases of Defence OTS naval ship acquisitions as it aligns with guiding principle two in Section 3.1; assist the stakeholders to make defensible decisions that account for competing goals and objectives. Finally, the researcher has previously written on SBD in OTS acquisitions [17: p. 4]:

> '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 identify any capability risk arising from the OTS constraint, not to produce a specific design.'

3.3 Model-Based Methods

A second key feature within the open literature focused on the engineering of systems is the increasing use of model-based approaches in engineering design [73]. Model-based approaches are synonymous with model-driven approaches, simulation-based approaches, and model-centric development approaches. Several of these approaches satisfy the guiding principles given in Section 3.1 and each of these is summarised in the following subsections.

3.3.1 Model-Based Conceptual Design

A recent feature from within the practice of conceptual design is Model-Based Conceptual Design (MBCD). An INCOSE MBCD Working Group (WG) was chartered in 2013 [21] and has defined MBCD as '..the application of MBSE to the Exploratory Research and Concept stages of the generic life-cycle defined by INCOSE...' [21: p. 1]. It is worth noting that the latest version of the SE Handbook [6], which is aligned with the most recent ISO/IEC/IEEE 15288 [18], has moved the Exploratory Research stage to be part of the Concept stage within the generic life cycle.

There is also a broader interpretation than that used by the MBCD WG of what MBCD constitutes. This is evidenced by Reichwein *et al.* [22: p. 1] who state that ‘Model-based concept design is often used to allow engineers to describe and evaluate various system aspects’. They go on to highlight the wide range of models that can be used during conceptual design, including [22: p. 1]: mathematical models, geometric models, software models, system models, control system models, multi-body system models, requirement models and function models. This insight is important, as it suggests that like Model-Based Systems Engineering (MBSE), MBCD requires practitioners to implement a methodology in the sense defined by Estefan (i.e. a collection of related processes, methods and tools [74]).

MBCD has been an issue theme for the INCOSE practitioner journal *Insight,* where theme editors described some of the proposed benefits of MBCD as [75: p. 7]:

> ‘Employing model-based methodologies to enhance the technical processes earlier in the system lifecycle has the potential to reduce the chance of poor decisions, and identify defects earlier, and therefore offers the potential for a greater return on investment of engineering effort.’

Although the authors describe it as a framework, the MBCD methodology proposed by Chami and Bruel [76] (for mechatronic systems) provides a useful example of the process, methods and tools that can be used in MBCD. The methodology is shown in Figure 16.

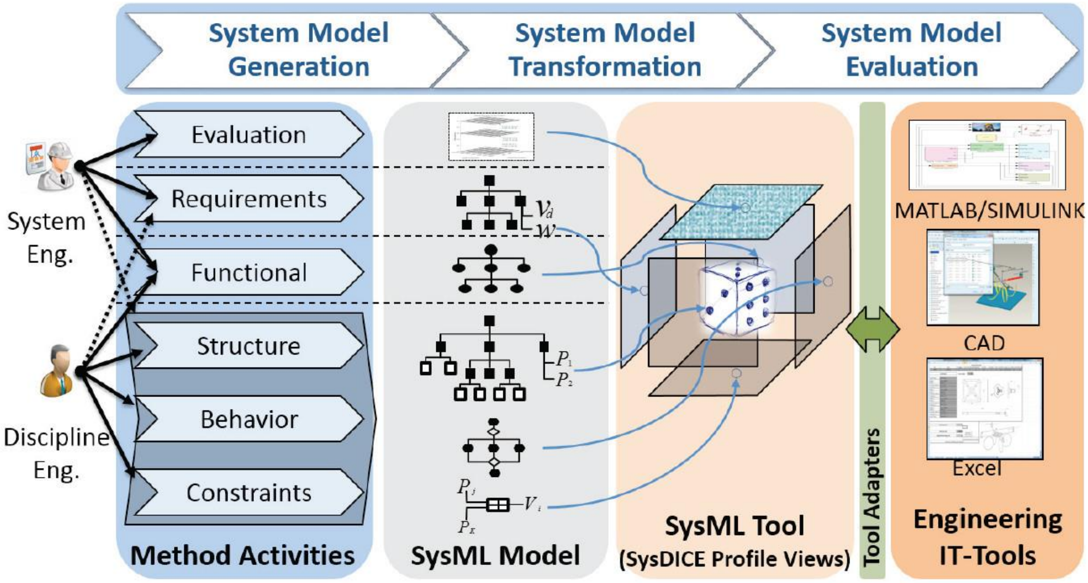


Figure 16: The SysDICE methodology for MBCD [76].

Some issues and successes associated with implementing and performing MBCD and conceptual design in general were uncovered in two surveys of people involved in MBCD conducted by the researcher in 2014 [77] and 2015 [23]. The most common issue in both surveys was a 'lack of best practice examples and return on investment information' [23: p. 9], indicating that the potential benefits of MBCD listed above are yet to be quantified. The most common MBCD success recorded in the survey was that MBCD provided 'clearer understanding of the problem space' [23: p. 11]. Several key insights were also uncovered from the survey data, including a reiteration of the need for MBCD practitioners to implement a methodology, as well as the need for modelling to be performed with a clear purpose to avoid 'modelling for the sake of modelling' [23: p. 11]. Although the survey responses were mostly from people who had performed MBCD in the North America and Oceania regions [23: p. 6], the data appears to be useful for understanding the challenges faced, and the benefits realised, when implementing MBCD.

3.3.1.1 Defence MBCD

3.3.1.1.1 MBCD in the Australian Defence Organisation

The state of model-based approaches to Australian Defence capability development activities was described in a 2012 paper co-authored by the researcher as [28: p.1]:

> ‘Australian Defence capability definition currently stands in a transition phase for the INCOSE anticipated [78] transformation from document-centric to model-centric systems engineering. During this transition phase, which has been referred to as a transition along a continuum of centricity [79], a combination of model-centric and document-centric systems engineering is being performed. In this combined approach, the Capability Engineer utilises model-based techniques to generate document-based deliverables [28].’

In a later paper, Hue [80: p. 17] described the state of MBCD in Australia during 2014 as:

> ‘Model-based approaches have been employed early in the capability development process with some success; however, initial forays into MBSE in Australian Defence have been constrained by policy to automated generation of the Operational Concept Document and Function and Performance Specification using customised scripts from models created in a specific vendor tool.’

Hue went on to state [80: p. 17]:

> ‘While model-based methodologies…are well matured in industry, extending a model-based approach more broadly to the earlier stages of concept exploration and development in Australia in lieu of documentation for defence acquisition required more deliberation.’

The team that developed the Whole-of-System Analytical Framework (WSAF) were early adopters of MBSE and MBCD within Defence acquisitions. In 2012, the author noted [27: p. 3]:

> ‘The WSAF was initially developed to provide an architectural method for defining capability analysis [81]. It has since been expanded into the capability definition domain [82] whilst maintaining Department of Defense Architecture Framework (DoDAF) compliance. The WSAF also has the advantages of previously being extended for use with Model-Based Systems Engineering (MBSE) tools and is underpinned by MBSE

> principles and methods [82]. The WSAF is also gaining increasing acceptance within the ADO[4] from repeated usage."

In 2014, the WSAF was endorsed for MBSE practice within the Defence Group responsible for early-phase capability development activities at the time [83]. The WSAF approach has since been successfully used during early-phase acquisition activities in a good number of Defence acquisition projects.

The WSAF has also been utilised in several research efforts within the Australian context. These efforts include a study into suitable MBSE methodologies for early-phase capability development by Power *et al.* [84], the development and evaluation of a Model-Based Technical Risk Assessment approach by Cook *et al.* [85], and the researcher's work ([27], [29], [30], [13] and [17]).

With a focus on Defence being a 'smart buyer' in the Interim Capability Lifecycle Manual (ICLCM) [4], and the emphasis within Defence acquisitions to maintain traceability of requirements, it would seem that model-based approaches such as the WSAF can go a long way to providing the support required to facilitate smart buying. A potential enhancement to the WSAF would be to integrate the analytical activities that support requirements definition into the approach.

3.3.1.1.2 MBCD in the United States of America Department of Defense

In the US DoD there is an initiative termed "Digital Engineering" that is being championed by the Office of the Deputy Assistant Secretary of Defense Systems Engineering (ODASD(SE)). The ODASD(SE) states that Digital Engineering, which is synonymous with MBSE in the US DoD [86]:

> 'has the potential to promote greater efficiency and coherence in defense programs by ensuring stakeholders have access to accurate, relevant, and consistent information throughout the life of a program.'

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[4] ADO = Australian Defence Organisation

The Digital Engineering Working Group has released a useful set of fundamentals [87] to apply when adopting model-based approaches to support acquisition. These fundamentals include [87]:

- Programs can use a digital model to develop depictions of the system to support activities including: requirements analysis, architecture design and cost trades, design evaluations, optimisations, system and subsystem definition and integration, cost estimation, risk management, and scheduling.
- Programs should develop system models using standard model representations, methods and underlying data structures (metamodels).
- At a minimum, the model should trace from operational capabilities through to requirements, design constructs, test, training and sustainment.
- Models can be used by Systems Engineers to define, understand, evaluate communicate and indicate the project scope and maintain an 'authoritative source' about the system. The system model can also be used to produce documentation and other artefacts to support program decisions.

This initiative appears to be in its infancy and its website provides an insight into the maturity of model-based practice within the US DoD with [86]:

> 'The Digital Engineering Working Group will help promote digital engineering principles throughout the services and in other government agencies. It will explore ways to transfer traditional acquisition processes to a digital model-centric environment, and it will develop and implement the digital engineering concept across engineering functions and within the Defense Acquisition System.'

While examples of model-based approaches to support acquisition in the US DoD have been found, uptake appears to be patchy. The examples of the Framework for Assessing Cost and Technology (FACT) by Ender *et al.* [88] and Whole Systems Trade Analysis (WSTA) by Edwards *et al.* [89] appear to be outliers (however, they are excellent examples of what can be achieved when resources are applied to developing model-based approaches) rather than common practice. That the Digital Engineering initiative has been established to promote model-based approaches to support acquisition reinforces this viewpoint. However, it is worth noting the model-based approaches

FACT and WSTA appear to have required significant developmental effort to create bespoke software packages. These approaches also appear to be domain specific and require significant human and computational effort to implement – resources that are typically not present in Australian naval ship acquisitions.

The establishment of the Digital Engineering initiative is a positive step towards wider implementation of MBCD approaches to support US Defence acquisition and the research covered in this thesis could provide another example to support the initiative.

3.3.1.1.3 MBCD in the United Kingdom Ministry of Defence

No specific mention of the use of model-based approaches other than DOORS® for requirements modelling could be found in the UK MoD Acquisition System Handbook (ASH) [49]. The ASH references the MoD System-of-Systems Approach (SOSA), which is described on the acquisition website as [51]:

> ‘The SOSA represents the way in which UK Defence applies Systems Engineering or Systems Approaches best practice to achieve effective and affordable military capability.’

Unfortunately, the details on the SOSA are not available to people without access to the MoD intranet. This makes it difficult to ascertain the level of adoption of model-based approaches to support early stage capability acquisition activities. Nonetheless, evidence of model-based approaches to support SOSA activities was found in Coffield [9], who describes ‘capability reference frameworks’ as [9: p. 41]:

> ‘build(ing) upon a common underpinning metamodel (typically the Ministry of Defence Architecture Framework - MODAF) to enable federation and reuse of common elements.’

Coffield goes on to state that the capability reference frameworks [9: p. 41]:

> ‘provide a high level logical construct of how capabilities link together. They provide a common framework and common language (taxonomy) to exchange information across defence.’

Coffield describes the key benefits of the model-based capability reference frameworks include [9: p. 41]:

- A common language to describe capabilities
- Understanding of capability boundaries and dependencies
- Integrated evidence to support decisions
- Support for development of user requirement documents and concepts of employment
- Validation of user requirement documents and concepts of employment
- Enhanced communication

Coffield provides an insight to the pervasiveness of the SOSA and hence model-based approaches within UK MoD acquisitions with [9: p. 41]:

> ‘Engineers applied SOSA to over 140 projects and it continues to deliver benefits to the defence enterprise. There is a general agreement that SOSA provides better management of defence-level risks, improved evidence-based decision making, optimisation of investment in key enablers, improved management of dependencies, improved functional, horizontal, temporal and functional coherence, and improved operational agility of military capabilities.’

These benefits experienced at the enterprise level in the UK MoD, particularly the improvement of evidence-based decision making, provide a good case for the adoption of model-based approaches at the individual system level acquisition projects.

3.3.1.2 Non-Naval Ship MBCD Methodologies

A summary of the general MBCD methodologies identified within the open literature and reviewed for this chapter, along with the features, or approaches they comprise is given in Table 2. In the table, acronyms for the approaches the MBCD methodologies include are: Model-Based Systems Engineering (MBSE), Modelling and Simulation (M&S), Design Space Exploration (DSE) and Multi-Disciplinary Analysis and Optimisation (MDAO). These methodologies were rarely identified in the literature as MBCD and could conceivably be labelled model-centric, simulation-based or model-driven methodologies as well. However, given the broader interpretation of MBCD in

Section 3.3 above, the author believes they can be classed as examples of MBCD. This list is not intended to be exhaustive and it is likely there are many MBCD methodologies employed within large companies that are not published in the open literature.

Table 2: Summary of general MBCD methodologies reviewed and the approaches they include.

MBCD Methodology and Key References	**MBSE**	**M&S**	**DSE**	**MDAO**	**Resilient Systems**	**Other**	**Comments**
Framework for Assessing Cost and Technology (FACT) [88], [90]	X	X	X			Also used an architectural pattern (WBS) and ‘middle-out’ SE.	Developed for land vehicles. Comparisons between design options can be made.
IMCSE [91], [92]	X	X	X		X	Also incorporates epoch-era analysis, data visualisation and value models.	Not constrained to conceptual design.
WSAF [82], [81]	X	X				Also developed tools to generate specification documents (MBSE tool specific).	M&S performed separately.
SysDICE [76]	X	X				Includes option evaluation	Developed for mechatronic domain.
Steimel *et al.* Chemical Process MBCD [93]		X		X			Approach models chemical process structure, which is simulated and optimised using MDAO.
GATech ASDL Aircraft Design Process [94]		X	X			Includes option evaluation.	Uses House of Quality to manage and allocate requirements.
GATech UTE [95], [96]		X	X			Uses Response Surface Methods to develop a design space comprising requirements and vehicle characteristics.	Introduces technology aspects to the design space (i.e. sensitivity of design space to technology improvements).
Whole Systems Trade Analysis (WSTA) [89]		X	X	X		Includes option evaluation and a WBS design pattern.	Focused on land vehicles. Maps from functional requirements to components using stakeholder input.

3.3.1.3 Naval Ship MBCD

Although the conceptual design phase is a topic of much discussion in the naval architecture literature, no specific mention of MBCD was found. Nonetheless, evidence of applying model-based methodologies during conceptual design of naval ships was identified. These methodologies and the features of MBCD they include are summarised in Table 3. The acronyms used for the approaches the methodologies include are the same as those in Table 2 above.

Table 3: Summary of naval ship MBCD methodologies reviewed and the approaches they include.

MBCD Methodology and Key References	**MBSE**	**M&S**	**DSE**	**MDAO**	**Resilient Systems**	**Other**	**Comments**
Virginia Tech. Concept & Requirements Exploration (C&RE) [97], [98], [99] and [100]	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.
Off-the-Shelf C&RE [13]	X	X	X			Includes integrated MBSE and M&S.	Uses MBSE for requirements, architecture and parametrics, along with integrated M&S and DSE.
Response Surface Methods (RSM) Approach [101] and [72]		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.
WSAF [29]	X	X	X				MBSE integrated with M&S via parametrics.
SubOA/IPSM [102]/[103]		X	X				Both approaches use OEMs for submarine option/configuration evaluation during conceptual design. No integration with MBSE models.
Design Building Block (DBB) [97] and [104]		X	X			Hullform’s performance (e.g. seakeeping, resistance and stability) can simulated using synthesised CAD model.	Approach facilitates rapid synthesis of a Computer Aided Design (CAD) hullform based on ship functions.

While the features used in MBCD methodologies were reasonably common for naval ships and other systems, there are differences in the level of integration of models (less integration in naval ship MBCD) and types of Modelling and Simulation (M&S) (i.e.

more Operational Effectiveness Model (OEM) type M&S in naval ship MBCD). Both naval ship and general MBCD methodologies included some option evaluation.

3.3.2 Modelling and Simulation

Modelling and simulation (M&S) has been identified as being valuable for conceptual design for many years. Aughenbaugh and Paredis [105] 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 [106], or [59]). They 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' [105: 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' [105: p. 3].

A theme of integrating system (MBSE) models and system analytical, or behaviour models begins to appear in the open literature around 2005. Branscomb *et al*. [107] in 2013 noted that 'although there have been several research efforts that have focused on enabling analysis of systems within an MBSE context, most of these previous efforts have focused on the integration between a SysML (Systems Modelling Language [108]) tool and a variety of analysis tools' [107: p. 80]. Other MBSE approaches such as the Object Process Methodology (OPM) [11], Vitech CORE® approach have been integrated with behaviour modelling using either open source or proprietary means. 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' [109: p. 296].

From the literature reviewed on integrated MBSE and M&S models, tools are available, however, the state-of-practice is still relatively immature. Nonetheless, there is widespread use of M&S in conceptual design. More widespread adoption of integrated MBSE and M&S during conceptual design appears to be the next step in the state-of-practice.

3.3.2.1 M&S in Naval Ship Conceptual Design

M&S was a feature of all the naval platform MBCD methodologies in Table 3. Only two of all the MBCD methodologies in Table 2 and Table 3 incorporated integrated MBSE and M&S ([29] and [13]). It is worth noting these two MBCD methodologies utilised simple M&S (parametric and surrogate) models. The other naval platform MBCD methodologies utilised more complex M&S models (Operational Effectiveness Models (OEMs)) and maintained either separate M&S and MBSE models, or no MBSE model. Albarello and Kim note the difficulty of integrating MBSE and more complex M&S models with 'currently, system level analysis from within the SysML modelling tools is generally limited to the evaluation of simple parametric equations' [110: p. 86].

Integrated MBSE and M&S aligns with guiding principles one and two for identifying suitable approaches to support the early phases of naval platform acquisitions, 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 a defensible business case for the acquisition project milestones.

3.3.3 Design Space Exploration

Kang *et al.* define Design Space Exploration (DSE) as 'the activity of discovering and evaluating design alternatives during system development' [111: p. 1]. Other authors, such as Spero *et al.* [63], along with Ross and Hastings [112] refer to DSE as Tradespace Exploration (TSE), with Ross defining the tradespace as 'the space of possible design options' [112: p. 2]. They go on to discuss the need for tradespace exploration during conceptual design with [112: p. 3]:

> 'The design process can be thought of as a space of decisions that designers constantly prune in order to reduce the set of alternatives before settling on a "solution" to the problem at hand...premature focusing, however, can introduce artificial constraints on the design process and reduce the potential value created and delivered to the customers.'

Haveman and Bonnema [109] propose the generalised DSE process shown in Figure 17.

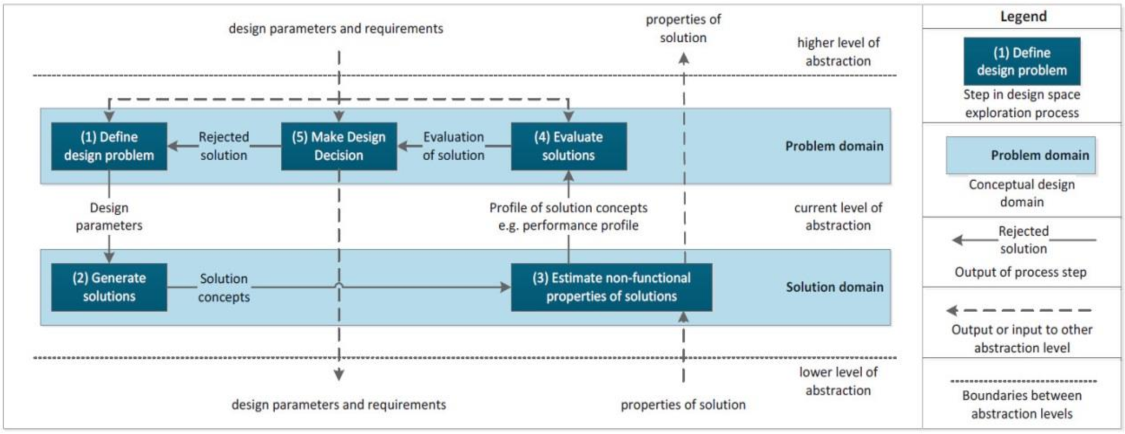

Figure 17: Generalised DSE process from Haveman and Bonnema [109].

As shown in Figure 17, Haveman and Bonnema [109] propose a generic five-step iterative process for DSE:

1. Define the design problem,
2. Generate solutions,
3. Estimate non-functional properties (e.g. performance) of solutions,
4. Evaluate the solutions,
5. Make the design decision.

Typically, M&S is the means by which the non-functional properties are estimated in this process and the evaluation typically utilises some form of value model. Recent DSE research efforts have focused on developing frameworks for conducting DSE. The frameworks have been developed in order to ensure the DSE covers the broadest range of designs possible. The frameworks can be grouped under three top-level categories:

i. **Structured DSE** – Exploration using algorithms to ‘jump around’ the design space (e.g. see [111]).
ii. **Value-Driven DSE** – Exploration using Multi-Attribute Utility, or other value models (e.g. see [112]), where the end-user’s preferences, or weights, are applied to the metrics used in the DSE.
iii. **Data-Driven DSE** – the exploration is achieved iteratively through interactions with those doing the M&S and the stakeholders who are informed by the M&S (e.g. see [63] and [109]).

3.3.3.1 DSE in Naval Ship Conceptual Design

In naval ship conceptual design, the terms synonymous with DSE are Concept and Requirements Exploration (C&RE) and 'requirements elucidation' depending on which side of the Atlantic Ocean the author resides. Brown, from the US side of the Atlantic states: 'During C&RE we use a total systems approach, including an efficient search of the design space…' [100: p. 2]. Similarly, McDonald *et al.*, from the UK side of the Atlantic [104: 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 of the naval platform MBCD methodologies reviewed in Table 3 contained DSE in either a value-driven (Virginia Tech. 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). It is worth noting that for the OTS acquisition case, the concept exploration will be constrained to a search of the existing ship design space. All of the naval ship MBCD approaches in Table 3 utilised M&S in the DSE. M&S introduces uncertainties into analysis due to its approximate nature. Ross and Hastings [112] suggested that DSE could be improved through the introduction of approaches to deal with uncertainty.

DSE, in the form of C&RE, was identified as an approach that could support early-phase naval ship acquisition activities as it aligns with guiding principle two from Section 3.1, i.e. it supports defensible decision making that accounts for competing goals and objectives.

3.3.4 Multidisciplinary Design Analysis and Optimisation

Multidisciplinary Design Analysis and Optimisation (MDAO), synonymous with Multidisciplinary Design Optimisation (MDO) [113], is a feature of conceptual design that has become prevalent, particularly in the aerospace, mechanical, automobile and electric/electronic engineering industries in the last 25 or so years [114: p. 1]. MDAO tools are usually linked to M&S, which can lead to a limitation of MDO due to the computational expense involved [115: p. 4]. Periaux *et al* state [115: p. 3]:

> ‘MD(A)O refers to an approach that formalises the design process accounting for the interaction amongst the different physics involved, while optimising for a number of objectives and constraints.’

Schweiger *et al.* [116: p. 3], along with Mavris and Pinon [61: p. 6] highlight the region in the system lifecycle where MDAO is most efficient and has the most benefit is the conceptual design phase, as shown in Figure 18. In part, this benefit is due to the fact that empirical data and experience from previous similar designs can be used to help address the lack of relevant knowledge about the solution at the concept stage [116: p. 3]. They go on to note that this ‘…is fine as long as the new project is more or less a derivative of previous ones…’ [116: p. 3].

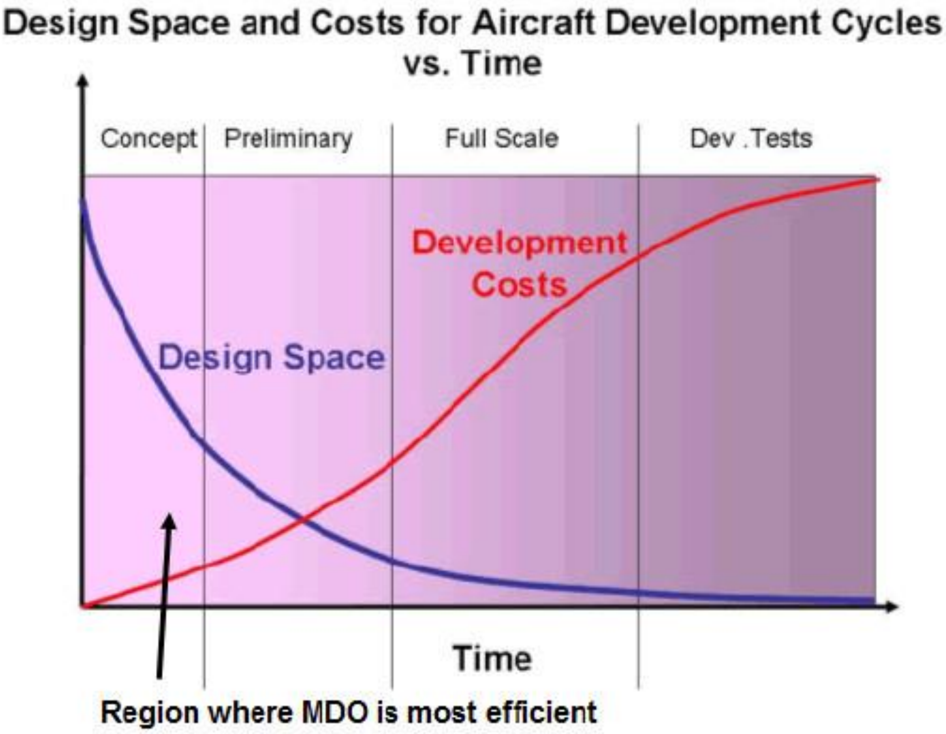

Figure 18: Region where MDO is most useful according to Schweiger et al. [116].

Pahl and Beitz, although discussing design in general make the interesting note that [36: p. 2]:

> ‘In *systematic* respects, designing is the optimisation of given objectives within partly conflicting constraints. Requirements change with time, so that a particular solution can only be optimised in a particular set of circumstances.’

From this, it could be inferred that while MDO provides an approach to optimise competing objectives during conceptual design, this optimisation will only be valid for the requirements at a given point in time. If requirements change, which they often do during conceptual design, then the optimised design may no longer be optimal due to a change in the competing objectives. Rhodes and Ross note the challenge of changing requirements with MDAO (as well as for DSE), together with a potential conflict between MDAO, DSE and system resilience (discussed in Section 3.2.1) [91: p. 37-38]. They propose Epoch-Era Analysis as a means of incorporating changing requirements and environments during early system design [117]. It is also worth noting that only one of the MBCD methodologies reviewed in Table 2 included MDAO.

3.3.4.1 MDAO in Naval Ship Conceptual Design

Naval ships, being an example of a system where multiple objectives interact, seem to be well suited to MDAO. However, the scope of applications within the open literature covering naval architecture conceptual design is relatively narrow. MDAO has most commonly been applied to hydrodynamic optimisation of hullforms (see for example [118], [119] and [68]). Ayob *et al.* provide a reason for this with [120: p. 1]:

> ‘Single or multi-objective hydrodynamic design optimisation is important as it aids designers to arrive at satisfying hullform designs while simultaneously considering loading, powering, manoeuvring, seakeeping and cost considerations.’

Of the naval platform MBCD methodologies reviewed in Table 3, only the Virginia Tech. C&RE methodology included MDAO. In this approach, MDAO is used to identify non-dominated naval platform design solutions in terms of overall mission effectiveness, cost and risk [97]. Non-dominated solutions are those for which no better solution exists to a specified problem and constraints [97]. Again, the suitability of MDAO to the early phases of design is questioned in the naval architecture literature, with Andrews [121] noting the need to recognise the limitations of optimisation during conceptual design in supporting a creative and divergent approach.

3.3.5 Model-Based Product Line Engineering

Product Line Engineering (PLE) is an approach to product development that has grown from production line intensive industries, such as the automotive, into becoming prevalent in the software development field [122]. Hummell and Hause describe PLE as: 'a method that defines the underlying architecture of an organisations product platform' [123: p. 4]. Pohl *et al.* [122: p. 4-7] identify the following principles of PLE:

- **Mass Customisation** – the large-scale production of goods tailored to customer's needs.
- **Platforms** – a base of technologies upon which other technologies or processes can be built.
- **Combined Platform-Based Development and Mass Customisation**

Model-Based PLE (MB-PLE) appears to have evolved from variability modelling. Pohl *et al.* [122: p. 74-75] describe an approach to variability modelling for PLE they call *Orthogonal Variability Modelling* (OVM), where the variability model, which defines the variability of a product line, is separate to the system development models. Pohl *et al*. note a perceived shortcoming with attempting to integrate traditional system models (such as UML and SysML models) with OVM [122: p. 99]: 'In their basic forms, these models are mostly not able to document variability as required by software PLE' because the diagrams only represent an instance of the variability (i.e. a product). They go on to note that 'diverse extensions of model-based requirements artefacts have been proposed by research and industry such as the use of stereotypes in UML diagrams' [122: p. 99] to overcome this issue.

A recent example of such an extension of a modelling language to PLE is given in a model-based approach to PLE proposed by Hummell and Hause [123] that integrates OVM with SysML. Hummell and Hause [123] address the Pohl *et al.* [122] perceived shortcoming of SysML (i.e. its inability to capture a product line's variability) through the use of a '150% model' [123: p. 4]:

> 'The Variant Model and the Base System or Software Family Model together represent the Product Line Model, also frequently referred to as the 150% Model or the Overloaded Bill-of-Materials (BoM). This is a full

> representation of the product line, with all of its commonality and variation.'

Hummell and House assert that dependency can be created in either OVM models or SysML models with [123: p. 4]:

- 'Dependencies can be created to all types of base model elements:
    - Structural such as UML classes, SysML blocks or parts
    - Behavioural such as Use Cases, Transitions or States
- In order to express this dependency, base model elements can be shown on Variability Diagrams and Variable Elements can be shown on Base Model Diagrams.'

An example of this dependency between OVM and SysML models is shown in Figure 19.

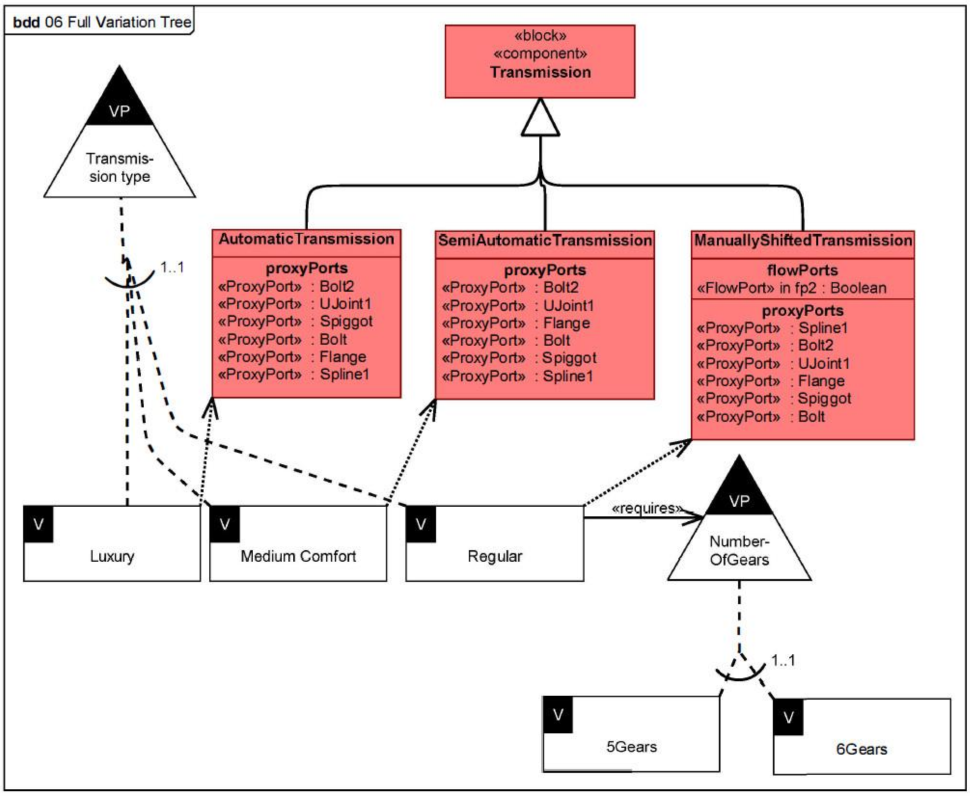

Figure 19: Example of a SysML-based model diagram showing the OVM variable elements [123].

Hummell and Hause highlight the benefits of MB-PLE with [123: p. 7]: "Independent survey results have shown that applying MB-PLE approaches can reduce total development costs by 62% and deliver 23% more products on time."

3.3.5.1 MB-PLE in Naval Ship Conceptual Design

While initially appearing to be suitable for naval vessel conceptual design, only one paper on MB-PLE by Hause and Hallett [124], which proposed an approach to plan and track submarine configurations, was found. This approach seems to be useful for planning subsystem upgrades and technology insertions during a naval platform's lifecycle, as well as planning for batch upgrades during construction of a series of submarines. Corl *et al.* [125] provide an indication that MB-PLE could be useful in naval vessel MBCD, with a methodology for optimising commonality decisions in multiple ship classes. They state [125: p. 626] 'in ship design, common hull blocks, main engines, engine rooms, ship service electrical generators, sensors and weapons can be used to provide commonality across multiple ship class variants.' While commonality has the potential to reduce procurement and through life costs of naval platforms, this will be offset with a 'loss of performance compared to the use of the optimal design developed for each class individually' [125: p. 626]. These aspects make MB-PLE appealing for ship designers wishing to track ship and submarine platform configurations and commonality across their design catalogue. However, the utility of MB-PLE to support acquisition stakeholders during the early phases of a project is less apparent.

3.3.6 Pattern-Based Methods

Pattern-Based Methods have arisen from the design patterns used by architects and planners in the late 1970s, which in turn, were adopted by software engineers in the early 1990s [126: p. 322]. Design patterns have been described as '...a way practitioners can represent invariant knowledge and experience in design' [126: p. 323]. The use of architectural design patterns in PLE is mentioned by Pohl *et al.* [122: p. 119] and Fant *et al*. [127], while Schindel and Peterson [128] assert that their approach to Pattern-Based Systems Engineering (PBSE), which is based on S*Patterns '…is an extension of the idea of the Platform (which is a configurable, reusable design' [128: p. 5]. The S*Pattern approach appears to extend the idea of Platform from PLE as it '…includes not only the platform, but all the extended system information (e.g., requirements, risk analysis, design trade-offs & alternatives, decision processes etc.)' [128: p. 5].

Schindel *et al.* allude to one of the purported benefits for PBSE with reference to Figure 20 [129: p. 3]:

> '…once an S*Pattern has been created for a given enterprise, product line, or other domain, it may be used during a delivery project to rapidly create a high-grade S*Model, typically an order of magnitude faster than by creating a new model, and configured for the specific needs at hand.'

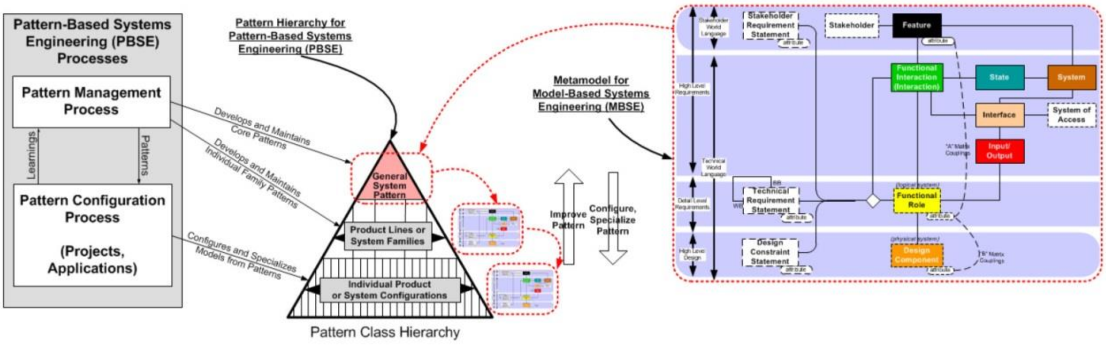

*Figure 20: S*Patterns are configured to create S*Models [129].*

Pfister *et al.* state that the objectives of design patterns in supporting humans to identify and solve problems are [126: p. 323]:

- 'To improve performance (comprehensiveness, relevance) and reliability (proven solutions, justified and context based),
- To gain economic value (time saving),
- To facilitate collaborative work by sharing design pattern repositories.'

3.3.6.1 PBSE in Naval Ship Conceptual Design

No literature on the topic of Pattern-Based Methods in naval ship design other than the researcher's work was found during this literature review. However, several generic structures that can conceivably be part of a design pattern are present in naval vessel conceptual design. Patterns are apparent in naval ship physical and functional architectures, as well as naval missions and performance measures. Design patterns that were identified in naval vessel design are given in Table 4.

Table 4: Design patterns that could be used in the naval platform option evaluation method [30].

Design Pattern	Pattern Describes	Uses
Universal Naval Task List (UNTL) [47]	Hierarchy of naval operational activities and measures	Building mission scenarios, Critical Operational Issues and performance evaluation criteria (KPPs)
Design Building Blocks (DBB) [130]	Naval platform functional architecture	Generic breakdown of naval platform functions into categories of fight, move, float and infrastructure
Extended Ship Work Breakdown Structure (ESWBS) [45]	Naval platform physical architecture	Generic breakdown of physical naval platform components, including loads and margins

Since pattern-based methods provide a means to reuse elements and knowledge from previous acquisitions, which should reduce the resources required in subsequent acquisition projects, they have been identified as having alignment with guiding principle three in Section 3.1.

3.4 Decision Support Methods

Decision support methods are not specific to the early phases of design or acquisition as design trades need to be made throughout the entire system development process.

3.4.1 Multi-Criteria Decision Making

Multi-Criteria Decision Making (MCDM) is a field of research that has grown since the late 1970s [131] to deal with decision problems having multiple competing objectives. MCDM methods have been developed with the purpose ‘to help the decision maker think systematically about complex decision problems and to improve the quality of the resulting decisions’ [131: p. 3]. MCDM therefore aligns with guiding principle two in Section 3.1 and could be used to support the evaluation and selection of OTS capability solutions submitted in response to a request for information, or request for tender in Defence acquisition projects.

Two top-level categories of MCDM have been developed: multiple-objective and multiple-attribute problems [131: p. 4]. Multiple-objective problems are characterised by a problem with a large number of feasible solution alternatives from within a continuous decision space [132], whereas multiple-attribute problems generally have relatively fewer solution alternatives [131: p. 4] from a discrete decision space [132]. OTS Defence capability acquisition projects are an example of a multiple-attribute problem.

MCDM methods available for multiple-attribute problems include; scoring methods, multi-attribute value analysis (MAV), multi-attribute utility theory (MAUT) and the Analytical Hierarchy Process (AHP) [131]. These methods share the typical steps involved in decision making techniques [132: p. 5-6]:

1. Determine the relevant criteria and alternatives.
2. Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.
3. Process the numerical values to determine a ranking of each alternative.

Several approaches, such as the use of value curves and swing weights [133], as well as the Rank Order Centroid (ROC) technique to elicit criteria weights [134] can be used during an evaluation to ensure the MCDM method is applied in a robust manner.

3.4.1.1 MCDM in Naval Ship Conceptual Design

During an OTS naval ship acquisition, responses to a request for tender (RFT) will need to be evaluated in order to select the most viable design prior to the acquisition stage. The researcher has previously noted that [17: p. 5] 'This evaluation is likely to be a focus of any oversight committee due to the typically large amount of taxpayer money at stake.' Also noted by the researcher [30: p. 6]:

> 'Naval platform 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.'

More broadly in the open literature covering naval ship design and acquisition, MCDM methods have been used in the Virginia Tech C&RE approach, where AHP is used to generate an Overall Measure of Effectiveness for mission performance (see [99], [135] and [100]). AHP was also used by Hootman (see [101] and [136]) in his framework for ship design and acquisition. Hootman describes his approach to MCDM as a philosophy and notes key characteristics of this philosophy include [136: p. 49]:

- The MCDM and Measure of Merit (MOM) hierarchy should be identical,
- Weighting schemes should be avoided when used with top-level MOMs. However, weighting methods for rolling-up lower level MOMs can be used when applied with AHP and Pareto analysis.

While agreeing with most of Hootman's thoughts above, the researcher has previously discussed the applicability of AHP to OTS naval platform option evaluation with [30: p. 6]:

> 'The need to make pairwise comparisons of attributes in the AHP, make it infeasible due the large number of attributes that typically need to be considered for naval platforms.'

3.5 Chapter Conclusions

This chapter covered a review of the open literature to identify approaches that could support the early phases of Australian Defence OTS naval platform acquisitions. Identification of suitable approaches was based on three guiding principles given in Section 3.1 that were linked to recurring themes within reviews of Defence. Three categories of approaches were reviewed: conceptual design processes, model-based methods, and decision support methods. Within these three categories, eight key approaches that adhered to the guiding principles were identified: Model-Based Conceptual Design (MBCD), Modelling and Simulation (M&S), Design Space Exploration (DSE), Multi-Disciplinary Analysis and Optimisation (MDAO), Resilient Systems, Model-Based Product Line Engineering (MB-PLE), Pattern-Based Methods and Multi-Criteria Decision Making (MCDM). Of these eight, MDAO and MB-PLE have the least potential to provide support to Defence OTS naval ship acquisition projects. MDAO appears to be better suited to developmental acquisition programs as there is no need to optimise a design during the early phases of OTS naval ship acquisitions. MB-PLE has been demonstrated to be useful to track and manage naval ship configurations, which will be beneficial in the later phases of OTS acquisition programs that adopt a batch-build strategy.

MBCD, M&S, DSE, Resilient Systems, Pattern-Based Methods and MCDM appear to have the most potential to supporting OTS naval ship acquisition. This potential lies in their ability to address the three guiding principles, as well as their previous use in naval ship design and acquisition. MBCD enables the structure and traceability of MBSE to be integrated with a range of model types, as well as providing the ability to reuse models. M&S, particularly in combination with DSE during conceptual design can provide evidence to aid defensible business cases for decision gate milestones in acquisition projects. SBD provides a means of incorporating a resilient systems approach to OTS naval ship acquisitions by considering a broad design space that is more capable of absorbing changes in operational requirements than a point-based design approach. Pattern-based methods provide a means to reuse elements and knowledge from previous acquisitions, which should reduce the resources required in subsequent acquisition projects. The systematic approach to decision making inherent in MCDM techniques makes it highly suitable to the option evaluation activities within OTS naval ship acquisitions.

While some of these individual approaches that can support the early phases of OTS naval ship acquisition have been combined as part of an MBCD methodology, they have not all been previously combined into a single model-based methodology comprising a process, methods and tools. Acquisition practitioners, particularly those of us working in environments with constrained resources, are likely to find it useful if these models could be integrated in order to maintain traceability of the acquisition activities and products to the originating capability needs. Furthermore, once tools to implement approaches such as M&S and DSE are integrated, the human and financial resources required to implement the methodology in subsequent OTS naval acquisitions with similar capability needs will be significantly reduced. The integration of software tools, which has been demonstrated in some of the MBCD methodologies reviewed in Table 2 and Table 3, can now be achieved using commercial software integration tools.

Finally, it is noteworthy that all of the approaches are used during the design of a system, which relates back to the opening quote of the chapter that design and requirements development activities are the same. Performing these design activities alongside the more traditional requirements engineering activities and integrating them into an MBCD methodology, will support Australian OTS naval ship activities in addressing the recurring themes from the numerous reviews of Defence acquisitions.

Chapter 4 – Identifying a Suitable Research Methodology

4.1 Introduction

According to Leedy and Ormrod [137: p. 64], research originates by asking an unanswered question, or identifying an unsolved problem. The unsolved research problem for this project has been identified as:

> *During the early phases of Australian Defence naval ship acquisition, how can stakeholders be supported to develop robust, defensible business cases (for milestone decisions) that result in the acquisition of a naval ship that appropriately addresses the capability need?*

Consideration now needs to be given to the method by which to conduct the research. Ferris [138] asserts that in most academic disciplines, there are only a few research methodologies that will be applicable and that these will not change until there is a paradigm shift within the discipline. However, there is an emerging view that Systems Engineering (SE) (which also infers Model-Based Systems Engineering (MBSE)) can be viewed as a transdiscipline [139]. This is particularly true of the present research project as it will integrate the discipline of naval architecture as well. This means there is likely to be many suitable methodologies, spanning the physical and social sciences ([138] [140]) that can be applied when conducting research into MBSE. Ferris *et al.* [141: p. 832] provide some insight into the nature of conducting research into SE with the statement:

> '…diversity of research methods is appropriate to the nature of the subject matter in SE, and that the outcome of research, likewise, will not be a unified theory of SE, but rather a number of interacting elements which need to be held close, but cannot be linked to make a monolithic whole.'

The problems typically of interest for research in the SE field, tend to be both technical and social in nature [142]. An overview of the recent literature covering the methodologies available for SE research given by Brown [140] identifies the following approaches:

- Case Studies
- Empirical Research
- Grounded Theory
- Value Laden Systems Approach
- Engineering Design

Ferris *et al*. [141: p. 825] propose that 'the ultimate purpose of (SE) research is to improve the ability to deliver systems that satisfy the needs of the procurer' and that the following methods are appropriate:

- Scholarship
- Positivist Hypothesis Testing
- Applications Driven Research
- Action Research
- Case Studies

In a later paper, Ferris [138] uses a philosophical angle to propose a taxonomy of research methods for SE and gives the following research methods as examples that fit within the taxonomy:

- Positivist Hypothesis Testing
- Action Research
- Grounded Theory
- Engineering Design

Within these methodologies that have been identified as suitable for SE research, only qualitative methodologies will be suitable for the research problem at hand. This is because the research problem above describes a complex situation that needs to be better understood [137]. Furthermore, to answer the "how" in the research problem, a new artefact will need to be constructed. The need to construct artefacts during research in software engineering, which can be seen to be analogous to research in SE due to its technical and social nature, has been noted by Génova *et al.* with [143: p. 116]:

> 'In the last decades of the 20th century a growing conviction consolidated: the scientific method developed for studying and analysing *natural*

> *phenomena* was not apt to understand the design and construction of *human artefacts*.'

In response to this requirement for new research methodologies, Génova *et al.*[143] identify the emergence of *design science* for construction-oriented research that is based on the identification of a need. An artefact is then constructed and evaluated in response to the need [143]. Génova *et al.*[143: p. 116] also note:

> 'the concept of "artefact" encompasses not only physical devices, but also conceptual and social systems: information structures, knowledge representations, methods, processes, organisations, etc.'

Design science and action research have been described as *interventionist* research methodologies [26, 144]. Piirainen and Gonzalez [26] compare another interventionist methodology, the Constructive Research Approach (CRA) with design science and note the many similarities between the two methods. The key difference appears to be the 'instantiation' of the artefact constructed in the CRA in order to validate it, which isn't required in design science [26].

4.2 Candidate Research Methodologies

From the numerous research methodologies identified in Section 4.1, the candidates that are most suitable for the research problem at hand are those that are relevant to SE, are qualitative in nature and involve the construction of an artefact. There may also be a case for a mixed-method approach to address the research problem. With these aspects in mind, the candidate research methodologies are: case studies, empirical research, grounded theory, engineering design and design science, action research and the constructive research approach. In the following subsections, each of these research methodologies is discussed and evaluated for its suitability for the research project.

4.2.1 Case Study Research

Case study research is suitable when the research question is of the form 'how' or 'why', but it is associated with issues of validity [140]. A case study is a qualitative research method where the researcher collects data, such as observations, interviews or documents, on the events, programs or individuals of interest [137]. Details that provide context to the case of interest, such as historical, social and economic factors are also recorded [137]. The collected data can be organised, categorised, interpreted, and patterns identified that can be used to draw conclusions, or generalisations [137]. The case study will generally be suitable for learning about a poorly understood situation and investigating how a program (or individuals) changes over time [137]. Case studies will struggle with external validity as the results may not be applicable to other situations [140].

This methodology doesn't explicitly involve the construction of an artefact, but could be combined with another methodology in a mixed-method approach. A key issue with this approach for Defence naval ship acquisitions will be data collection. These acquisition projects are undertaken relatively infrequently and involve classified elements, which will limit the dissemination of the data as well.

4.2.2 Empirical Research

Valerdi and Davidz [142] champion the use of empirical research in SE and describe the scientific process for systems engineering as shown in Figure 21.

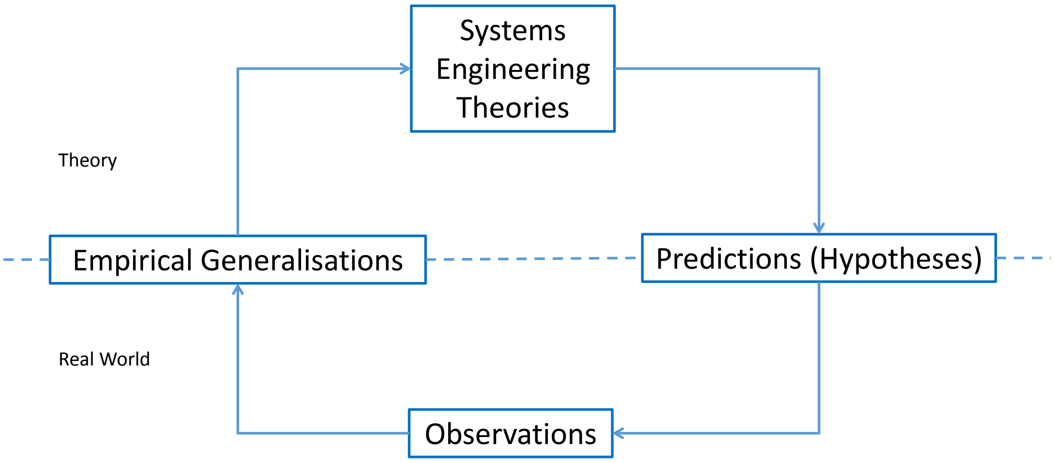

Figure 21: The scientific process for SE [142].

An empirical research approach may allow causal relationships to be uncovered [142] and either build or test theory, but as a general rule, qualitative studies (which are intrinsically part of empirical research) by themselves do not allow the researcher to identify these relationships [137]. In order to identify causal relationships, quantitative research, particularly experimental studies, are required [137]. This would mean adopting a mixed-method approach for the present research project. Valerdi and Davidz [142] also note the following four challenges facing empirical research in SE, which also apply to MBSE.

i. Relative immaturity of the field
ii. Lack of appreciation for empirical research
iii. Lack of access to data – often due to small sample sizes
iv. Lack of accepted metrics

As with all research comprising qualitative components, the empirical research approach will have validity issues to overcome [137], but measures can be borrowed from social science research to help address them [142]. While empirical research appears to be a worthy goal for SE research to strive for, the practical nature of much SE research and the issues identified above limits its suitability for the present research.

4.2.3 Grounded Theory

Grounded theory research is a qualitative approach where data is gathered (not from the literature, but the field, which makes it grounded) and examined in order to derive a theory. It is unique in that it begins with the collection of data, which is then used to develop a theory [137]. The grounded theory approach appears to have been extensively utilised in combination with the action research methodology described later. This is due to the research commencing without an hypothesis, but rather an assembly of data, from which action is taken (see for example [145], [146]). However, whether all of these studies are truly using a grounded theory methodology is debatable as the assembled data is often the experience of the researcher undertaking the study.

A genuine grounded theory methodology can often be used in combination with other qualitative or quantitative methodologies in a mixed-method approach and the approach is often used where the study is focused on a process [137]. A study of this nature usually includes an interest in the people involved in the process's actions and interactions, with the main aim of the research being to develop a theory regarding the process [137].

4.2.4 Engineering Design and Design Science

Ferris [138] makes the proposition that an engineer creating a design to address a novel problem is actually conducting research because they are solving a problem. Through the process of solving the problem, the researcher or engineer develops the practice of design, which in turn adds to the body of knowledge within the field [138]. This is an interesting proposition, particularly in the field of Naval Architecture, where accepted design practice is to commence a new design by studying existing ships that have been designed to have a similar capability in order to develop the design space for a new ship. This design activity could be seen as the naval architect conducting grounded theory research into the body of knowledge created by other naval architects. The novelty within engineering design research lies within either the problem addressed, the method(s) used to solve the problem, or both [138].

Similarly, design science (DS) research seeks to make a contribution through identifying a problem, demonstrating no solution currently exists and then developing an artefact that is evaluated to determine its contribution [147]. The artefact is evaluated thoroughly prior to implementing it in a real world situation [147]. Design science contributes to the body of knowledge by seeking novel and innovative solutions to non-trivial problems [26]. DS should adhere to the guidelines [26: p. 63]:

1. Produce a viable artefact (construct, model, method or instantiation),
2. Develop (technological) solutions for important and relevant business problems,
3. Demonstrate utility, quality and efficacy of the design rigorously,
4. Provide a contribution (a) in the form of an artefact and/or instantiation and (b) to the foundations (knowledge base) of the design,
5. Apply a rigorous methodology to construction and evaluation of the artefact,
6. Search for means to attain under the constraints of the environment,
7. Present the results to both technology and management-oriented audiences.

DS appears to encompass a broader view of engineering design, since the viable artefact is not limited to being an engineering design.

4.2.5 Action Research

Action research is a method that focuses on finding a local solution to a local problem in a local setting [137], it can be very useful for undertaking a study within the researcher's organisation [140]. The researcher becomes a participant in the system or practice being studied and explores the best way to influence the practice in order to effect a desirable outcome [141]. As such, the research will generally have poor external validity unless steps are taken such as a declaration of the intellectual framework used by the researcher, so that it can be used in other relevant situations, [140].

This methodology is attractive to SE research as it has the potential to make both a contribution to the system or practice being studied, along with providing the researcher an opportunity to conduct a study [140]. This attractiveness is reflected in the use of action research for the development of Checkland's Soft Systems Methodology [140].

4.2.6 Constructive Research Approach

The constructive research approach (CRA) is an interventionist approach developed by Finnish accounting researchers in the 1990s [144]. 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' [25: p. 363]. CRA comprises the features as translated by Piirainen and Gonzalez [26]:

1. A focus 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.

4.3 Selecting a Suitable Research Methodology

The interventionist research paradigm, which includes the action research, design science and constructive research approaches, appears well suited to qualitative SE and MBSE research. This is due to the purpose of SE research given by Ferris *et al.* [141] above being to improve SE methods. This type of research has also been described as *development* research, since common characteristics of these methods include ‘design, constructed artefacts, and/or interventions’ [24: p. 240].

Many examples of interventions in SE and MBSE research exist in the open literature. In these examples, the author develops frameworks, or methodologies, for the application of SE to certain circumstances or situations. Generally, in these examples, it initially appears as though a qualitative method such as grounded theory has been used to generate a hypothesis in the form of a framework or methodology. In most cases, the author then attempts to close the empirical research loop shown in Figure 21 by applying the proposed framework to either a past, imagined, or real situation. This can be seen in examples such as [148], [149], [150], [27], [29], [13] and [30], where the main difference in approaches is the number of test cases used by the authors. This can have implications on the external validity of the proposed methodologies. On the other hand, these examples can be seen to provide examples of the use of the DS or CRA research methods in SE and MBSE research. The relatively high number of papers using these approaches to SE and MBSE research, even though they may not be identified as examples of CRA or DS by the authors, indicate they are well suited and regularly applied in SE and MBSE research. As noted by Jonsson and Lukka [144: p. 377]:

> ‘the boundaries between the various streams of interventionist research are blurry. Most of them define themselves in relation to the original action research by Kurt Lewin, and none of them has actually distanced very far from his core ideas. Therefore we can argue that the various streams of interventionist research form a cluster of research approaches.’

When comparing the CRA and DS approaches, Piirainen and Gonzalez [26] note the key difference lies in the development of the solution artifact for the problem being researched. For CRA they note [26: p. 64]:

> ‘In CRA the solution is based on deep knowledge of the problem and of existing theory and is found through a heuristic process.’

Whereas for DS, Piirainen and Gonzalez [26]: p. 64 note:

> ‘Stereotypically, one takes a previously unresolved problem and tries to find a kernel theory which can help solve the problem.’

The intervention context for the present research is Australian OTS naval ship acquisition projects. It is worth noting that while the researcher can be a participant in these projects and this can be used to inform the construction of an artifact that addresses the research problem, it is highly unlikely the artifact will be able to be market tested within a real acquisition project during the course of the research. Validation, or market testing of the methodology will then be a topic for future research. The final step of the DS method given above (to present the results to suitable audiences), could provide a means of validating the artifact. Feedback received on the results could be recommendations for future research prior to the deployment of the artefact to a Defence acquisition project. Using the comparison between CRA and DS above, it is unlikely a single kernel theory will be applicable to the research problem for this thesis. This means the CRA research methodology will be used for this research project.

The experiences of the author during his candidature, as well as his aforementioned interest in the use of MBSE, need to be acknowledged as they will have resulted in bias in the decisions made during the construction of the research artefact, in this case a methodology. The candidature was undertaken at part-time load and for one year during the candidature, the author worked within the Center for Innovation in Ship Design (CISD) at the United States Navy (USN) Naval Surface Warfare Center Carderock Division (NSWCCD). This experience resulted in the author gaining knowledge of the USN ship acquisition system *in practice* as opposed to simply assimilating the process depicted in the DoD 5000.02 manual [40]. This experience also highlighted the differences between the developmental and OTS acquisition strategies, which reinforced to the researcher the need for a different approach to OTS acquisitions. Another significant experience was the two plus years during his candidature the author performed the role of Assistant Project Science and Technology Advisor for the RAN SEA1180 Phase 1 (Offshore Patrol Vessel) project. During this time the project progressed from project initiation to First Pass (in the old Defence capability lifecycle [43]) to Gate 2 (in the new Defence capability lifecycle [4]). The realisation that the bulk of early stage ‘above the line’ (or left of contract) capability development work is performed by a few, and sometimes only one or two people was important for this research. It has coloured the research with a practical bias and drove the construction of a methodology that is relatively easy to implement compared to the existing approaches found in the literature.

Chapter 5: Development of an MBSE Metamodel to link Strategy and Off-the-Shelf Naval Ship Acquisition

5.1 Introduction

This chapter is the first in the body of the thesis covering research undertaken to address the third research sub-question:

> *How can MBSE-based approaches enhance the current (acquisition) process and what is their utility?*

To address this question, the Constructive Research Approach was adopted and a Model-Based Systems Engineering (MBSE) methodology constructed to support Australian Naval Ship acquisition activities during the early lifecycle phases. The MBSE methodology was named the <u>M</u>iddle-out <u>E</u>arly-phase <u>A</u>bove-the-line <u>N</u>aval <u>S</u>hip (MEANS) MBSE methodology. The MEANS MBSE methodology incorporates the approaches that were identified in Chapter 3 as being suitable: 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). This chapter provides an overview of the development of the MBSE metamodel, which is covered in several of the researcher's publications produced during the research project. In simple terms, a metamodel has been described as a 'model of a model' [151]. A publication co-authored by the researcher provides the following more detailed overview of metamodels [28: p. 2]:

> 'A modelling language provides the syntax, notations and semantics that guide and define use of the language to develop and present a representation of a system of interest [20]. Each of these language aspects are interlocked as they are all linked to the description of the abstract concepts contained in a MBSE model. The syntax is described by a

metamodel (alternatively known as a reference model, schema or ontology) that defines the language structure as classes of elements and the permissible relationships between them. The notation describes how the concepts are visualised while the semantics define the meaning of each of the concepts in the metamodel. For instance, as shown in Figure 22, a requirement for a system to perform a specified function can be captured (i.e. 'modelled') as an instantiated element of the metamodel Requirement class.'

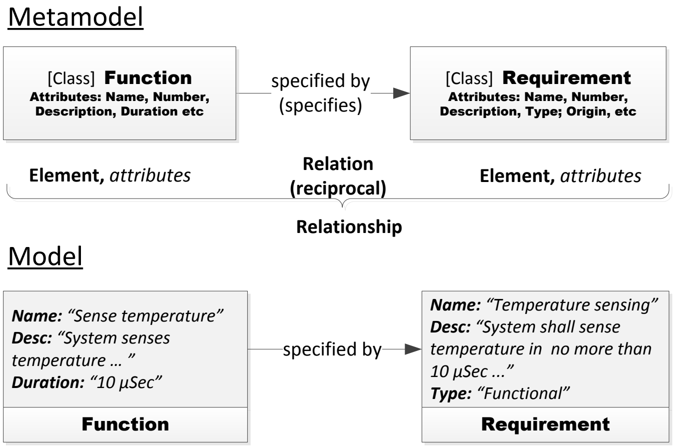

Figure 22: Example metamodel elements and model [28].

This chapter gives a summary of the development of the metamodel used in the research as it progressed through two main iterations. The chapter also discusses the key research contributions that were presented in the following publications during the researcher's candidature:

- Morris, B. and Sterling, G., 2012. "Linking the Defence White Paper to System Architecture Using an Aligned Process Model in Capability Definition." In *SETE APCOSE 2012*, Brisbane, Australia. [27] (Included in Appendix A).
- Logan, P.W., Morris, B., Harvey, D. and Gordon, L., 2013. "Model-Based Systems Engineering Metamodel: Roadmap for Systems Engineering Process." In *SETE 2013*, Canberra, Australia. [28]
- Morris, B.A., 2014. "Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships." In *SETE2014* Adelaide. [29] (Included in Appendix B).

- Morris, B.A. and Cook, S.C., 2017. "A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms." In *INCOSE International Symposium,* Vol. 27, No. 1, pp. 688-703. [30] (Included in Appendix D).
- Morris, B.A., Cook, S.C., and Cannon, S.M., 2018 "A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions.*"* In *International Journal of Maritime Engineering,* **160** (Part A1 2018): p. 21-40. [17] (Included in Appendix E).
- Morris, B.A., Cook, S.C., Cannon, S.M., and Dwyer, D.M., 2018. "An MBSE Methodology to Support Australian Naval Ship Acquisition Projects." In *15th Annual Acquisition Research Symposium*. Naval Postgraduate School, Monterey, CA [31] (Included in Appendix F).

In summary, the key research contributions related to the MBSE metamodel development are:

i. An existing metamodel was extended to include traceability to high-level strategic guidance and capability needs provided in a Joint Capability Needs Statement allows requirements definition activities and their outputs to be developed in a traceable manner. This traceability allows the golden thread from strategy to acquisition to be clearly demonstrated to decision makers.
ii. An 'analysis domain' was introduced into the extended MBSE metamodel. This allows analysis, synthesis, trade-off and option evaluation undertaken in support of early-phase acquisition activities to be executed and managed from within an MBSE model. By doing this, acquisition stakeholders can demonstrate clear links between the analysis that has underpinned the acquisition activities and the strategic needs for the capability being acquired.
iii. The identification and inclusion of an 'analytic' thread through the MBSE metamodel. This thread provides an analysis and synthesis roadmap within the metamodel to guide the MBSE modeller when building a model. This insight was leveraged during the construction of the metamodel when choosing stereotype names for the new elements and relationships included in the metamodel. This means the metamodel supports the implementation of the MEANS MBSE methodology.

The combination of these three enhancements to the MBSE metamodel enables the MEANS MBSE methodology to be implemented effectively from within an MBSE tool. Developing an MBSE model underpinned by this metamodel will provide traceable, defensible evidence to support the Business Cases for an Australian naval ship acquisition. This traceability from strategy to outputs in Defence acquisition is referred to as the "golden thread" [49]. The construction of the MEANS MBSE methodology to support Australian OTS naval ship acquisitions is covered in Chapters 6, 7 and 8.

5.2 Background

Systems Engineering (SE) is defined by the SE standard, ISO15288:2015 [18: p. 10] as an:

> 'Interdisciplinary approach governing the total technical and managerial effort required to transform a set of stakeholder needs, expectations and constraints into a solution and to support that solution throughout its life.'

A relatively recent development in SE has been the adoption of Model-Based Systems Engineering (MBSE). MBSE [20: p. 15]:

> 'applies systems modelling as part of the SE process…to support analysis, specification, design, and verification of the system being developed … This approach enhances communications between the development team, specification and design quality and reuse of system specification and design artefacts.'

When implementing MBSE, a methodology comprising a collection of processes methods and tools is used [27]. The researcher has noted: 'the metamodel is the method by which the underlying structure is embedded into the methodology' [29: p. 3]. This is consistent with ISO/IEC/IEEE 24765:2017, which defines a metamodel as the: 'specification of the concepts, relationships and rules that are used to define a methodology' [152: p. 273].

A deeper appreciation of the value of fit-for-purpose metamodels and how they could be leveraged to support the implementation of an MBSE methodology was gained during the research project. This appreciation is highlighted in a paper co-authored by the researcher with [28: p. 6]

> ‘In MBSE, while the modelling language provides the *means* of capturing the model data, it does not the *ways*. A planned process must be employed to identify, describe and relate the model elements. The fully elaborated process determines the activities, the sequencing of those activities, identifies and details the methods and techniques used within activities to acquire, analyse and synthesis data model and report product content. The documented process, together with identification of the resources required to implement the process constitutes a *systems engineering plan* [153], the essence of which can be depicted as a Process (meta)Model. The execution of the plan is *systems engineering*.
>
> While a Process Model makes explicit the analysis and design activities necessary to generate a model, the metamodel can be viewed as a road map, explicitly showing the waypoints (the elements), and a path between them (the relationships). An analytic thread, determined by the purpose of the model, can be identified as a sequence of waypoints and paths. To travel the analytic paths between waypoints involves undertaking a chosen analytic and design process/method(s), the rigour of which is determined by the available resources, predominately time i.e. schedule. Each of the relationships in the metamodel implies an associated process – the Process Model overlayed on the metamodel path makes this explicit.’

This appreciation of the roadmap that an MBSE metamodel can provide was leveraged during the remainder of the research to construct the MBSE methodology to support OTS naval ship acquisitions. The following sections provide an overview of the research contributions related to MBSE metamodels (summarised in Section 5.1 above) that were presented in publications during the researcher’s candidature.

5.3 Linking Strategic Guidance to Requirements Definition

In the refereed publications [27] and [28] presented to the Systems Engineering, Test and Evaluation (SETE) conferences in 2012 and 2013 respectively, the researcher described research to extend an existing metamodel (also known as a reference model, schema or ontology) to enable traceability between the government's strategic guidance and early-phase acquisition activities. As well as the unclassified refereed conference papers, this research was utilised within Defence to link strategic guidance provided in the 2009 Defence White Paper [154] through operational needs elicited from stakeholders, to various candidate classes of Unmanned Aerial System (UAS), which was covered in a classified Defence Science and Technology Group Technical Report [155].

The research to link strategic guidance to acquisition activities utilised the Whole-of-System Analytical Framework (WSAF) metamodel as its starting point. The WSAF metamodel was primarily selected because at the time (2012) [28: p. 3]:

> 'The WSAF is gaining increasing acceptance within the ADO[5] from repeated usage and has recently been mandated as the metamodel for MBSE practice within the Australian Defence Capability Development Group [83].'

Up until the time of the research to extend the WSAF metamodel in 2011 and 2012, the WSAF metamodel did not explicitly link requirements to strategic guidance. It had been initially developed as a tool to frame capability analysis rather than support requirements definition [81]. It was noted in Logan, Morris *et al.* [28: p. 5]:

> 'In much of the previous work to which the WSAF was applied, done in accordance with the Defence Capability Development Handbook (DCDH) and Capability Definition Documents (CDD) Guide, the starting point was the given capabilities needed to satisfy strategic guidance, usually stated as the ability to achieve operational missions and tasks. While a summary of the justification of these needs and reference to strategic guidance should be included in the capability definition documents [156], the traceability between government guidance and specific operational tasks examined in scenario-based operational needs analysis was rarely made explicit in the

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[5] ADO = Australian Defence Organisation. Defence is its equivalent term that has been used throughout this thesis.

> scenario models and consequently not in the associated documents and reports.'

The decision by the researcher to extend the WSAF metamodel whilst maintaining the WSAF element stereotypes also meant the extended metamodel would be consistent with the DoDAF Version 2.0 high-level conceptual data model. This consistency is due to the WSAF's initial development being undertaken using the Vitech CORE® MBSE tool schema, which is DoDAF-based.

Extending the WSAF to link strategic guidance to requirements definition was achieved by firstly implementing the WSAF in a SysML (Systems Modelling Language) based tool using profiles with WSAF metamodel element stereotypes [27]. The WSAF metamodel was then extended by introducing new elements and exchanging others to align with the Strategy-to-Task (StT) framework [33] and Defence's 2010 The Strategy Framework (TSF) [34]. This alignment is shown in Table 5 (reproduced from [27]).

Table 5: Aligned StT, TSF and WSAF elements and explanation [27].

StT Element	**TSF Document**	**WSAF Element**	**Explanation**
National Goals	N/A	N/A	This level is beyond the Defence context
National Security Objectives	White Paper (WP)	None – need to create	The WP articulates the strategic priorities that guide Defence [34]. As such, the "strategic priorities" can be interpreted as security objectives.
National Military Objectives	Defence Planning Guidance (DPG)	None – need to create	The DPG outlines Australia's military strategy and amplifies the WP policy guidance [34]. This military strategy can be interpreted as military objectives.
Campaign Objectives	Australian Capability Context Scenarios (ACCS)	Mission	The WSAF Mission element is described as: "A mission identifies a task, together with its purpose, that clearly indicates the action to be taken and the reason therefore." This aligns with TSF which states: "Each ACCS consists of a scenario leading to a planning directive, operational plan and operational level effects to achieve…" [34].
None – this level refines the campaign objectives	CDF Planning Directive Part A (CDF PD PtA)	Scenario Context	This element in the TSF provides further direction to the campaign objectives set out in the ACCS by giving strategic level objectives and end-states [34]. These strategic objectives and interests give a strategic context to the scenario being considered, which aligns it with the WSAF scenario context element.
Operational Objectives	CDF Planning Directive Part B (CDF PD PtB)	Scenario	While the WSAF scenario element's name can be misleading when discussing ACCS etc, from the perspective of a StT framework, the WSAF scenario aligns with the operational objectives provided by the proposed mission given in the CDF planning directive Part B [34].
Operational Tasks	Operational Plan (OPLAN) Key Tasks/Activities	Operational Activity	The WSAF operational activity element is described as "an action or process needed to fulfil a mission, task or role." This reflects the nature of the Key Tasks that are given in the CDF Planning Directive Key Tasks.

Subsequent research (presented in [29], [13], [30] and [17]) used the same approach to extend the WSAF metamodel to enable strategic guidance (in the form of the top-level military roles (Operational Tasks) for a capability need), to be linked to requirements definition. These roles are now typically expressed in a Joint Capability Needs Statement (JCNS) at Gate 0 in the Defence ICLCM [4] lifecycle.

Figure 23 shows an instantiation of the WSAF metamodel for a United States Coast Guard Maritime Security Cutter, Medium (WMSM) test implementation of the MBSE methodology constructed for the research project, which was covered in [13] and [17]. This test implementation extracted the WMSM Operational Tasks from an unclassified Concept of Operations (CONOPS) [157]. Note that not all WSAF metamodel elements are shown in Figure 23.

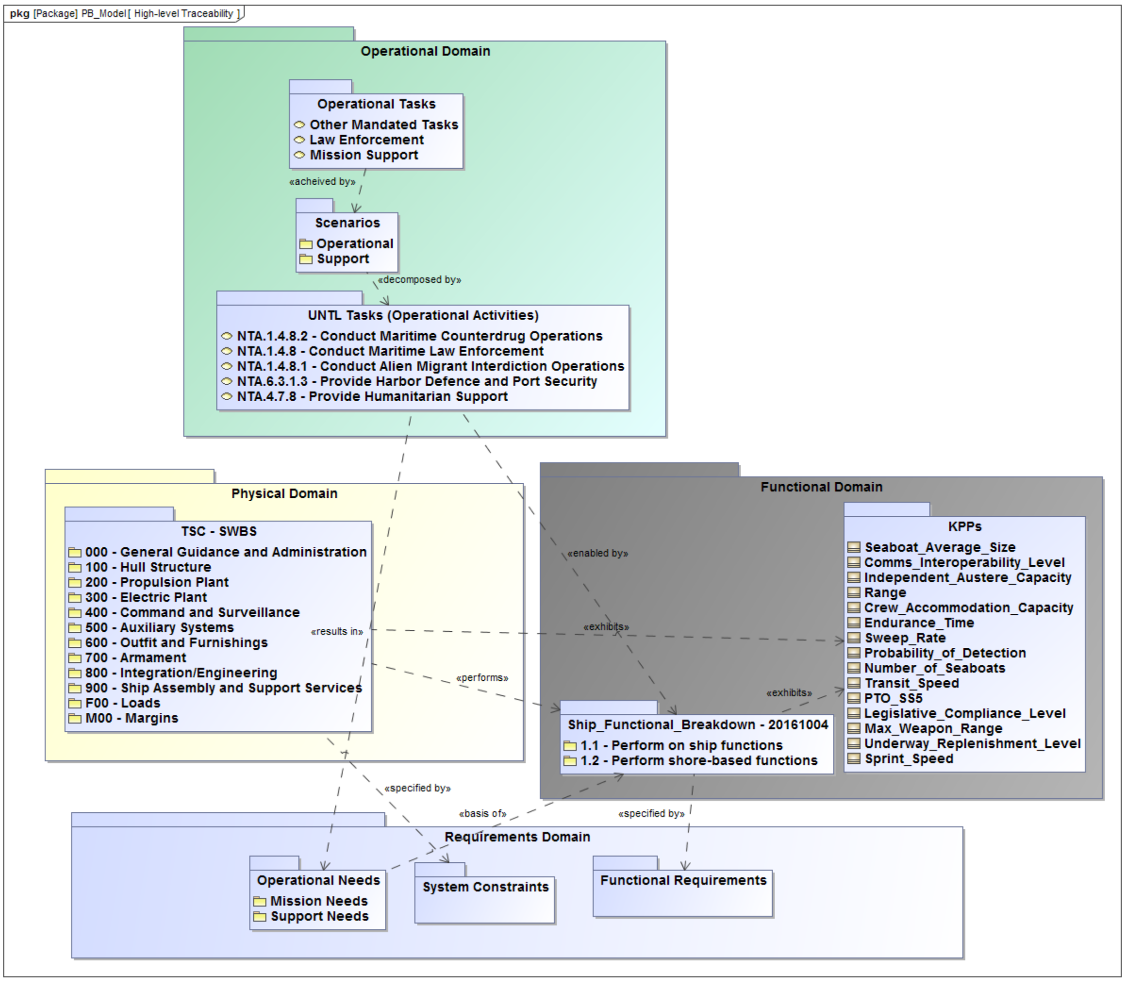

Figure 23: Instantiation of the extended WSAF metamodel developed to link strategic guidance to requirements definition.

Figure 23 shows the high-level operational tasks (within the green operational domain package) that would be identified from the Joint Force Design process, and their traceability through operational activities and needs, functions and Key Performance

Parameters (KPPs) to physical ship systems. This supports the top-down development of KPPs and mission performance evaluation criteria in the MBSE methodology and is discussed further in Section 5.5.

5.4 Introducing the Analysis Domain

5.4.1 Early Development

After gaining an appreciation of the importance of suitable metamodels and learning how to extend them to link strategic guidance and top-level capability requirements to requirements definition activities, research to investigate other methods to support acquisitions commenced. Subsequent chapters cover the bespoke synthesis of methods to support early stage OTS naval ship acquisitions, whilst this section focuses on the metamodel extensions that enabled these methods to be implemented as part of the MBSE methodology.

The first iteration of research to extend the WSAF metamodel to enable analytical activities to be performed and managed from within an MBSE model was covered in Morris [29]. In this research, an approach to execute, or mathematically solve systems of equations built in SysML Parametric diagrams via an MBSE tool plugin was developed. The researcher noted [29: p. 3]:

> ‘Parametric diagrams can be used to build systems of equations that constrain the properties of block elements [20]. Typically, SysML-based MBSE tools have not had the capability to execute, or mathematically solve parametric diagrams. However, recently commercial software developers have released add-ins, for these tools, such as Solvea™ for Enterprise Architect®, that provide the capability to solve systems of equations built in parametric models.’

The researcher described the extension of the WSAF metamodel to include an analysis domain, shown within the red border of Figure 24, and how the elements within the domain can be used to support analysis for OTS naval ship acquisitions with [29: p. 3]:

> ‘Within the analysis domain are the ship representation, physical constraints and simulation classes. The ship representation class contains the ship design parameters that are used in the governing equations of the

> simulations. The physical constraint class contains the equations that govern both the simulations (contained in the simulation class elements) and ship representation class elements. In SysML modelling terms, the ship representation class elements are blocks, the physical constraint class elements are constraint blocks and the simulations are parametric diagrams.’

In Figure 24, the first iteration of the analysis domain to enable analytical activities to be undertaken from within an MBSE model is shown inside the red border at the top right of the figure.

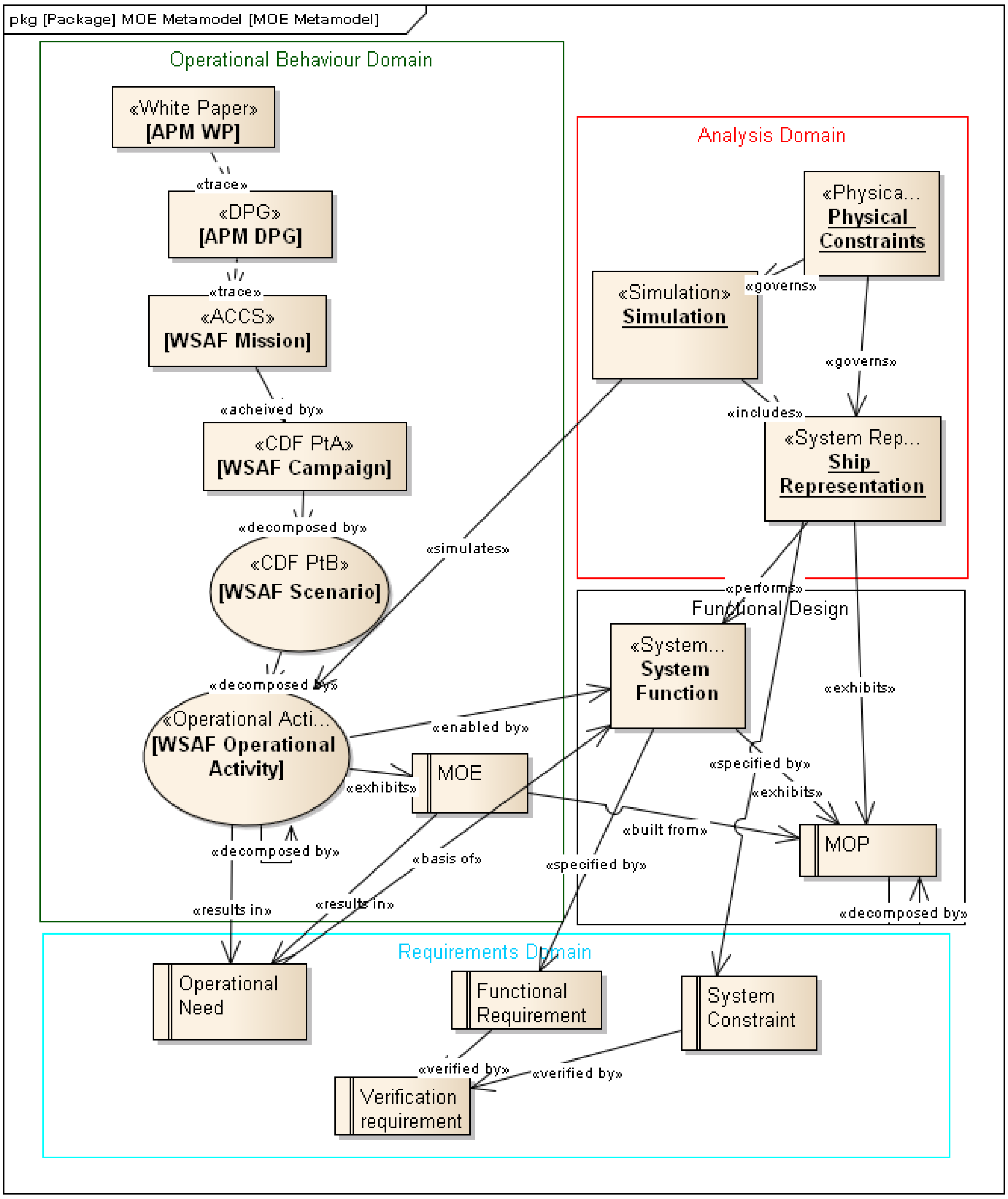

Figure 24: Part of the extended WSAF metamodel.

The first iteration of the research that extended WSAF metamodel to include the analysis domain was followed by a second iteration of research that focused on incorporating a broader range of methods and Measures of Performance (MOPs) into the analysis. Different software tools to address an issue of long execution runtimes were also used in the second iteration. The second iteration employed model integration software (Phoenix Integration's ModelCenter®) to integrate analytical software tools including Wolfram's Mathematica®, Microsoft Excel®, and naval architecture software for ship seakeeping and resistance (drag) calculations. This research was covered in the researcher's publications [13], [17] and [31], which are provided in Appendices C, E and F respectively. The change in software tools allowed more complex analyses to be undertaken and managed within an MBSE tool, with relatively fast runtimes. The improved computational performance and the researcher's improved understanding of executing analysis from within an MBSE model, led to the development of a model-based option evaluation method. This method is able to support the identification of high-value design changes and the overall evaluation of responses to a Request-for-Tender during OTS naval ship acquisitions. The research covering the development if this model-based option evaluation method was published in [30] and [17] and is covered in Chapter 7 of the thesis.

The option evaluation method further extended the WSAF metamodel as shown in Figure 25. This extension included elements for executing the Multi-Criteria Decision Making calculations (option evaluation), as well as elements for storing the evaluation criteria and the representation of the ship system.

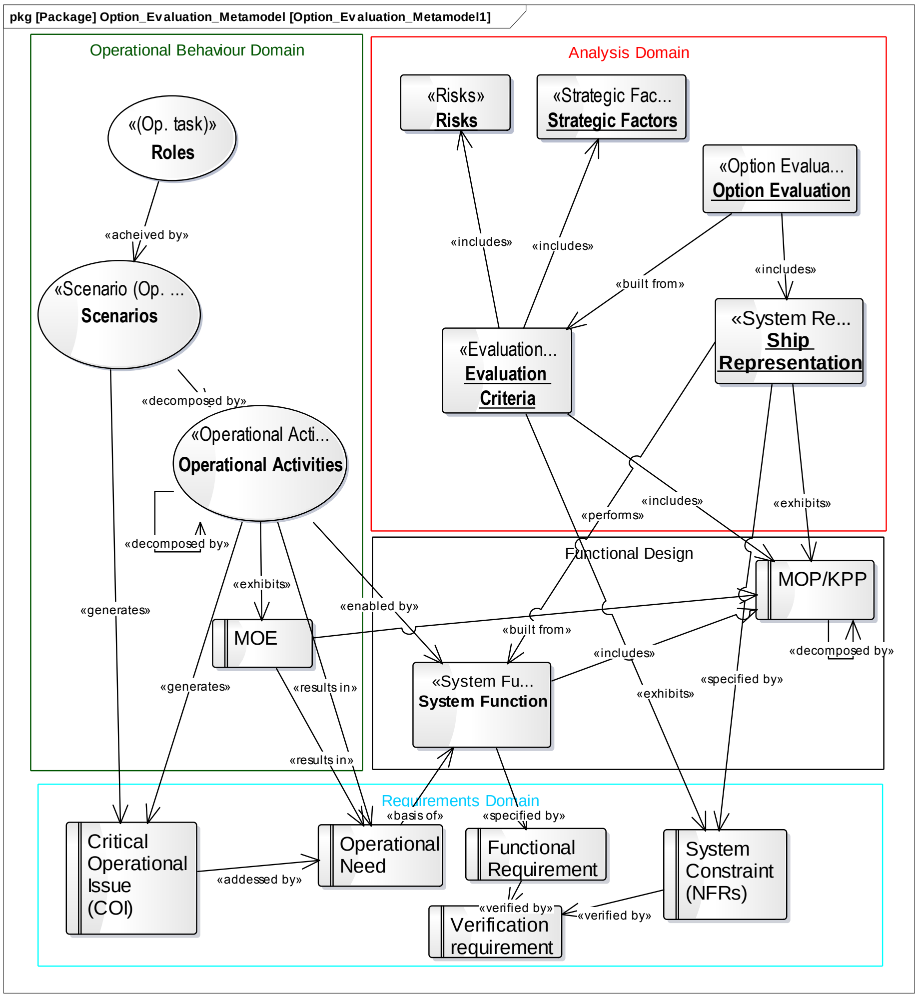

Figure 25: Extended WSAF metamodel following the second iteration of analysis domain development.

5.4.2 Final Analysis Domain

An instantiation of the final extended WSAF metamodel developed during the research is given in Figure 26. In Figure 26, the high-level traceability extensions are the elements shown in the green operational domain and the extensions to facilitate executable analysis from within an MBSE model are the elements shown in the red analysis domain.

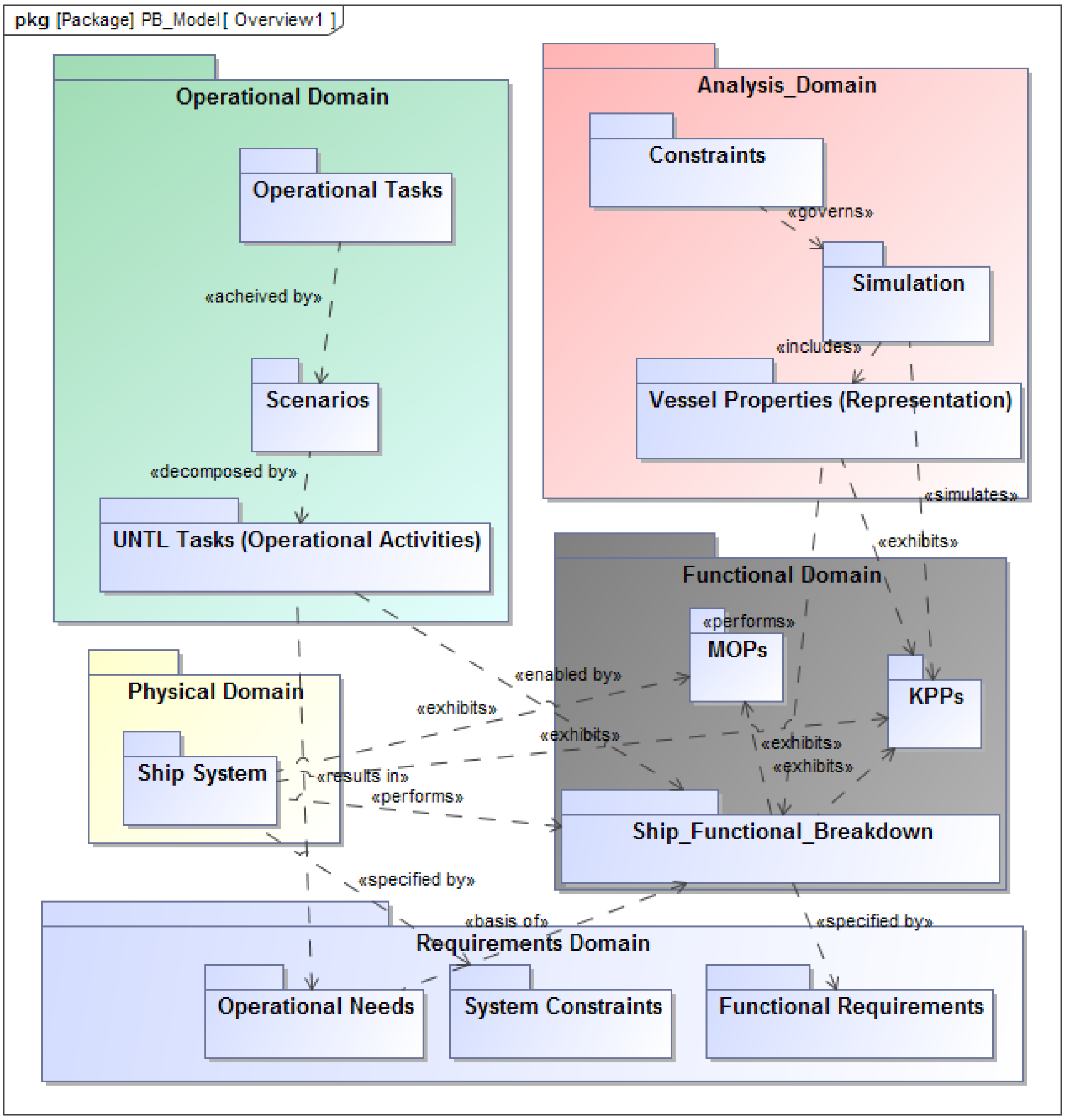

Figure 26: Instantiation of the final extensions to the WSAF metamodel developed as part of the research to construct the MEANS MBSE methodology to support OTS naval ship acquisitions.

Within the red analysis domain shown in Figure 26, are packages containing the ‘constraints’, ‘simulation’ and ‘ship properties’ stereotyped elements. A summary of the content of these elements and the related Modelling and Simulation (M&S) terminology is given in Table 6. Overviews of each of the elements within the analysis domain are provided in Sections 5.4.2.1 to 5.4.2.3.

Table 6: Summary of the analysis domain elements, their content and equivalent M&S term.

Analysis Domain Element	**Content**	**Equivalent M&S Term**[6]
Constraint	Representations of equations or mathematical models.	Analytical Model[7]
Simulation	SysML blocks containing parametric diagrams that link the constraints with the vessel properties used in an analysis.	Simulation[8]
Vessel Properties	SysML block properties that represent the characteristics of a ship design.	Variables[9]

5.4.2.1 Constraints Element

The ‘Constraints’ element was created in the analysis domain of the extended WSAF metamodel to contain representations of the executable models used in the simulations performed when implementing the MEANS MBSE methodology. The Constraints element was so named because in SysML, constraint blocks are used to define an equation or model and its parameters [20]. Constraint properties are variables used in an equation or model and are contained as properties within SysML blocks in the ‘Vessel Properties’ element covered in Section 5.4.2.3. The ‘Constraints’ elements can be generated manually when they are simple equations, or automatically when they represent more complex models. In the first iteration of research to extend the MBSE metamodel to include an analysis domain, the constraint blocks needed to be generated manually as the software that executed the parametric diagrams (contained in the ‘Simulation’ elements discussed in section 5.4.2.2) exported the equation and solved it using a Modelica language compiler. The model integration software used in the final iteration of metamodel development enabled automatic generation of the constraint blocks. The model integration software also allows the constraint block to link to models that are solved in domain-specific software applications. Figure 27 shows the ‘Constraints’ package containing representations of the executable models used in the research for the WMSM test implementation (covered in Chapter 8). The executable

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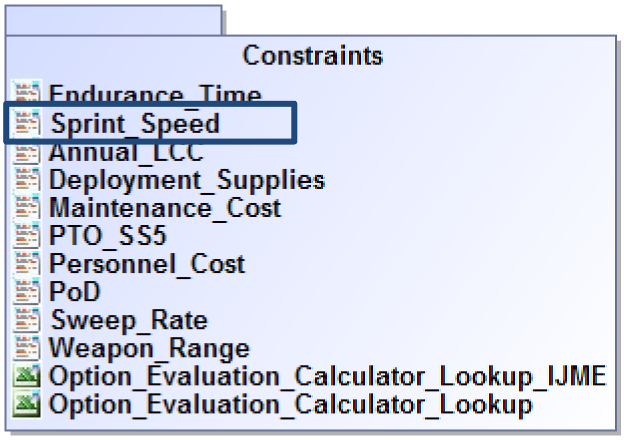
[6] Based on the US DoD M&S Glossary – Available from http://www.acqnotes.com/Attachments/DoD%20M&S%20Glossary%201%20Oct%2011.pdf

[7] The US DoD M&S glossary defines an analytical model as: “a model consisting a set of solvable equations.”

[8] The US DoD M&S Glossary defines a simulation as: “a method for implementing a model over time.”

[9] The US DoD M&S glossary defines a variable as: “a quantity or data item whose value can change.”

models include the models generated to calculate the KPPs for combinations of ship design parameters during the Concept and Requirements Exploration part of the MEANS MBSE methodology (e.g. Endurance_Time and Sprint_Speed). The constraints package shown in Figure 27 also contains representations of the spreadsheet models used to calculate overall weighted values (e.g. Option_Evaluation_Calculator_Lookup) during the Option Evaluation part of the MEANS MBSE methodology.



Constraints

- Endurance_Time
- Sprint_Speed
- Annual_LCC
- Deployment_Supplies
- Maintenance_Cost
- PTO_SS5
- Personnel_Cost
- PoD
- Sweep_Rate
- Weapon_Range
- Option_Evaluation_Calculator_Lookup_IJME
- Option_Evaluation_Calculator_Lookup

Figure 27: Constraints package from the instantiation in Figure 26 showing the constraint blocks that link to the executable models used in the C&RE and option evaluation analyses for the WMSM test implementation.

The constraints are modelled as 'constraint block' stereotypes in a SysML-based MBSE tool. From the element relationships within the Analysis Domain shown in Figure 26, it can be seen that the 'constraints' 'govern' the simulations retained in the 'simulation' element. In the case of the 'Sprint_Speed' constraint shown in Figure 27 for example (inside the blue rectangle, which corresponds to the same constraint in Figure 28 and Figure 29), the model it represents is given by Equation 1:

$$5.045\frac{\Delta V_{max}}{P_p} - 1.9288\ \exp\left(0.8324 * \frac{\sqrt{gL}}{V_{max}}\right) = 0 \qquad (1)$$

Where: Δ = Displacement (full load) (tonnes)

V_{max} = Sprint Speed (knots)

P_p = Propulsive Power (kW)

g = Gravitational Constant (9.81 m/s^2)

The variables, or constraint properties (which are created in the ‘Vessel Properties’ elements – discussed in Section 5.4.2.3), are linked to the constraint block in a parametric diagram as shown in Figure 29.

5.4.2.2 Simulation Element

The ‘Simulation’ stereotype element within the analysis domain was created to act as a repository within an MBSE model for the simulations that solve, or execute the ‘Constraints’ that were covered in the previous section. A SysML block with a ‘Simulation’ stereotype is created to act as this repository and then a parametric diagram for each simulation is created within this block. The parametric diagram links the executable models in the ‘Constraints’ element to the SysML block part properties that represent the characteristics of a ship design in the ‘Vessel Properties’ element. Figure 28 shows a SysML block with the “Simulation’ stereotype in which the simulation elements (i.e. SysML parametric diagrams) were created for the WMSM test implementation of the MEANS MBSE methodology (covered in Chapter 8).

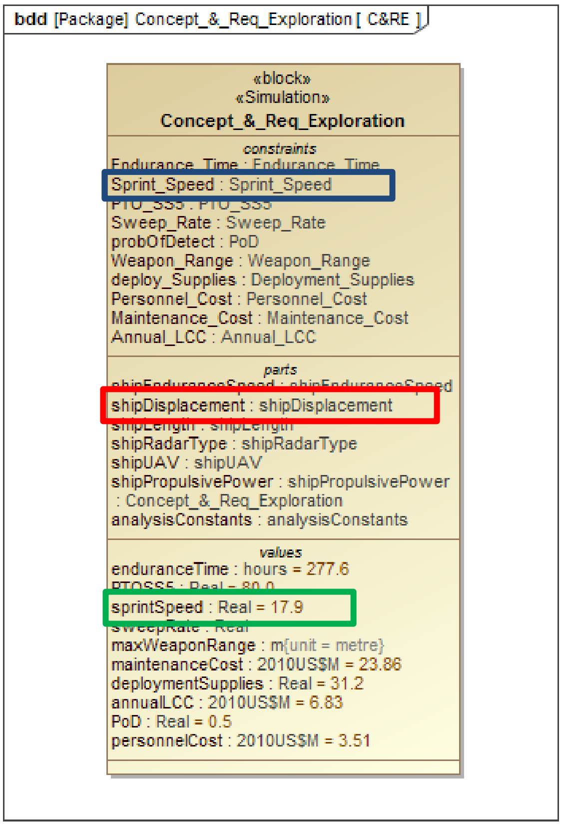


Figure 28: Simulation element for the Concept and Requirements Exploration analysis performed in the WMSM test implementation.

In Figure 28 the three compartments within the ‘Simulation’ block show the different elements that are linked together within the Analysis domain of the metamodel. The top compartment (constraints) contains the representations of the executable models, which are the ‘Constraints’ stereotyped elements. The parts compartment contains the ‘Vessel Properties’ stereotyped elements, or variables used in the models. Within the values compartment are SysML block properties, which are the solutions calculated when the models are executed via the SysML parametric diagram that represents a simulation.

The blue, red and green rectangles in Figure 28 correspond to the same elements in Figure 27, Figure 29 and Figure 30. The blue rectangle highlights the Sprint_Speed model (discussed in the previous section) used in the sprintSpeed simulation that is represented by the SysML parametric diagram shown in Figure 29.

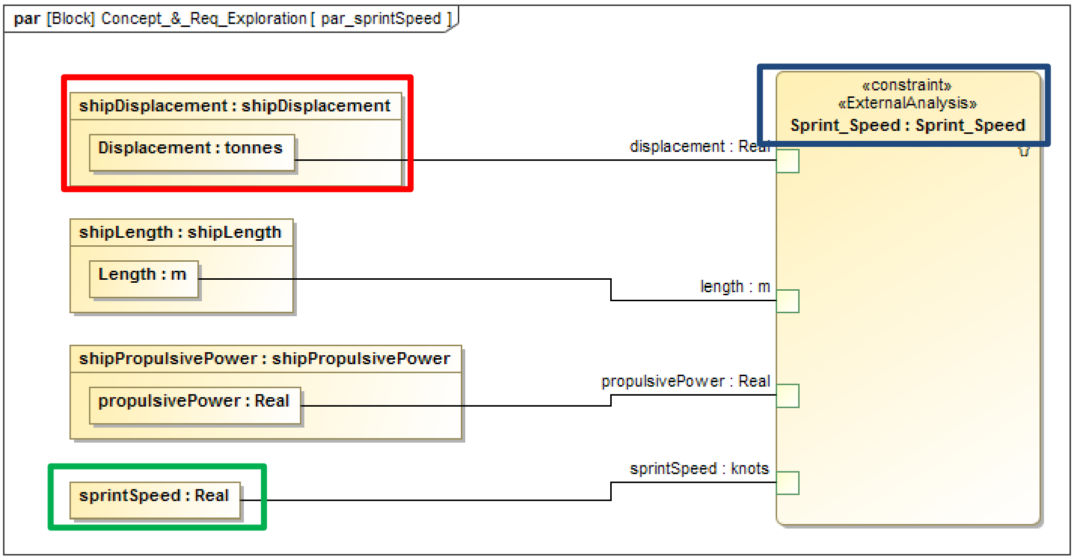


Figure 29: Parametric diagram used to simulate the Sprint Speed KPP in the WMSM test implementation.

In Figure 29, the constraint block ‘Sprint_Speed’ containing the link to the external executable model is on the right-hand side, and the ‘Vessel Properties’ used in the simulation are shown on the left-hand side. The red rectangle in Figure 28, Figure 29 and Figure 30 highlights the ‘shipDisplacement’ Vessel Property, which is the variable Δ in Equation 1.

The green rectangle in Figure 28 and Figure 29 highlights the ‘sprintSpeed’ KPP value that is calculated when the simulation represented by Figure 29 is executed. As shown by the relationships between the analysis domain elements in Figure 26, a ‘Constraint’ ‘Governs’ a ‘Simulation’, which ‘Includes’ the ‘Vessel Properties’.

5.4.2.3 Vessel Properties Element

The ‘Vessel Properties’ stereotype element within the analysis domain was created to act as the repository of a ship design’s characteristics (or ship design parameters). These ‘Vessel Properties’ are used in the analyses executed from within the ‘Simulation’ elements. The Vessel Properties are modelled as SysML blocks containing value properties that allow a number type and value to be assigned to each Vessel Property. DesignA and DesignB in Figure 30 are packages of Vessel Properties, which are used to store a representation of a ship design.

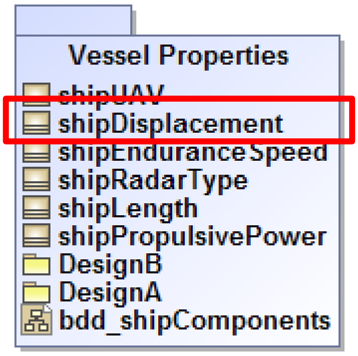
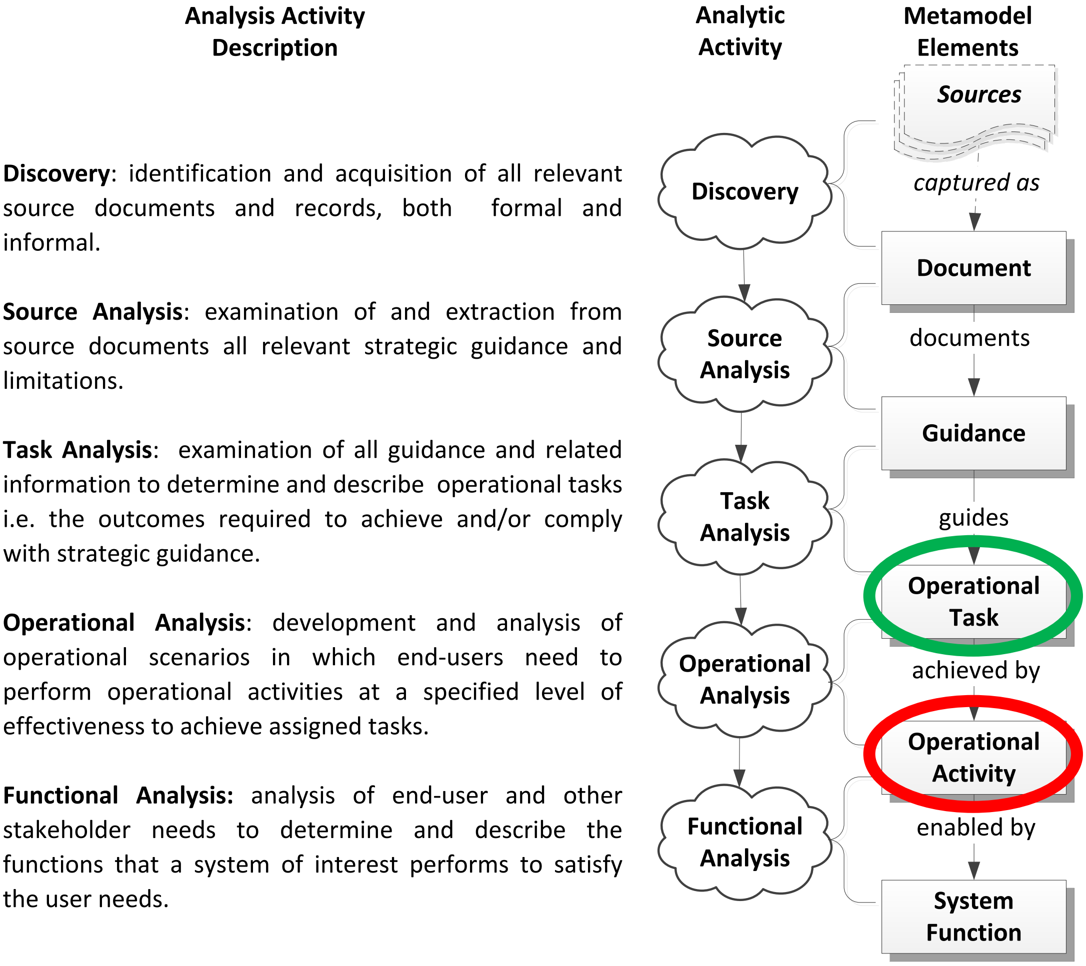


Figure 30: Ship properties, including designs, used during the WMSM test implementation.

The ‘Vessel Properties’ are linked to the functional domain as they ‘perform’ the ship functions and ‘exhibit’ Key Performance Parameters when they are simulated, as shown in the metamodel in Figure 26.

5.5 Supporting the MBSE Methodology with the Metamodel

While conducting the research to extend the WSAF metamodel to link strategic guidance and high-level capability needs to requirements definition, the researcher became involved in an activity to support the top-down development of traceable requirements for Australia’s Future Submarine (FSM) program. During this activity, the participants came to realise that using an appropriate MBSE metamodel facilitated sound SE practice [28]. This realisation was built upon and published in a refereed conference paper [28]. The key contribution from this paper is that a well-constructed metamodel can guide the MBSE modeller, in conjunction with acquisition stakeholders, to undertake methodical, analytical and synthesis activities to develop related elements while constructing a model. An example of this guidance is extracted from [28] and shown in Figure 31.


Analysis Activity Description

Discovery: identification and acquisition of all relevant source documents and records, both formal and informal.

Source Analysis: examination of and extraction from source documents all relevant strategic guidance and limitations.

Task Analysis: examination of all guidance and related information to determine and describe operational tasks i.e. the outcomes required to achieve and/or comply with strategic guidance.

Operational Analysis: development and analysis of operational scenarios in which end-users need to perform operational activities at a specified level of effectiveness to achieve assigned tasks.

Functional Analysis: analysis of end-user and other stakeholder needs to determine and describe the functions that a system of interest performs to satisfy the user needs.

Figure 31: Metamodel as a roadmap [28].

The research project covered in this thesis subsequently leveraged and built upon this understanding throughout the remaining development of the metamodel. This meant the metamodel element and their relationship stereotypes could be used to guide a modeller developing an MBSE model while implementing the MEANS MBSE methodology. The guidance is provided to the MBSE modeller implementing the methodology in the form of a generic question that the modeller can ask when entering content into each related MBSE model element. The question triggers the analytical or synthesis activity the modeller needs to conduct to generate the content in the related elements. These activities include operational analysis and functional analysis as shown under the 'Analytic Activity' column in Figure 31. While not always grammatically flawless, the generic question takes the form:

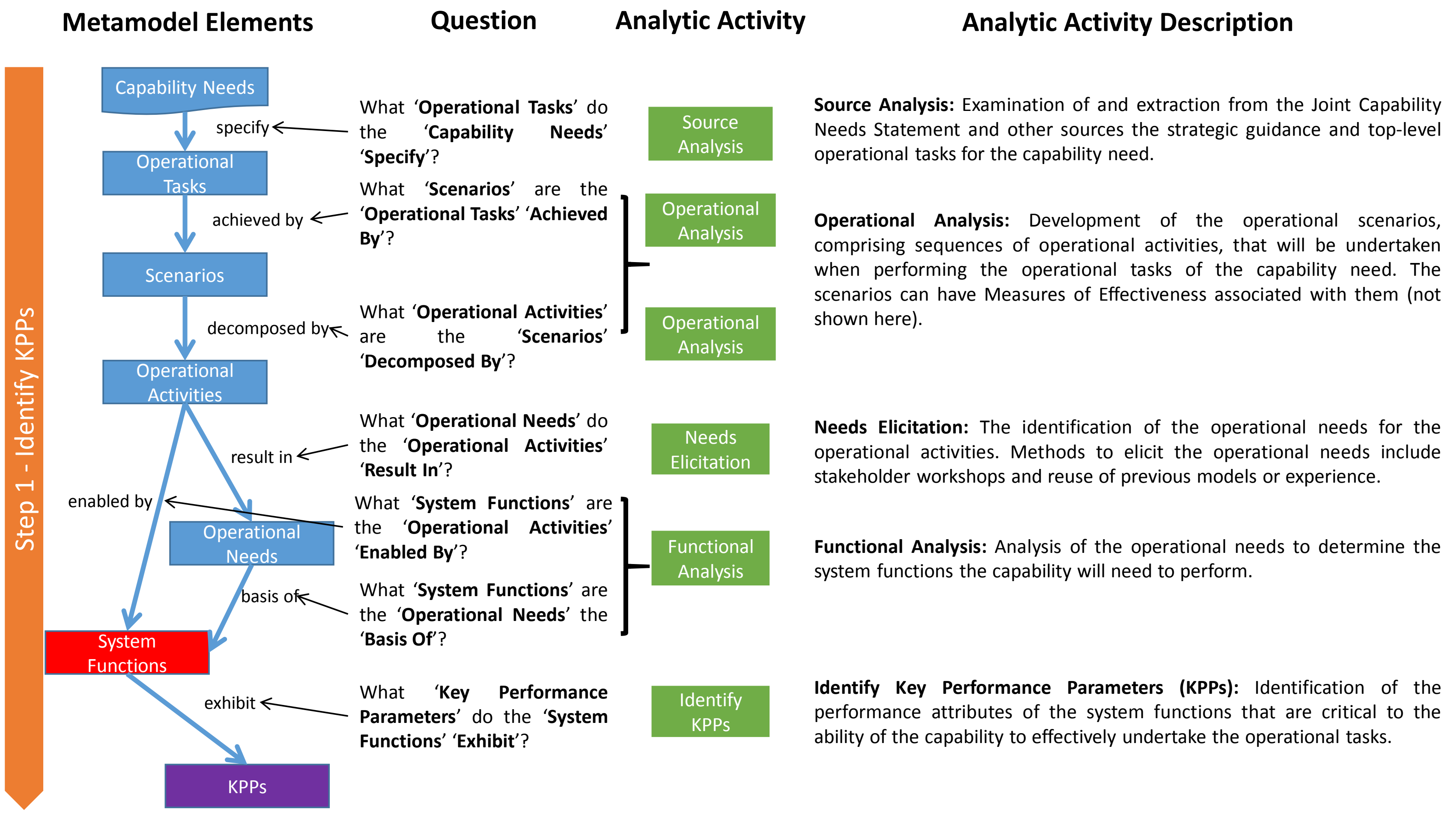
> “What <<**Related Element stereotype**>> do/are/does the <<**Completed Element stereotype>>** (the) <<**Relationship between Elements stereotype**>>?”

An example of applying this question can be seen by referring back to Figure 31. If someone implementing the MEANS MBSE methodology was in the process of identifying the Key Performance Parameters (KPPs) and the ‘Operational Task’ stereotyped model element (highlighted in the green oval) contained content, the modeller can then use the generic question based on the relationship (‘achieved by’) and related element stereotype (‘Operational Activity’) to enter content into the ‘Operational Activity’ (highlighted in the red oval) element. The generic question would be phrased:

> “What ‘**Operational Activities**’ are the ‘**Operational Tasks**’ ‘**achieved by**’?”

This triggers the operational analysis to identify the content for the related ‘Operational Activity’ model elements (inside the red oval).

Figure 32 shows an example of the metamodel elements, questions and analytic activities that a modeller is guided to complete for the top-down decompositions that are undertaken as the first step in the Concept and Requirements Exploration (C&RE) (covered in Chapter 6) part of the MEANS MBSE methodology. Similarly, examples of the metamodel elements, questions and analytic activities the modeller is guided to complete for the C&RE Design Space Exploration, which utilises elements within the analysis domain, and C&RE Develop Request for Tender (RFT) Requirements steps within the MEANS MBSE methodology are shown in Figure 33 and Figure 34 respectively. The red elements (System Functions) and purple elements (KPPs) correspond to each other in the three figures.



What '**Operational Tasks**' do the '**Capability Needs**' '**Specify**'?

What '**Scenarios**' are the '**Operational Tasks**' '**Achieved By**'?

What '**Operational Activities**' are the '**Scenarios**' '**Decomposed By**'?

What '**Operational Needs**' do the '**Operational Activities**' '**Result In**'?

What '**System Functions**' are the '**Operational Activities**' '**Enabled By**'?

What '**System Functions**' are the '**Operational Needs**' the '**Basis Of**'?

What '**Key Performance Parameters**' do the '**System Functions**' '**Exhibit**'?

Source Analysis: Examination of and extraction from the Joint Capability Needs Statement and other sources the strategic guidance and top-level operational tasks for the capability need.

Operational Analysis: Development of the operational scenarios, comprising sequences of operational activities, that will be undertaken when performing the operational tasks of the capability need. The scenarios can have Measures of Effectiveness associated with them (not shown here).

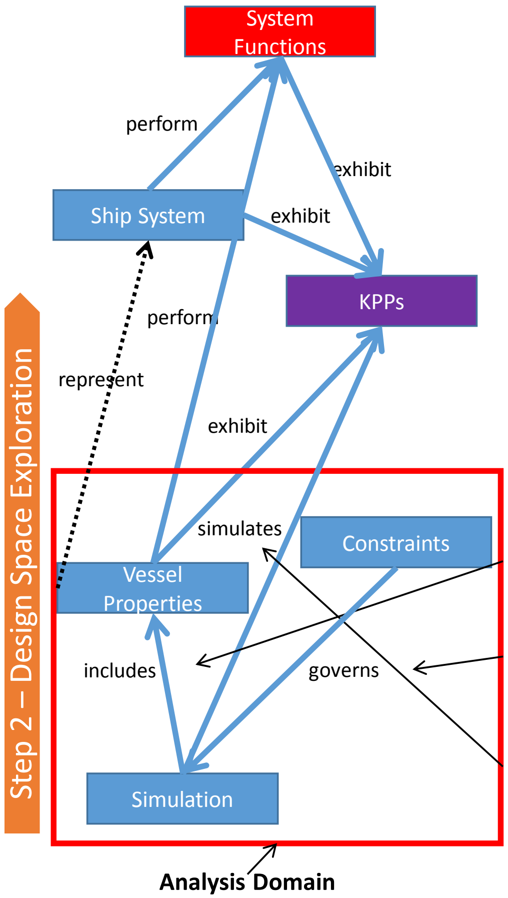
Needs Elicitation: The identification of the operational needs for the operational activities. Methods to elicit the operational needs include stakeholder workshops and reuse of previous models or experience.

Functional Analysis: Analysis of the operational needs to determine the system functions the capability will need to perform.

Identify Key Performance Parameters (KPPs): Identification of the performance attributes of the system functions that are critical to the ability of the capability to effectively undertake the operational tasks.

Figure 32: Using the MBSE Metamodel as a roadmap for the MBSE modeller – Example of process to Identify KPPs during C&RE.

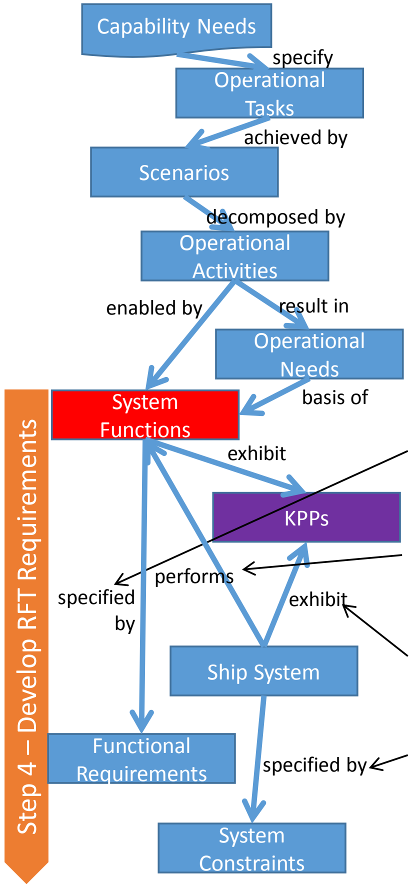
Metamodel Elements



Question	Analytic Activity	Analytic Activity Description
	Conduct Modelling & Simulation	**Conduct Modelling and Simulation:** (Overarching activity performed when developing the analysis domain) Determine experimental approach and execution of the simulation models to build design spaces that link vessel properties to mission performance for Concept & Requirements Exploration, and to assess alternative designs for Option Evaluation.
What '**Vessel Properties**' does the '**Simulation**' '**Include(s)**'?	Identify Vessel Properties for Simulation	**Identify Vessel Properties for Simulation:** Identify the ship design parameters that are required for the simulation to calculate the KPPs.
What '**Simulation**' do the '**Constraints**' '**Govern(s)**'?	Develop Simulation Models	**Develop Simulation Models:** Development of constraints, or executable models that allow the vessel properties (that represent a vessel's physical architecture) of a range of vessels to be simulated in order to evaluate KPPs and assess alternative designs.
What '**KPPs**' does the '**Simulation**' '**Simulate(s)**'?	Identify KPPs for Simulation	**Identify Key Performance Parameters (KPPs) for Simulation:** From the KPPs identified top-down, identify those that can be simulated and build simulations that link the vessel properties and executable models. Some KPPs may need to be determined qualitatively from a set of vessel properties rather than a simulation.

Figure 33: Using the MBSE Metamodel as a roadmap for the MBSE modeller - Example of the process to conduct Design Space Exploration during C&RE.

Metamodel Elements



Question	Analytic Activity	Analytic Activity Description
What '**Functional Requirements**' are the '**System Functions**' '**Specified By**'?	Requirements Engineering	**Specify Key System Constraints:** Using the knowledge of what ship system characteristics exhibit the necessary level of performance (from M&S), specify constraints on the ship system that ensure these characteristics are included in the tender responses.
What '**System Functions**' do the '**Ship System**' '**Perform(s)**'? What '**KPPs**' does the '**Ship System**' '**Exhibit**' (and to what level?)?	Functional Allocation	**Functional Allocation:** Allocation of the system functions to the physical components of a vessel that perform them.
What '**System Constraints**' is the '**Ship System**' '**Specified By**'?	Specify Key System Constraints	**Specify Key System Constraints:** Using the knowledge of what ship system characteristics exhibit the necessary level of performance, specify constraints on the ship system that ensure these characteristics are included in the tender responses.

Figure 34: Using the MBSE metamodel as a roadmap for the MBSE modeller - Example of the process to Develop RFT Requirements during C&RE.

A noteworthy point from Figure 33 is that the Design Space Exploration is driven ‘bottom-up’ from the ‘Vessel Properties’ element. This element is used to contain naval ship designs that are representative of the existing OTS naval ship marketplace. These are included in simulations governed by models or equations contained in the constraints elements. This step requires some understanding of naval architecture and is covered in more detail in the researchers publications [29], [17] and [31] and summarised in Chapters 6 and 8.

5.6 Chapter Summary

Chapter 5 gave an introduction and overview of the research that has been presented in publications by the author covering development of the underlying metamodel used in the MBSE methodology to support Australian OTS naval ship acquisitions. The development of the metamodel underpinning the research to construct an MBSE methodology to support OTS naval ship acquisition provides three key research contributions.

- Firstly, the extension of the WSAF metamodel to include traceability to high-level strategic guidance and capability needs provided in a Joint Capability Needs Statement allows requirements definition activities and their outputs to be developed in a traceable manner. This traceability allows the golden thread from strategy to acquisition to be clearly demonstrated to decision makers.
- The second contribution is the extension of the WSAF metamodel to include an analysis domain. This allows analysis undertaken in support of early stage acquisition activities to be executed and managed from within an MBSE model. By doing this, acquisition stakeholders can demonstrate clear links between the analysis that has underpinned the acquisition activities and the strategic needs for the capability being acquired.
- The third contribution is the insertion of an analytic thread through the MBSE metamodel. This thread provides an analysis and synthesis roadmap within the metamodel to assist the MBSE modeller when building a model. This insight was leveraged during the construction of the metamodel when choosing stereotype names for the new elements and relationships included in the

metamodel. This means the metamodel supports the implementation of the MEANS MBSE methodology.

The publications containing the original content upon which this chapter is based are provided in Appendices A, B, D, E and F.

Chapter 6 – MEANS MBSE Methodology Part 1: Concept and Requirements Exploration

6.1 Introduction

This chapter is the second in the body of the thesis covering research that addresses the third research sub-question:

> *How can MBSE-based approaches enhance the current (acquisition) process and what is their utility?*

The research project addresses this question through the construction of the Middle-out Early-phase Above-the-line Naval Ship (MEANS) MBSE methodology. In tandem with the research to develop a suitable metamodel covered in Chapter 5, an MBSE approach to support the early phase OTS naval ship acquisition project activities was constructed that incorporated the suitable approaches identified from the literature introduced in Chapter 3. The focus of this part of the research is the Australian Defence Risk Mitigation and Requirements Setting Phase up to Gate 1 as shown in Figure 35.

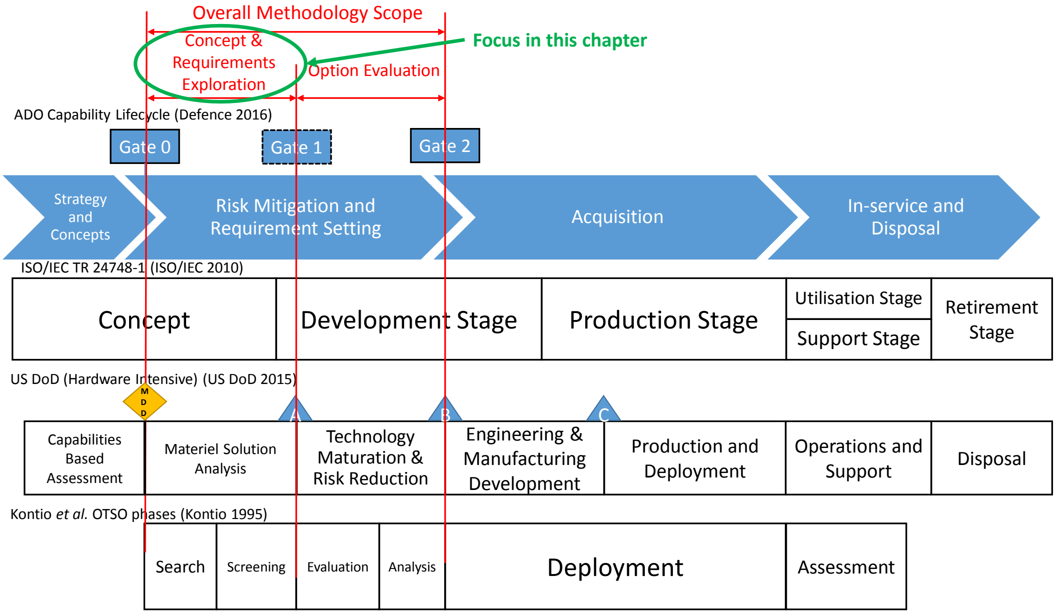


Figure 35: Various system lifecycles and the focus of the research covered in this chapter.

The key activity in this part of the lifecycle related to the specification of the materiel system is defining the requirements. This activity can be supported by robust analysis using a Concept and Requirements Exploration (C&RE) approach, which were introduced in Section 3.3.3. This chapter provides an introduction and summary of the publications covering the research to construct the MEANS MBSE approach for C&RE:

- Morris, B.A., 2014. "Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships." In *SETE2014* Adelaide. [29] (Included in Appendix B).
- Morris, B.A. and Thethy, B.S., 2015. "Towards a Methodology for Naval Capability Concept and Requirements Exploration in an Off-the-Shelf Procurement Environment." In *Pacific 2015 International Maritime Conference*. 2015: Sydney, Australia. [13] (Included in Appendix C).
- Morris, B.A., Cook, S.C., and Cannon, S.M., 2018 "A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions*."* In *International Journal of Maritime Engineering,* **160** (Part A1 2018): p. 21-40. [17] (Included in Appendix E).
- Morris, B.A., Cook, S.C., Cannon, S.M., and Dwyer, D.M., 2018. "An MBSE Methodology to Support Australian Naval Ship Acquisition Projects." In *15th Annual Acquisition Research Symposium*. Naval Postgraduate School, Monterey, CA [31] (Included in Appendix F).

The key research contributions related to the construction the MEANS MBSE approach for C&RE between Gate 0 and Gate 1 in the Defence lifecycle are:

i. Embedding traceability from top-level capability needs to the analytical activities that support requirements elucidation. This allows inputs and outputs from these analysis and synthesis activities to be traced between needs and requirements.
ii. Enabling analytical activities to be conducted and managed from within an MBSE tool, which can then be traced to any resulting requirements.
iii. Formalising the approach to conducting activities to support the early phases of OTS naval ship acquisitions through a methodology comprising a process, methods, and tools.

6.2 Background

Model-Based Conceptual Design (MBCD) was introduced in Chapter 3 (Section 3.3.1) and is an emerging approach for naval ship conceptual design. The existing naval ship MBCD methodologies (see Table 3) at the time of the first iteration of the research to construct the MEANS MBSE methodology (2013-2014), were resource intensive [29]. Nonetheless, based on the literature review covered in Chapter 3, the ability to develop a design space using Modelling and Simulation (M&S) (Section 3.3.2) and use C&RE techniques (Section 3.3.3) to understand and elucidate the ship requirements appears to be highly valuable as a means of supporting early-phase acquisition activities. The researcher noted when discussing the existing MBCD methodologies in 2014 [29: p. 2]:

> 'The existing methodologies to link performance analysis with ship concept design methodologies typically comprise separate operational performance and ship architecture models from the domains of Operations Analysis (OA) and Naval Architecture (NA) [158]. The evolution of these separate domain models appears to be a result of their complexity and relatively high level of fidelity. The intent of linking these models is to give acquisition stakeholders an early and thorough understanding of the influence of ship design parameters on the ship's military effectiveness [158]. The key benefits of stakeholders having an earlier understanding of the influence of the design on the mission effectiveness is that the likelihood of costly changes in later stages of design could be decreased [72]. Furthermore, the impact of design changes on mission effectiveness can be explored [72].'

The existing MBCD methodologies referred to above had been developed in the United States and United Kingdom. The situation in Australian Defence naval ship acquisition projects, where resources, both financial and human are constrained, and the default strategy is to acquire OTS solutions, is significantly different. These differences led the researcher to state [29: p. 2]:

> ‘This leads to the assumption that coarse fidelity Operations Analysis and Naval Architecture models will suffice in the initial stages of ADO[10] conceptual design. Coarse fidelity models are also likely to be more suited to integration with each other due to the possibility of using a less disparate set of modelling and analysis tools. As a result, there is a need to develop an integrated methodology for providing a rapid Rough Order of Magnitude (ROM) view of the effect on performance that the design of a major system will have for ADO naval ship acquisition projects.’

6.3 Initial OTS Concept and Requirements Exploration Research

The initial research to develop an OTS C&RE approach to include in the MEANS MBSE methodology was presented in a refereed paper by the researcher to the SETE conference in 2014 (reference [29] included in Appendix B). This research utilised Set-Based Design (SBD) principles, which were covered in Section 3.2.1.1, as well as executable SysML parametric diagrams that allowed parametric and surrogate modelling and simulation techniques to be implemented from within an MBSE model.

At the time, the author noted [29: p. 3]:

> ‘…recently commercial software developers have released add-ins, for these tools, such as Solvea™ for Enterprise Architect®, that provide the capability to solve systems of equations built in parametric models.’

This development made it possible for those without extensive software development skills to mathematically solve systems of equations from within an MBSE model. The researcher took this development, and in combination with Design of Experiments (DOE) methods, exploited it to create a Rough Order of Magnitude (ROM) design space that linked combinations of ship design parameters to naval mission Measures of Effectiveness (MOEs), from within an MBSE model. The inclusion of the Analysis domain in the MBSE metamodel (covered in Chapter 5) meant the MOEs could be traced back to strategic guidance within an MBSE model. It also enabled functional

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[10] ADO = Australian Defence

requirements and system constraints to be specified based on the knowledge provided by the design space on favourable combinations of ship design parameters, within an MBSE model.

The initial research to develop a C&RE approach that could be conducted from within an MBSE model led to the activity sequence summarised in Figure 36.

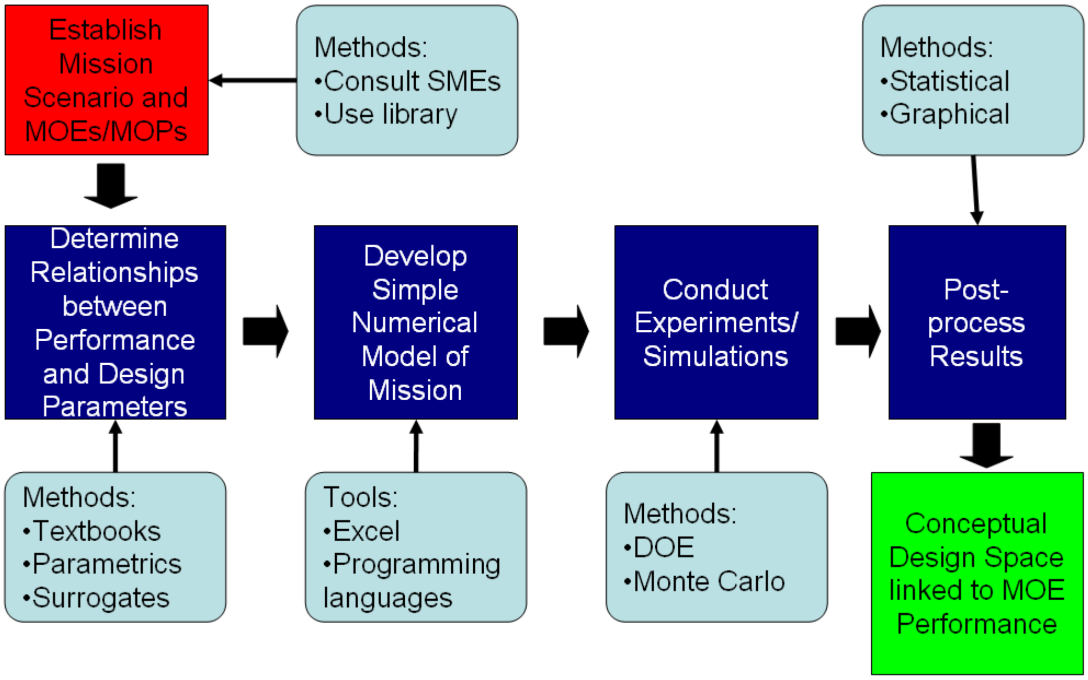


Figure 36: Initial MBSE C&RE approach summary showing the process, along with the methods and tools that could be used [29].

Each of the steps in the process is covered in more detail in the paper (reference [29] included in Appendix B), which also includes an example implementation for an Anti-Submarine Warfare (ASW) naval ship based on a barrier patrol mission scenario. Several key insights were gained during this initial research. These included the ability to build a library of missions and MOE/MOP relationships to ship design parameters through reuse of the approach. This library could include models of relationships of varying fidelity and exploited rapidly. Another key insight described by the author [29: p. 13]:

> 'was that ship design aspects, which are intuitive to an experienced naval architect (e.g. a larger ship having better seakeeping abilities, which leads

> to the ship being operationally available in a larger range of sea-states), can be demonstrated to non-naval architects with a degree of rigour.'

This rigour also allows the differences in performance levels for different combinations of ship design parameters to be clearly demonstrated. MBSE model views from the model developed for the ASW naval ship capability test implementation, underpinned by the initial metamodel shown previously in Chapter 5 in Figure 24, are given in Figure 37 to Figure 43. These figures demonstrate the traceability from high-level guidance to C&RE activities that is enabled by the MEANS MBSE methodology.

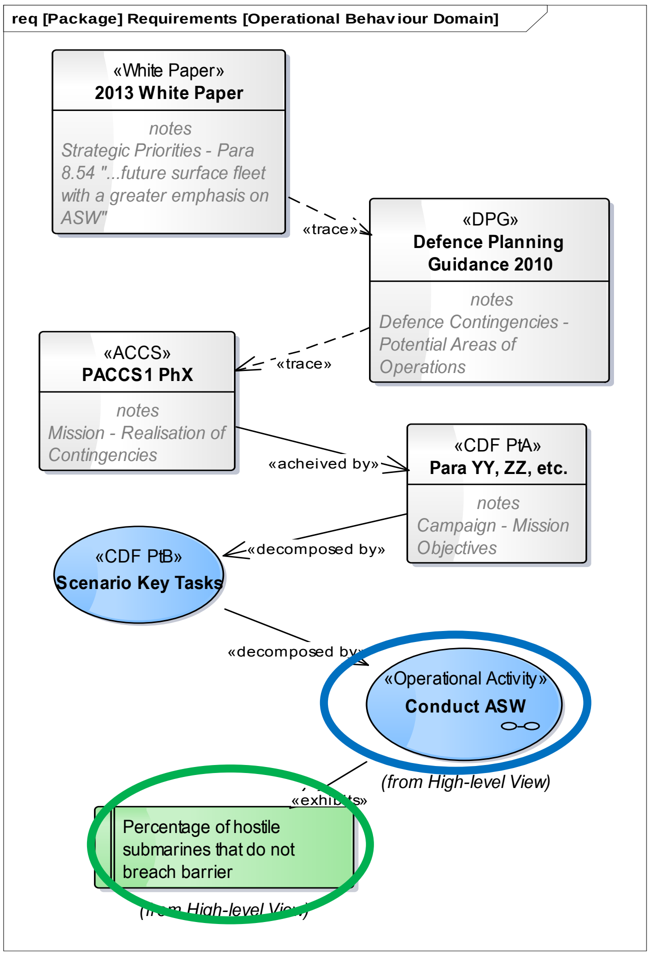


Figure 37: High-level traceability from guidance provided in the 2013 Defence White Paper to the Operational Activity 'Conduct Anti-Submarine Warfare (ASW).'

In Figure 37, the 'Conduct ASW' operational activity decomposed from strategic guidance given in the Defence White Paper can be seen inside the blue oval. Conduct ASW 'exhibits' the Measure of Effectiveness (MOE) 'percentage of submarines that do not breach barrier', which can be seen inside the green oval.

Figure 38 shows the traceability from the ‘conduct ASW’ operational activity (inside the blue oval) through the operational need ‘the ship shall perform ASW’ and MOPs to the three ‘analysis domain’ elements (light blue) in the upper right corner of the diagram. Figure 39 shows the decomposition of the MOE for ‘conduct ASW’ into its three MOPs. In this manner, the analysis executed in the parametric diagram shown in Figure 40, which generates a design space for the probability of detection MOP shown in Figure 42, is explicitly linked to the high-level guidance in the MBSE model.

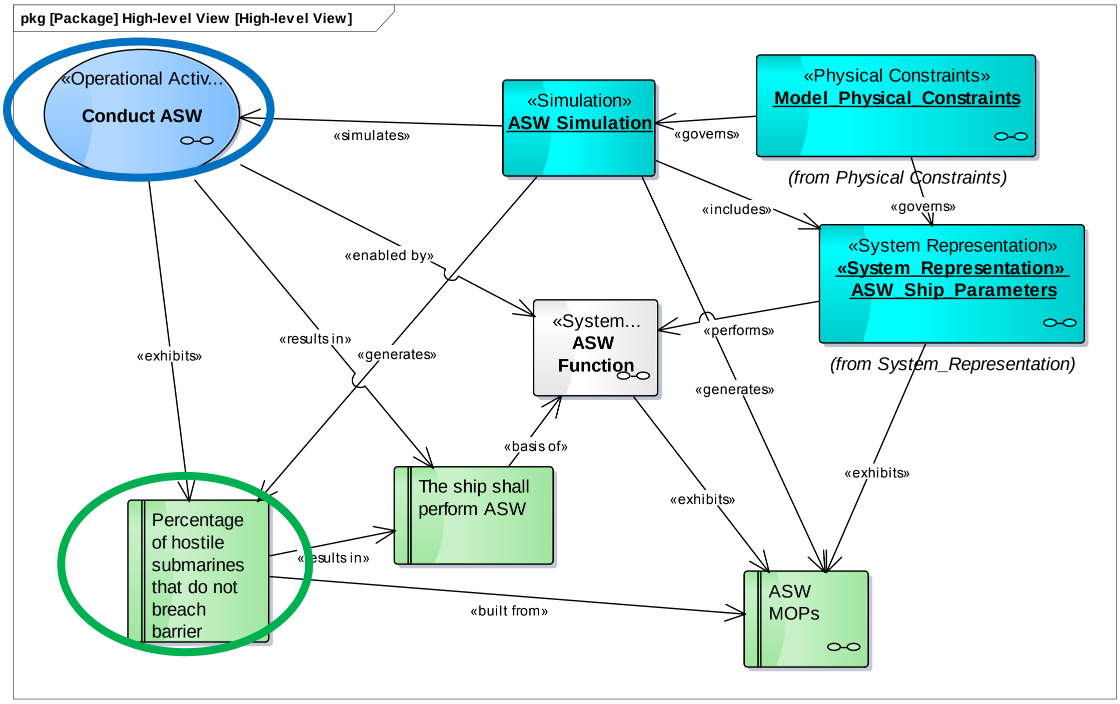


Figure 38: Traceability from the 'Conduct ASW' Operational Activity to MOPs and Analysis Domain elements used in the C&RE. Elements highlighted in the blue and green ovals are from the previous figure.

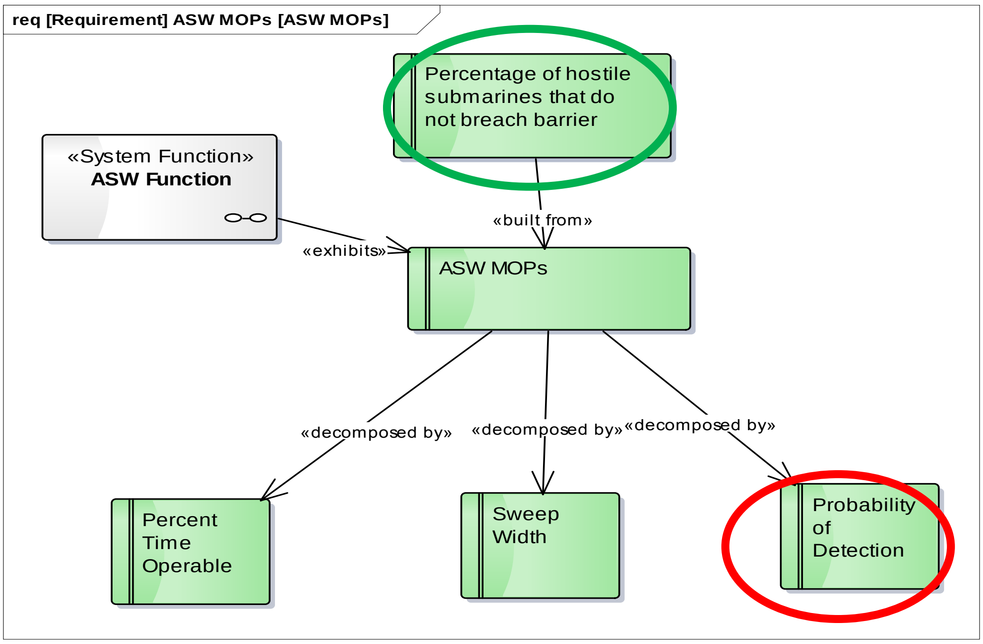


Figure 39: Traceability from barrier patrol ASW operational activity MOE to its MOPs. The MOP Probability of detection is highlighted in the red oval and the parametric diagram solved to calculate it is given in the following figure.

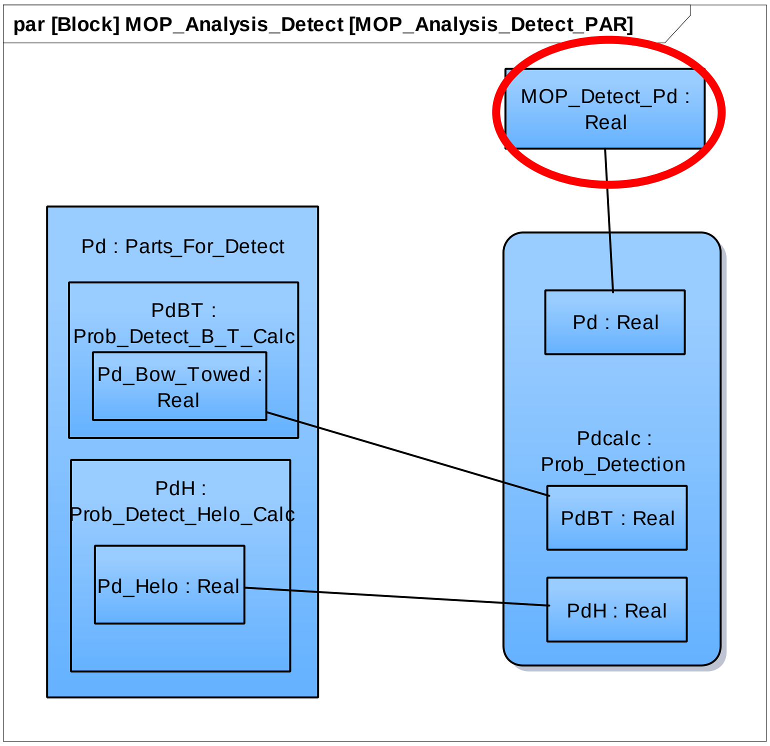


Figure 40: Parametric diagram for the Probability of Detection MOP that is solved by the SysML plug-in to calculate its value for a set of ship design parameters. The ship design parameters are held as parts in the MBSE model as shown in the following figure.

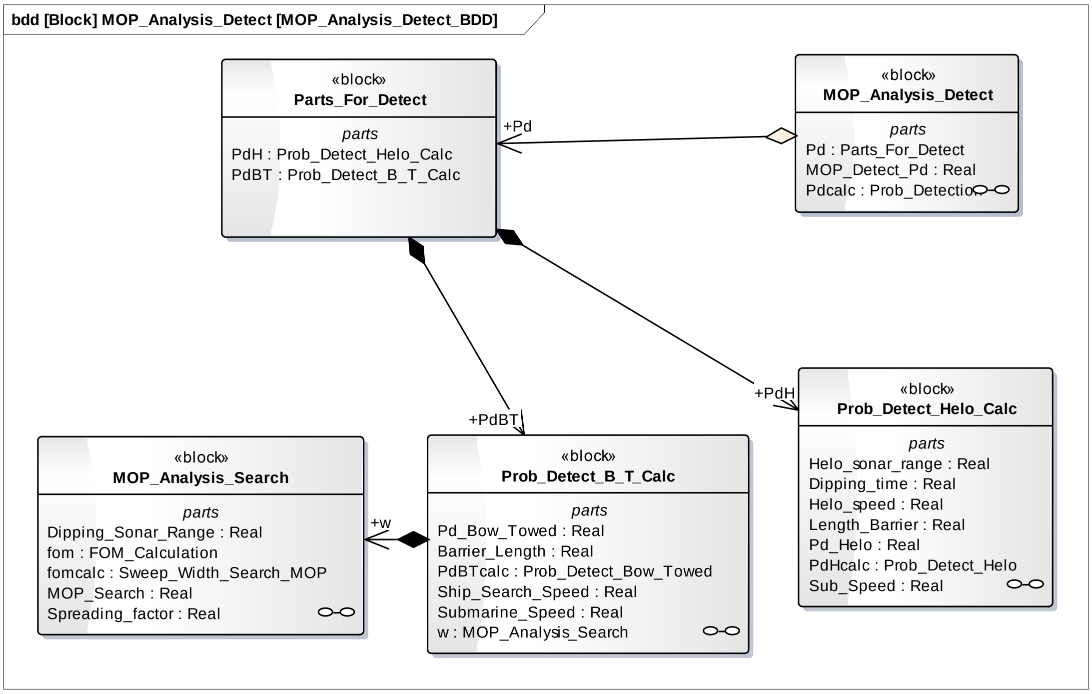


Figure 41: Parts, or ship design parameters, used in the calculation of the probability of detection MOP in the parametric diagram shown in the previous figure.

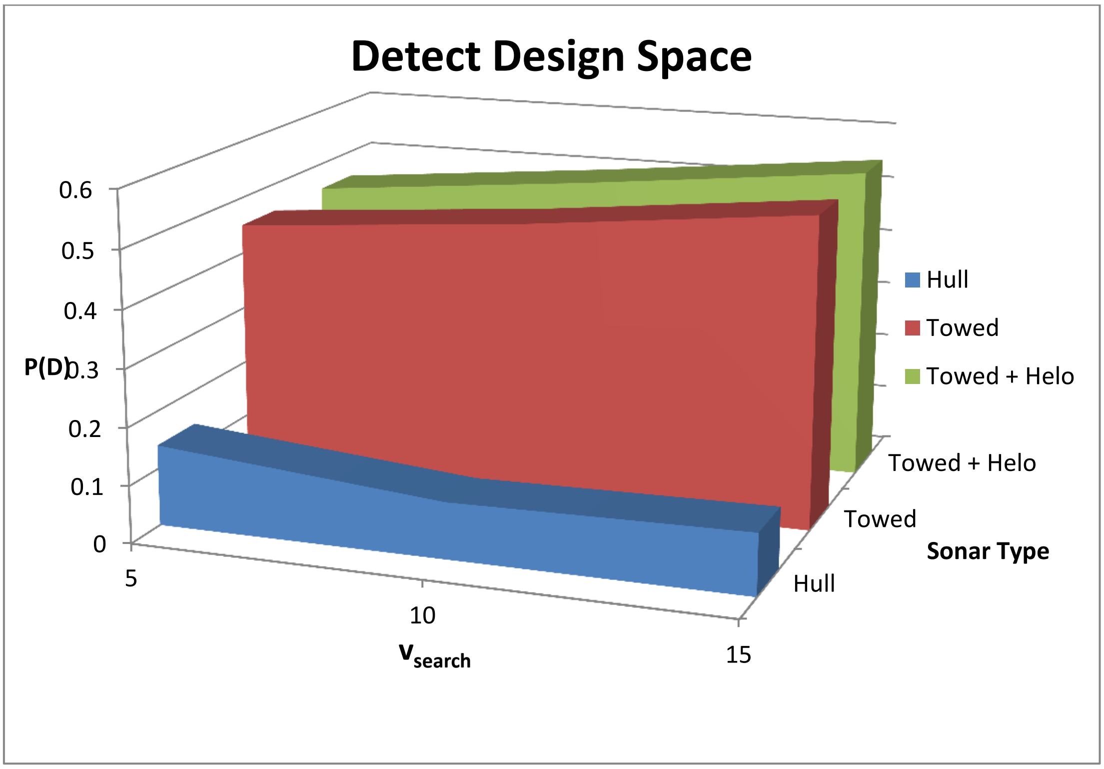


Figure 42: Design space for the Probability of Detection (P(D)) MOP against Search Speed (v_{search}) and Sonar Type.

The results shown in Figure 42 demonstrate a relatively large performance increase in the Probability of Detection KPP can be gained from using a ship with a towed array sonar system installed over a hull mounted sonar system in the barrier patrol scenario. Using this knowledge, acquisition stakeholders could conduct trades-off against other MOPs/KPPs, such as cost. If justified in the trades-off amongst KPPs, a constraint could be specified in the MBSE model, which in turn is specified in the request for tender requirements, that the ship be fitted with a towed array sonar, as shown in Figure 43.

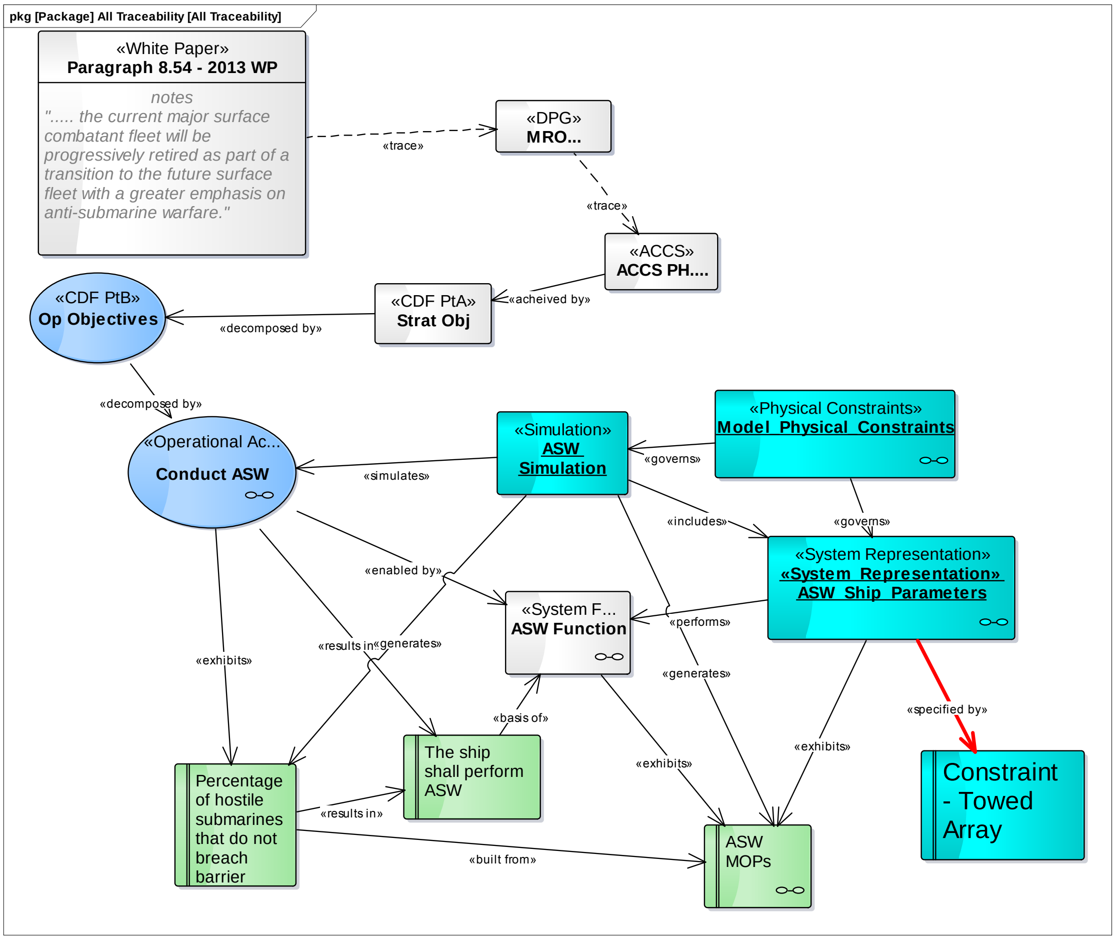
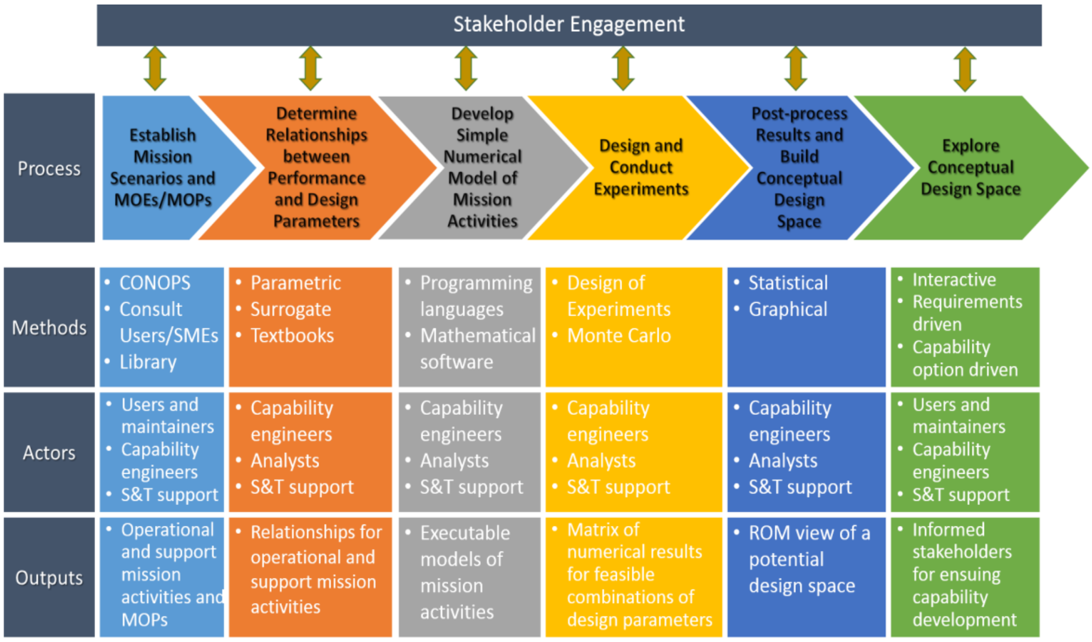


Figure 43: Traceability from the top-level guidance, through the C&RE activities to a 'Towed Array' sonar system constraint.

6.4 Second Iteration of the OTS Concept & Requirements Exploration Research

The second iteration of the research to develop an approach to OTS C&RE for the MEANS MBSE methodology was presented in a refereed paper to the Pacific 2015 International Maritime Conference (reference [13] included in Appendix C). This research iteration focused on including Fundamental Inputs to Capability (FIC) other than the major system into the C&RE. This iteration also sought to investigate whether the analytical activities performed as part of the C&RE approach could be more easily implemented from within an MBSE model by trialling different software tools. Another focus in the second iteration was the methods of presenting the information generated when building the ROM design space to stakeholders to inform decision making.

Supporting FICs (i.e. Support, Supplies, Personnel, Facilities, and Command and Management) were incorporated into the C&RE though the inclusion of support activities to the mission scenario from which suitable MOPs and KPPs could be identified. A summary of the second iteration of the C&RE approach is shown in Figure 44.



Stakeholder Engagement

Process	**Establish Mission Scenarios and MOEs/MOPs**	**Determine Relationships between Performance and Design Parameters**	**Develop Simple Numerical Model of Mission Activities**	**Design and Conduct Experiments**	**Post-process Results and Build Conceptual Design Space**	**Explore Conceptual Design Space**
Methods	• CONOPS • Consult Users/SMEs • Library	• Parametric • Surrogate • Textbooks	• Programming languages • Mathematical software	• Design of Experiments • Monte Carlo	• Statistical • Graphical	• Interactive • Requirements driven • Capability option driven
Actors	• Users and maintainers • Capability engineers • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Users and maintainers • Capability engineers • S&T support
Outputs	• Operational and support mission activities and MOPs	• Relationships for operational and support mission activities	• Executable models of mission activities	• Matrix of numerical results for feasible combinations of design parameters	• ROM view of a potential design space	• Informed stakeholders for ensuring capability development

Figure 44: Summary of the second iteration of the MBSE C&RE approach [13].

The steps in each stage of the refined process developed during the second iteration of the research are covered in more detail in the Pacific 2015 paper [13]. This process was implemented in an MBSE environment.

The MEANS MBSE methodology was exercised to build an indicative Offshore Patrol Ship capability as covered in [13] that utilised a descoped, unclassified United States Coast Guard (USCG) Maritime Security Cutter, Medium (WMSM) Concept of Operations. The MBSE model was linked via SysML parametric diagrams generated by the model integration software (Phoenix Integration ModelCenter®), to executable models written in Wolfram Mathematica® code. This approach utilised different software tools to those used in the first iteration and it was more easily implemented. Comprehensive MBSE model views showing traceability from the top-level roles to the analytical activities undertaken during C&RE are provided for the WMSM test implementation that is stepped through in Chapter 8.

6.5 Final Iterations of the OTS Concept &Requirements Exploration Research

Two final iterations of development of the C&RE approach were completed near the end of the researcher's candidature. This research was presented in an international journal paper [17] (Included in Appendix E) and a conference paper presented at the US Naval Postgraduate School's 15th Annual Acquisition Research Symposium [31] (Included in Appendix F). The final iterations of the C&RE approach are presented as part of the final MEANS MBSE methodology described in Chapter 8. The key refinements in the final iterations of the C&RE approach's development were the inclusion of a feedback loop and the introduction of an explicit market survey activity.

The feedback loop in the C&RE approach makes it clearer that each time the OTS design space is generated and explored, and a decision made to specify requirements or constraints (i.e. the requirements are elucidated), it is prudent to revisit the traceability path from the capability needs to the requirements through the design space in order to consider any competing objectives. This serves to verify the requirements to a degree and may necessitate several iterations of looking at different views of the design space so that all trade-offs between KPPs are considered.

The market survey activity was incorporated into the C&RE approach in order to identify whether suitable ship designs for the operational needs already exist. If the operational needs cannot be satisfied by OTS designs, the needs would have to be revisited and adjusted until they reflect the marketplace. Alternatively, a case would need to be made that the capability risk of using OTS designs is unacceptable and an alternative acquisition strategy must be adopted. Details on how the market survey activity can be performed as part of the C&RE approach are given in [31], which includes a test implementation of the final C&RE approach for an indicative hydrographic survey vessel capability (provided in Appendix F).

6.6 Chapter Summary

Chapter 6 provided a brief introduction and summary of the key aspects uncovered during the research to construct a Concept and Requirements Exploration (C&RE) approach for the MEANS MBSE methodology. Test implementations of the C&RE approach have been undertaken for indicative Anti-Submarine Warfare, Offshore Patrol and Hydrographic Survey naval ship capabilities, which are covered in references [29], [13] and [31] respectively. A walk-through of the Offshore Patrol Vessel test implementation is provided in Chapter 8. These test implementations indicated the C&RE part of the MEANS MBSE methodology will provide useful information to acquisition stakeholders. This information can be used to inform requirements definition, requirement trade-off decisions and capability risk identification. Implementing the C&RE approach using an MBSE environment facilitates reuse of mission and requirement decomposition and analysis activities. This insight was exploited further in research covered in the following chapters, when pattern-based methods were introduced to enhance the ability to reuse MBSE model elements.

The key research contributions of the C&RE approach constructed for the MEANS MBSE methodology are:

i. Embedding traceability from top-level capability needs to analytical activities that support requirements elucidation. This allows inputs and outputs from these analysis and synthesis activities to be traced between needs and requirements.
ii. Enabling analytical activities to be conducted and managed from within an MBSE tool, which can then be traced to any resulting requirements.
iii. Formalising the approach to conducting activities to support the early phases of OTS naval ship acquisitions through a methodology comprising a process, methods and tools.

Chapter 7 – MEANS MBSE Methodology Part 2: Off-the-Shelf Naval Ship Option Evaluation

7.1 Introduction

Chapter seven is the third chapter in the body of the thesis that addresses the third research sub-question:

> *How can MBSE-based approaches enhance the current (acquisition) process and what is their utility?*

The research project addresses this research sub-question through the construction of the Middle-out Early-phase Above-the-line Naval Ship (MEANS) Model-Based Systems Engineering (MBSE) methodology. Following on from the development of a suitable metamodel (Chapter 5), and exploring different software tools and Concept and Requirements Exploration (C&RE) techniques (Chapter 6), the next stage of the research project involved the construction of a model-based method to support OTS naval ship design option evaluation. The focus of this part of the research is the Australian Defence Risk Mitigation and Requirements Setting Phase between Gate 1 and Gate 2 as shown in Figure 45.

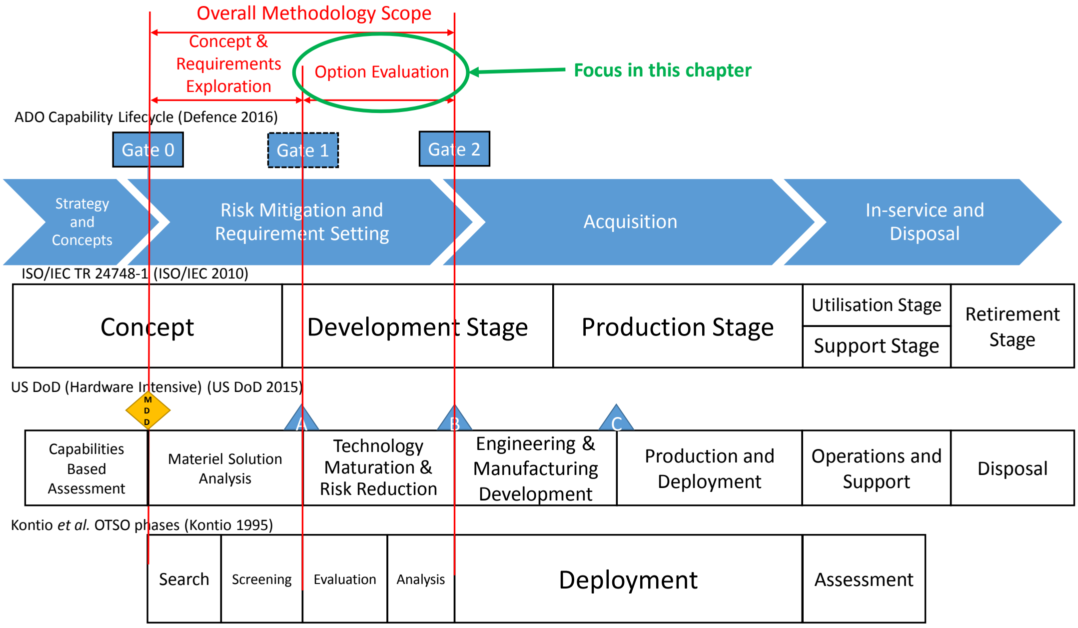


Figure 45: Various systems lifecycles and the phase of interest for the research covered in this chapter.

As noted by the researcher [30: p. 688]:

> ‘The final step in this pre-acquisition stage of OTS naval platforms, is to select a design option that best meets the capability need. Selection of this option requires an evaluation to be performed. In this stage of the ADO[11] lifecycle, option evaluation is specifically referenced with “each option is assessed to confirm feasibility, acceptability and suitability” [4: p. 31]. Option evaluation is classified as a ‘Decision Management Process’ in the INCOSE Systems Engineering Handbook (SEH) [6] and ISO/IEC/IEEE 15288:2015. The stages in the Off-the-Shelf Option (OTSO) method (shown at the bottom of Figure 45) provide a useful reference for such an OTS system lifecycle, with the evaluation of the shortlisted alternatives and analysis of the evaluation aligning with the second part of the ADO risk mitigation and requirements setting stage. The alignment arises as the evaluation stage “produces data on how well each alternative (option) meets the criteria defined” [42: p. 8].’

This chapter of the thesis provides a brief introduction to the model-based OTS naval ship design option evaluation method that was constructed as part of the MEANS MBSE methodology. This research is covered in the researcher’s publications:

- Morris, B.A. and Cook, S.C., 2017. “A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms.” In *INCOSE International Symposium*, Vol. 27, No. 1, pp. 688-703. [30] (Included in Appendix D).
- Morris, B.A. and Tait S., 2019. “Progress Report on an Option Evaluation Method for RAN Surface Ship Acquisitions during Risk Mitigation and Requirements Setting.”. (For-Official-Use-Only) Defence Science and Technology Group, Department of Defence (In publication) [35].

Morris and Cook [30] is the definitive publication on the research covered in this chapter and for further details on this part of the MEANS MBSE methodology, the reader is referred to Appendix D. The key research contributions related to the construction of the model-based method to support the selection of a preferred OTS

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[11] ADO is the Australian Defence Organisation, which is generally referred to as Defence in this thesis.

naval ship design option between Gate 1 and Gate 2 in the Defence capability lifecycle are summarised as:

i. Traceability from top-level capability needs to the evaluation criteria used in an OTS design option evaluation can be clearly demonstrated.
ii. A Multi-Criteria Decision Making method was integrated into an MBSE tool.
iii. Pattern-Based methods were introduced into the MEANS MBSE methodology to facilitate knowledge reuse and faster model building.

7.2 Background

Guidance on approaches to conduct option evaluation is widely available in in standards and texts. Examples include Buede [159], Kontio, Chen *et al.* [42], Julian, Lucy *et al.* [58] and Edwards, Cilli *et al.* [89]. The Edwards, Cilli *et al.* [89] approach provides an example of how traceability can be embedded into the development of the evaluation criteria. Their approach comprises the following steps [89]:

1. Requirements Analysis
2. Define functional objectives
3. Map requirements to functional objectives
4. Establish product structure
5. Map functional objectives to product structure
6. Define metrics
7. Craft value functions
8. Determine (MOP) priority weightings
9. Optimise product configuration.

When discussing the existing approaches to conducting option evaluation, the researcher noted that they [30: p. 691]:

> '…appear suitable for developmental systems acquisitions, along with systems including a high proportion of OTS components. Typically, there is a need to initially trade-off OTS naval platform design options at the whole-of-platform level rather than develop design variants from OTS components, which suggests a tailored method is required. Furthermore, where scope for design changes exists, which technically violates the OTS acquisition strategy, yet often occurs, the method should also allow for the

> identification of 'weak spots' to highlight potentially high-value subsystem trades."

7.3 Construction of a Model-Based OTS Naval Ship Design Option Evaluation Method

When searching for suitable techniques to use in the MEANS MBSE methodology, the Australian Defence First Principles Review [2] provided an overview of the recurring themes identified in previous reviews of Australian Defence. Three of these themes related to the need for the Defence to be a 'smart buyer'[12] and were adopted to provide guiding principles for the construction of the model-based option-evaluation method. These guiding principles were [30: p. 691]:

1. Maintain traceability of evaluation criteria – ideally, these will be linked to the original, strategic intent of the platform being acquired in order to ensure a defensible, rigorous evaluation.
2. Assist the stakeholders to make defensible decisions, in a structured manner, that account for competing goals and objectives.
3. Maximise the capacity to reuse model elements – thereby reducing subsequent acquisition efforts to implement the method and the resources required to manage these projects.

The researcher noted at the time the model-based option evaluation method was being constructed (mid-2016) [30: p. 691]:

> 'From the open literature, three key resources that adhere to these principles have been identified to facilitate the construction of a model-based naval platform option evaluation method: MBSE, Multi-Criteria Decision Making (MCDM), and Pattern-Based Systems Engineering (PBSE).'

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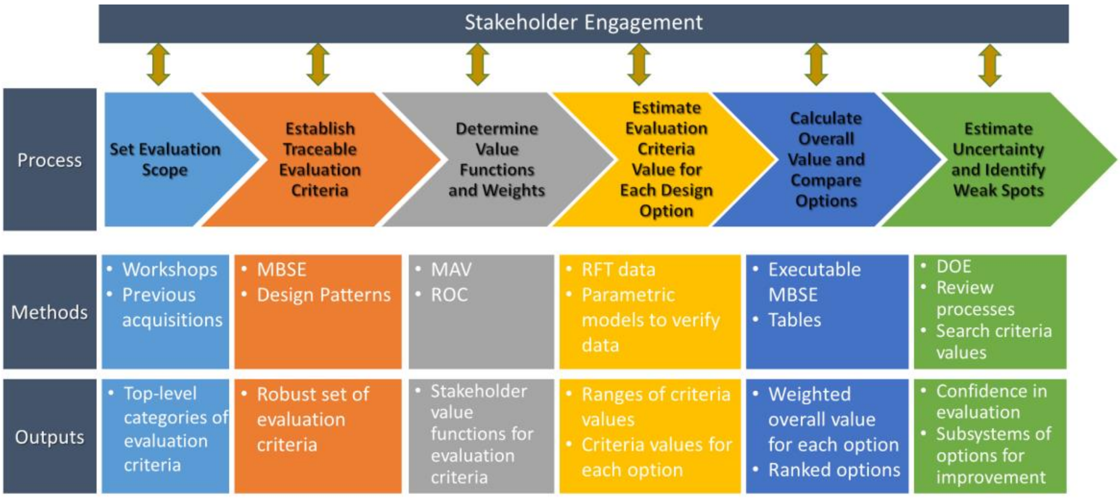
[12] The author prefers the original definition of a smart buyer given on page 33 of the FPR of someone who can 'accurately define the technical services needed, recognise value during the acquisition of such technical services and evaluate the quality of services ultimately provided' rather than the definition currently adopted in Defence.

MBSE was introduced in Section 1.4, while MCDM and PBSE were introduced in the Chapter 3 literature review in Section 3.4.1 and Section 3.3.6 respectively. Pattern-Based methods are also described in more detail in Chapter 8.

The proposed model-based method to support OTS naval ship design option evaluation using these three key resources is shown in Figure 46.



Process	Set Evaluation Scope	Establish Traceable Evaluation Criteria	Determine Value Functions and Weights	Estimate Evaluation Criteria Value for Each Design Option	Calculate Overall Value and Compare Options	Estimate Uncertainty and Identify Weak Spots
Methods	• Workshops • Previous acquisitions	• MBSE • Design Patterns	• MAV • ROC	• RFT data • Parametric models to verify data	• Executable MBSE • Tables	• DOE • Review processes • Search criteria values
Outputs	• Top-level categories of evaluation criteria	• Robust set of evaluation criteria	• Stakeholder value functions for evaluation criteria	• Ranges of criteria values • Criteria values for each option	• Weighted overall value for each option • Ranked options	• Confidence in evaluation • Subsystems of options for improvement

Figure 46: The model-based OTS naval platform option evaluation method [30]. A feedback loop was subsequently added, which is covered in Chapter 8.

Details on each of the steps shown in Figure 46 are given in Morris and Cook [30] (included in Appendix D of this thesis), so are not repeated here. Some minor refinements were made to the method following the publication of Morris and Cook [30], which are covered in Chapter 8 and a journal paper that was subsequently written by the researcher (reference [17], which is included in Appendix E). The most significant of these was the inclusion of a feedback loop through the process shown in Figure 46 to account for a re-evaluation of OTS options following design changes resulting from the identification and eradication of design-option weak spots. This addition is covered in Chapter 8, where the final MEANS MBSE methodology to support OTS naval ship acquisitions is presented.

7.4 Multi-Attribute Value Analysis

The only technique included in the option evaluation method that perhaps requires some expansion beyond the content in Morris and Cook [30], is the implementation of the MCDM method that was used. This is because some colleagues who reviewed Morris and Cook [30] and Morris, Cook *et al.* [17] have sought clarification on the calculation approach. The MCDM method that has been utilised in the model-based option evaluation method part of the MEANS MBSE methodology is the Multi-Attribute Value Analysis (MAV) approach described by Buede [159]. In this approach, the Overall Weighted Value (OWV) of each option is given by Equation 2:

$$OWV = \sum_{i=1}^{n} w_i v_i(x_i) \qquad (2)$$

Where: n = number of evaluation criteria.

w = weight of each evaluation criterion.

$v_i(x_i)$ = normalised value of each evaluation criterion.

A key point to note is that the evaluation criteria in naval ship acquisition projects are likely to include factors related to [30]:

- Mission Performance
- Economics
- Schedule and Technical risk
- Non-Functional Requirements
- Strategic factors

Guidance on how evaluation criteria for each of these factors can be developed is given in Morris and Cook [30] (see Appendix D). The mission performance evaluation criteria for example, will be the Key Performance Parameters (KPPs) that were identified during the Concept and Requirements Exploration part of the MEANS MBSE methodology.

The Rank Order Centroid (ROC) technique is used to determine the numerical weights w_i directly from the ranking of acquisition stakeholders for the evaluation criteria importance. ROC calculates the weight of each evaluation criteria w, for k evaluation criteria with ranks, r, using Equation 3.

$$w_i = \left(\frac{1}{k}\right) \sum_{j=i}^{k} \left(\frac{1}{r_j}\right) \qquad (3)$$

The next calculation is to calculate the normalised value of each criteria value using Equation 4.

$$x_i = \frac{(x - x^0)}{(x^* - x^0)} \qquad (4)$$

Where: x = evaluation criteria value of the design option

x^0 = threshold value of the evaluation criteria

x^* = objective value of each evaluation criteria

The normalised single-dimensional value of each criteria, $v_i(x_i)$ is then found by applying the value function selected by stakeholders for each evaluation criterion, v_i, at the normalised criteria value, x_i. Common value function curves are shown in Figure 5 of Morris and Cook [30], which were taken from Figure 13.1 of Buede [159: p. 364] and are reproduced below in Figure 47.

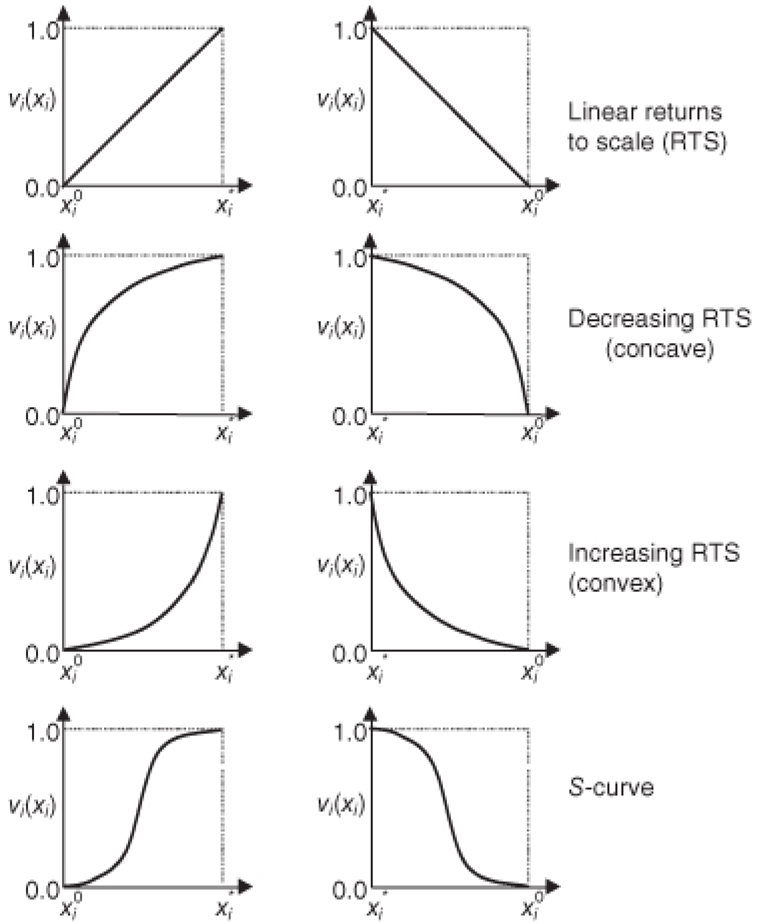


Figure 47: Most common value curves for use in the MAV decision making approach [159].

The final calculation in the MAV approach is to calculate the Overall Weighted Value for each design option, which can be achieved using Equation 2 above.

7.5 Chapter Conclusion

Chapter 7 provided a brief introduction to the research to construct a model-based OTS naval ship design option evaluation method. The design option evaluation method is the second part of the MEANS MBSE methodology to support Australian OTS naval ship acquisitions. The research was covered in reference [30] and presented by the author at an international conference. A test implementation of the model-based option evaluation method was undertaken for an indicative Offshore Patrol Vessel naval ship capability and covered in Morris and Cook [30]. This test implementation is covered in more detail in Chapter 8. The test implementation indicated the method is useful for maintaining traceability of the evaluation criteria, managing design and evaluation data, as well as supporting the identification of weak spots in OTS naval ship designs. Implementing the method in an MBSE methodology means that the evaluation criteria related to mission performance will be the KPPs identified during the Concept and Requirements Exploration activities covered in Chapter 6. It also means the same MBSE model can be developed and maintained throughout the Defence Risk Mitigation and Requirements Setting Phase, The MBSE model, when developed using the MEANS MBSE methodology, provides supporting traceability and rigour to the development of business cases for milestone decisions in Defence naval ship acquisitions.

The key research contributions related to the construction of the model-based OTS naval ship design option evaluation method are summarised as:

i. Traceability from top-level capability needs to the evaluation criteria used in an OTS design option evaluation can be clearly demonstrated.
ii. A Multi-Criteria Decision Making method was integrated into an MBSE tool.
iii. Pattern-Based methods were introduced into the MEANS MBSE methodology to facilitate knowledge reuse and faster model building.

Chapter 8 – Bringing it all Together: The MEANS MBSE Methodology to Support Early Phase Australian Off-the-Shelf Naval Ship Acquisitions.

8.1 Introduction

This chapter is the capstone of the thesis that presents the final refinements of the Middle-out Early-phase Above-the-line Naval Ship (MEANS) Model-Based Systems Engineering (MBSE) methodology constructed to support Australian Defence Off-the-Shelf (OTS) naval ship acquisitions. The final iteration of the MBSE methodology is the culmination of the research project that was undertaken to answer the third research sub-question:

> *How can MBSE-based approaches enhance the current (acquisition) process and what is their utility?*

Chapter 8 opens with an overview of the final refinements to the MBSE methodology, which have been presented in the International Journal of Maritime Engineering (IJME), as well as in a conference paper presented at the US Naval Postgraduate School's 15th Annual Acquisition Research Symposium. The publication details are:

- Morris, B.A., Cook, S.C., and Cannon, S.M., 2018 "A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions." In *International Journal of Maritime Engineering*, **160** (Part A1 2018): p. 21-40. [17] (Included in Appendix E).
- Morris, B.A., Cook, S.C., Cannon, S.M., and Dwyer, D.M., 2018. "An MBSE Methodology to Support Australian Naval Ship Acquisition Projects." In *15th Annual Acquisition Research Symposium*. Naval Postgraduate School, Monterey, CA. [31] (Included in Appendix F).

The chapter concludes with a worked example of the use of the MEANS methodology.

8.2 Final Refinements to the MEANS MBSE Methodology

Around the time the model-based option evaluation method was being constructed in 2016, a periodic review of acquisition manuals and the open literature identified additional suitable resources that were later included in the option evaluation method. These, along with some reviewer feedback received upon acceptance of the journal paper above (Morris, Cook *et al.* [17]), were included as final refinements to the MEANS MBSE methodology. These refinements adhere to the three guiding principles given in section 7.1 of Chapter 7 and seek to enable the methodology to provide higher-value support to acquisition stakeholders when preparing business cases for government decisions. These refinements are described below.

8.2.1 Key Performance Parameters

One of the final refinements to the MBSE methodology was to focus on using Key Performance Parameters (KPPs) as the key measures for both the C&RE and the mission performance evaluation criteria during option evaluation. The US DoD Joint Capabilities Integration and Development System (JCIDS) Manual gives the following descriptions of KPPs, Key System Attributes (KSAs) and Additional Performance Attributes (APAs) [46: p. D-A-1]:

- **KPPs** – ‘performance attributes of a system considered critical or essential to the development of an effective military capability.’
- **KSAs** – ‘performance attributes of a system considered important to achieving a balance solution/approach to a system, but not critical enough to be designated a KPP.’
- **APAs** – ‘performance attributes of a system not important enough to be considered KPPs or KSAs, but still appropriate to include in the Capability Definition Document or Capability Production Document.’

By focusing on the KPPs to inform Concept and Requirements Exploration (C&RE) and option evaluation decisions, rather than the wider Measures of Performance that were used in earlier iterations of the C&RE approach, the MEANS MBSE methodology will support trades-off based upon the critical aspects of the capability needs. On the topic of identifying whether a performance characteristic for a capability is a KPP, the

JCIDS Manual provides the following useful set of questions to consider [46: p. D-A-6]:

- ‘Is the performance attribute traceable to, and a necessary component of satisfying, one or more operational attributes of capability requirements validated in the Initial Capabilities Document, or one of the mandatory KPPs…?’
- ‘Does the threshold value of the performance attribute contribute to significant improvement in warfighting capabilities, operational effectiveness, and/or operational suitability, where an inability to meet the threshold value should call into question the continued value of the program?’
- ‘Are the necessary combinations of KPPs, KSAs and/or APAs, and their threshold/objective values, identified in a manner which allows assessment of ability to achieve mission success in the operational context?’
- ‘Are the recommended threshold and objective values of the KPP, KSA or APA reflective of reasonable operational risks, applicable technology maturity, timeframe the capability is required, and supported by analysis?’
- ‘Is the threshold value of the KPP, KSA or APA achievable and affordable, considering project life cycle costs and constraints of Service…?’

The JCIDS Manual also provides a useful exemplar process for developing KPPs, KSAs and APAs that is essentially top-down in nature and was used by the researcher in the test implementations of the MEANS MBSE methodology covered in [17] and [31]. The JCIDS process for developing performance measures is [46: p. D-A-7]:

1. ‘List the capability requirements for all missions or functions described in the proposed Capability Development Document (CDD) or Capability Production Document (CPD). These requirements should include any related to the System-of-Systems context. Performance metrics identified in the Initial Capabilities Document (ICD) should be included.
2. Review a list (or design pattern) of performance attributes associated with each of the Joint functions (Appendix A to Enclosure D of the JCIDS Manual provides such a list) for applicability. Generate a list of potential

performance attributes based on the review and include any others essential to meeting the capability requirements validated in the ICD.

3. Build at least one measurable performance attribute for each critical mission or function without designating KPPs, KSAs or APAs within these attributes.
4. Determine the most critical performance attributes and designate them as KPPs. KSAs and APAs can be assigned to other important performance attributes. “Note that a KPP need not be created for all missions and functions for the systems(s), as a KSA or APA may be used without an overarching KPP. In contrast, certain mission and functions may require two or more KPPs.”
5. Document the traceability from the operational attributes and associated values of the capability requirements identified in the ICDs and DODAF CV-3 (capability phasing) to the KPPs, KSAs and APAs.
6. Set threshold and Objective values for KPPs, KSAs and APAs.’

Finally, it is also worth noting there is sometimes an emergent need to change KPPs during the course of an acquisition project with [46: p. D-A-11]:

- ‘While the KPPs (and KSAs and APAs) documented and validated in capability requirement documents represent the validation authority’s best military advice at an instant in time, knowledge gained through acquisition activities, changes to strategic guidance, external threats, mission requirements, or budgetary realities may make relief from previously validated KPPs appropriate.’

8.2.2 Pattern-Based Methods

Although the researcher recognised repeating patterns in the MBSE models he was building during the research, literature covering pattern-based methods was only identified during the construction of the model-based option evaluation method. Pattern-based methods were used in the model-based option evaluation method and were subsequently extended back through to the C&RE approach during the final iteration of the work that brought the entire MEANS MBSE methodology together. A summary of the research related to the inclusion of pattern-based methods in the MBSE methodology is included in Section 2.6 of Morris, Cook *et al.* [17] (see Appendix E).

8.2.3 Changes to the C&RE and Option Evaluation Processes

Final refinements were made to the C&RE and option evaluation processes that incorporated some key insights gained late in the researcher's candidature. The final refinements to the C&RE process again included the use of the ModelCenter® model integration software, but this time it was combined with a new ship performance M&S framework co-developed by the researcher. The M&S framework leverages higher-fidelity physics-based naval architecture simulation tools [37]. The final iteration of the C&RE approach is summarised in Figure 48.

A second final refinement of the C&RE approach was the introduction of an explicit market survey activity as the third step in the process (shown in the grey elements in Figure 48). Morris *et al*. noted [31: p. 7]:

> '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.'

Details on how the market survey activity can be performed as part of the C&RE approach are given in [31], which includes a test implementation of the final C&RE

approach for an indicative hydrographic survey vessel capability (provided in Appendix F).

The introduction of a feedback loop into the model-based option evaluation part of the MEANS MBSE methodology (between Gate 1 and Gate 2 in the Australian Defence capability lifecycle), accounts for a re-evaluation of each OTS design option following any design changes that may have resulted from the identification and treatment of design option weak spots.

8.2.4 Final Methodology Summary

A summary of the final C&RE approach was given in Figure 5 and is repeated in Figure 48 for convenience.

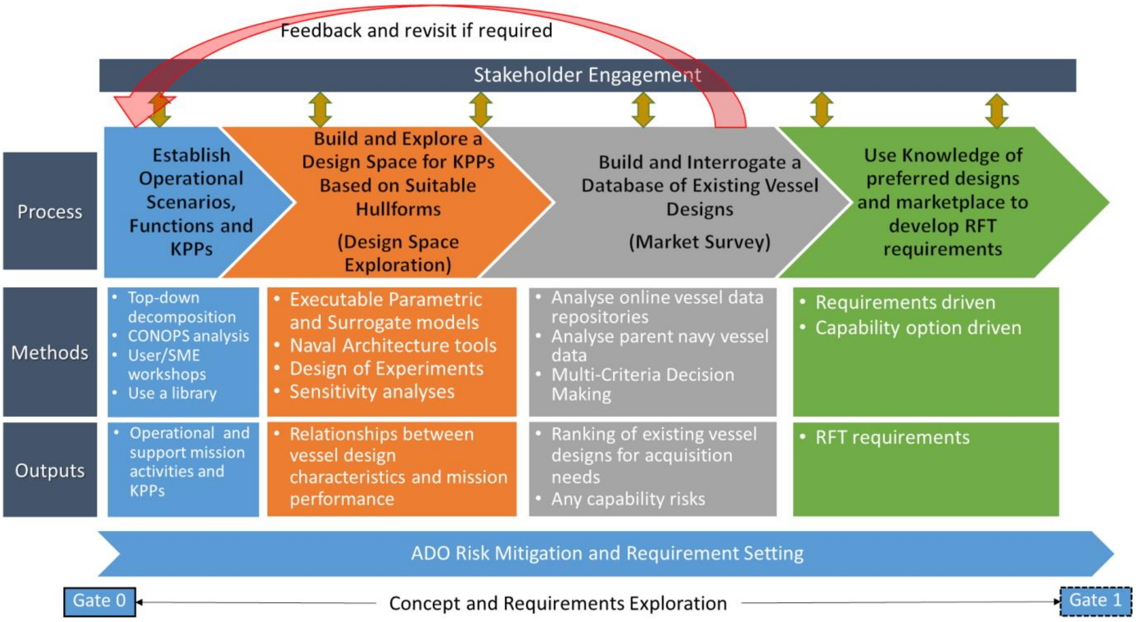


Figure 48: Summary of the final C&RE approach [31].

A summary of the final model-based OTS design option evaluation part of the MEANS MBSE methodology was given in Figure 6 and again in Figure 49 below for convenience.

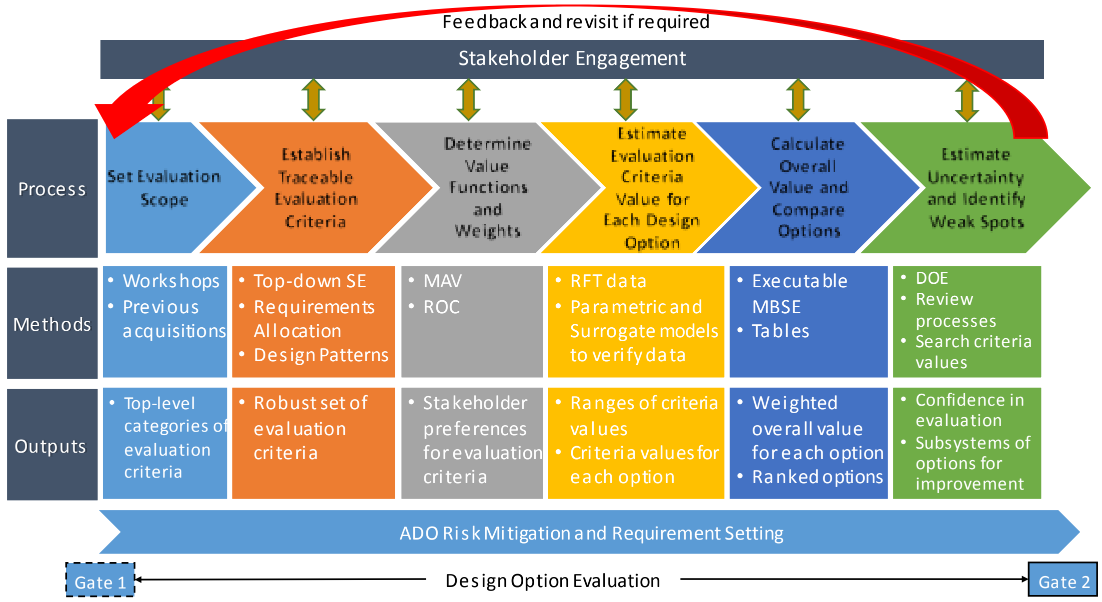


Figure 49: Summary of the final model-based OTS design option evaluation method [17].

8.3 MEANS MBSE Methodology Worked Example

The researcher implemented parts of the MEANS MBSE methodology at various stages during the research project. Some of these were in an official capacity and were published in Defence Science and Technology Group publications. Several others were used as test implementations in the unclassified publications (see [13, 17, 29-31, 37, 155]). In most of these publications, the test implementations of the MEANS MBSE methodology used an open source United States Coast Guard (USCG) Maritime Security Cutter, Medium (WMSM) CONOPS [157] as the basis of the capability needs. The capability needs in the Australian Defence context will typically be given in a Joint Capability Needs Statement [4], which can be an input to the methodology. This section summarises the steps in the MEANS MBSE methodology with a walk-through of the MBSE model that was built for the WMSM test implementation. It demonstrates how the MEANS MBSE methodology could be used to support business cases for government decisions in Australian OTS naval ship acquisitions. It is worth highlighting that the MBSE model developed during this test implementation is underpinned by the metamodel (discussed in Chapter 5) shown in Figure 26.

8.3.1 Concept and Requirements Exploration

This part of the MEANS MBSE methodology covers the Australian Defence Risk Mitigation and Requirements Setting Phase between Gate 0 and Gate 1 in the capability lifecycle (CLC). The objective is to develop a set of request for tender (RFT) requirements that are traceable and based on robust analysis, thereby conforming to the 'smart buyer' approach.

8.3.1.1 Step 1 – Establish Scenarios, Functions and KPPs.

The researcher's International Journal of Maritime Engineering (IJME) paper provided an overview of this step with [17: p. A-26]:

> '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 researcher went on to note that the USCG WMSM CONOPS document [157] contained the military roles and missions the ship would need to perform. In the Australian Defence context, these roles and missions would typically be found in an Operational Concept Document (OCD) and would be traceable to the Force Design process. In terms of MBSE model development, the researcher stated [17: p. A-26]:

> 'These missions were entered into the MBSE model and traced to the design pattern of naval operational activities found in the UNTL [47]. Within the MBSE model, these operational activities were then decomposed and traced through a ship functional architecture design pattern, to the KPPs.'

The MBSE model views in Figure 50 to Figure 53 show the top-down development of a KPP. Figure 50 shows the top-level traceability from the capability needs, which were expressed in terms of military roles in the WMSM CONOPS [157] (termed Operational Tasks in the extended WSAF metamodel), to the Universal Naval Task List (UNTL) [47] scenarios that were equivalent to those in the WMSM CONOPS [157]. This MBSE model view corresponds to a part of a Defence Architecture Framework (DAF)

Operational View (OV) 5a, the operational activity decomposition tree. Using the generic question from Section 5.5, the MBSE modeller can use the element and relationship stereotypes that have been built into the metamodel to trigger the analytic activity that supports the generation of model content. For Figure 50, the analytic activity to generate the content of the scenario elements will be operational analysis as shown in Figure 32. This is triggered by asking: "What <<scenario>> is the <<operational task>> <<achieved by>>?"

In Figure 51, the 'Conduct Maritime Counterdrug Operations' scenario that is part of the 'Law Enforcement' role of the WMSM, is decomposed into the UNTL operational activities within the scenario. Again, this decomposition can be used as part of a DAF OV-5a and model content can be generated by asking the generic question from Section 5.5 based on the element and relationship stereotypes: "What <<operational activity(ies)>> is the <<scenario>> <<decomposed by>>?"

In Figure 52, the 'Sail Ship from Port, Anchorage or Mooring' Operational Activity is traced through the resulting Operational Needs and the System Functions, to the performance characteristics that were deemed to be KPPs (i.e. the MOPs critical to the WMSM being able to perform its Law Enforcement role). This model view is also a model-based version of a DAF System View (SV) 5a, the operational activity to systems function traceability matrix. It's worth noting the System Functions are from a design pattern of naval ship functions that has 'float, move and fight' as the three top-level functions. Figure 53 provides a summary of the traceability path shown in Figure 50, Figure 51 and Figure 52 from the Law Enforcement role to the Endurance Time KPP for the WMSM.

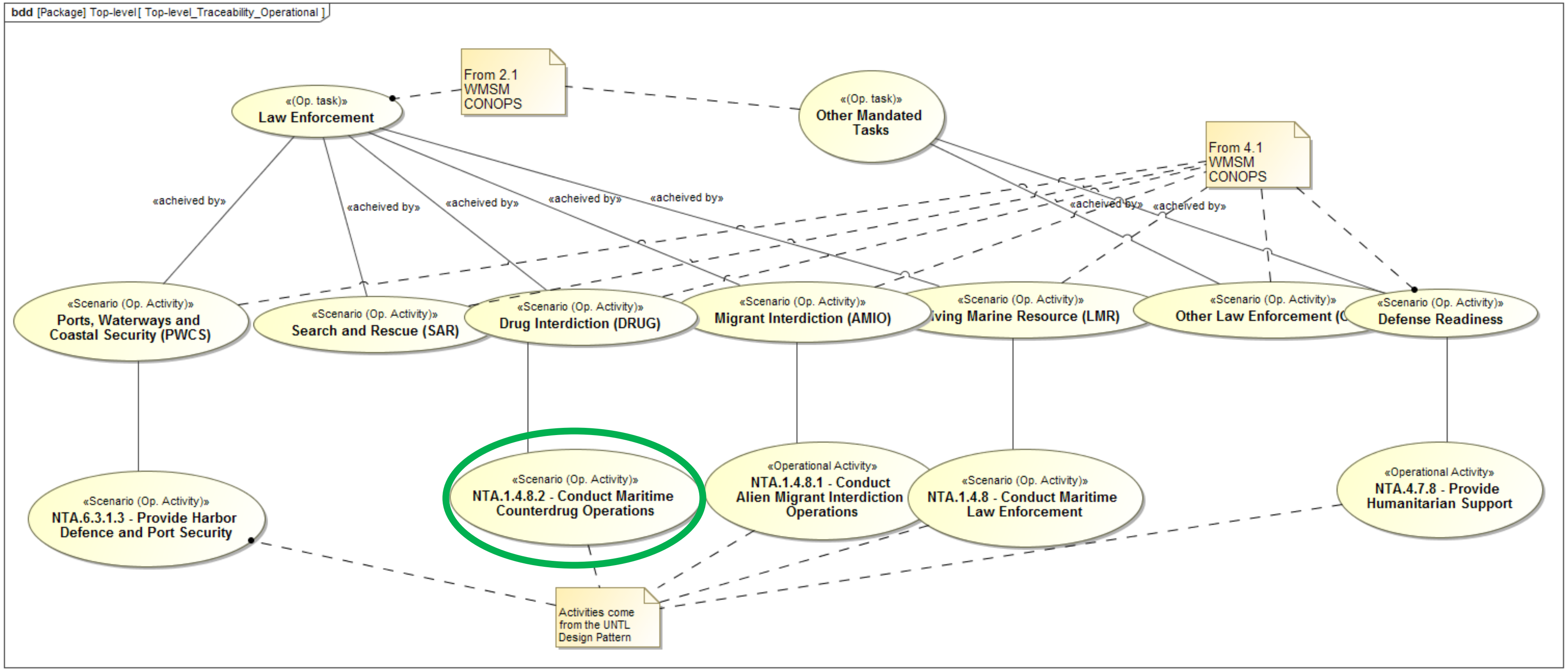


Figure 50: Top-level traceability from Primary Roles to Scenarios for the USCG WMSM example (DAF OV-5a part one). The Drug Interdiction Scenario (inside green oval) is decomposed in subsequent figures.

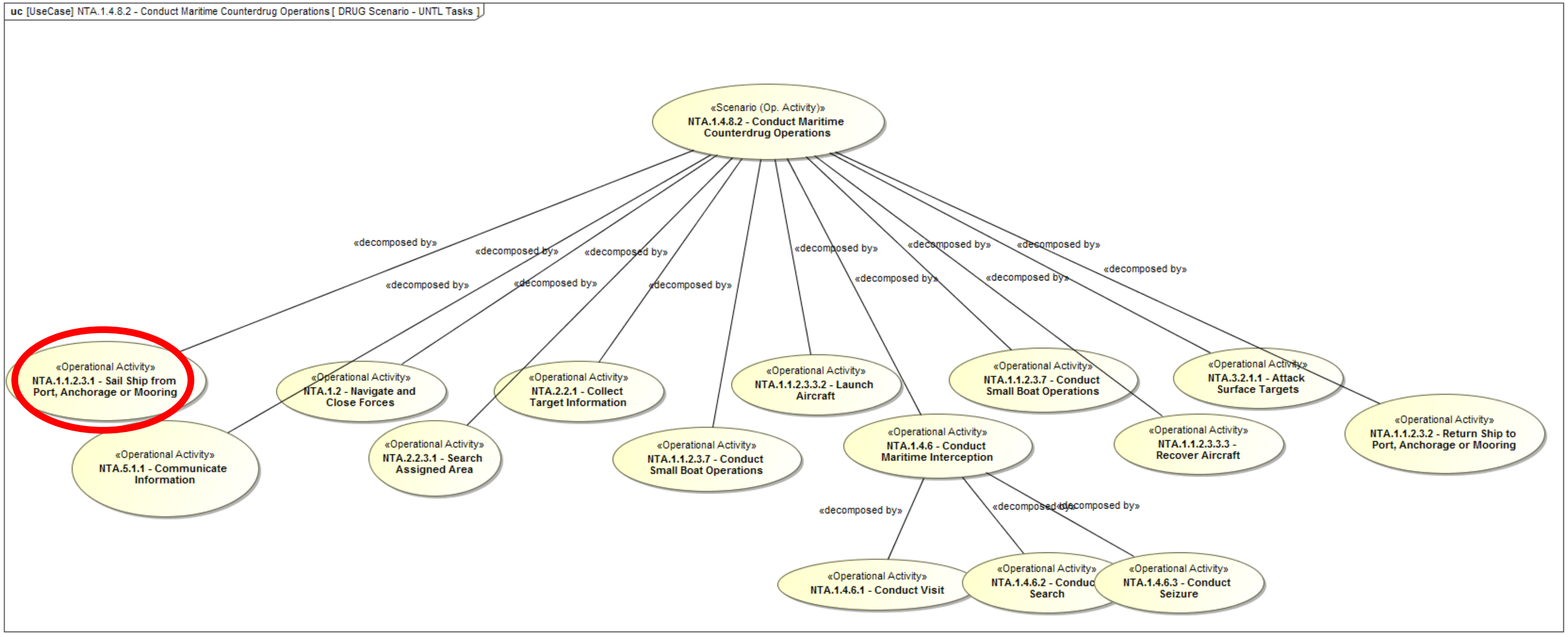
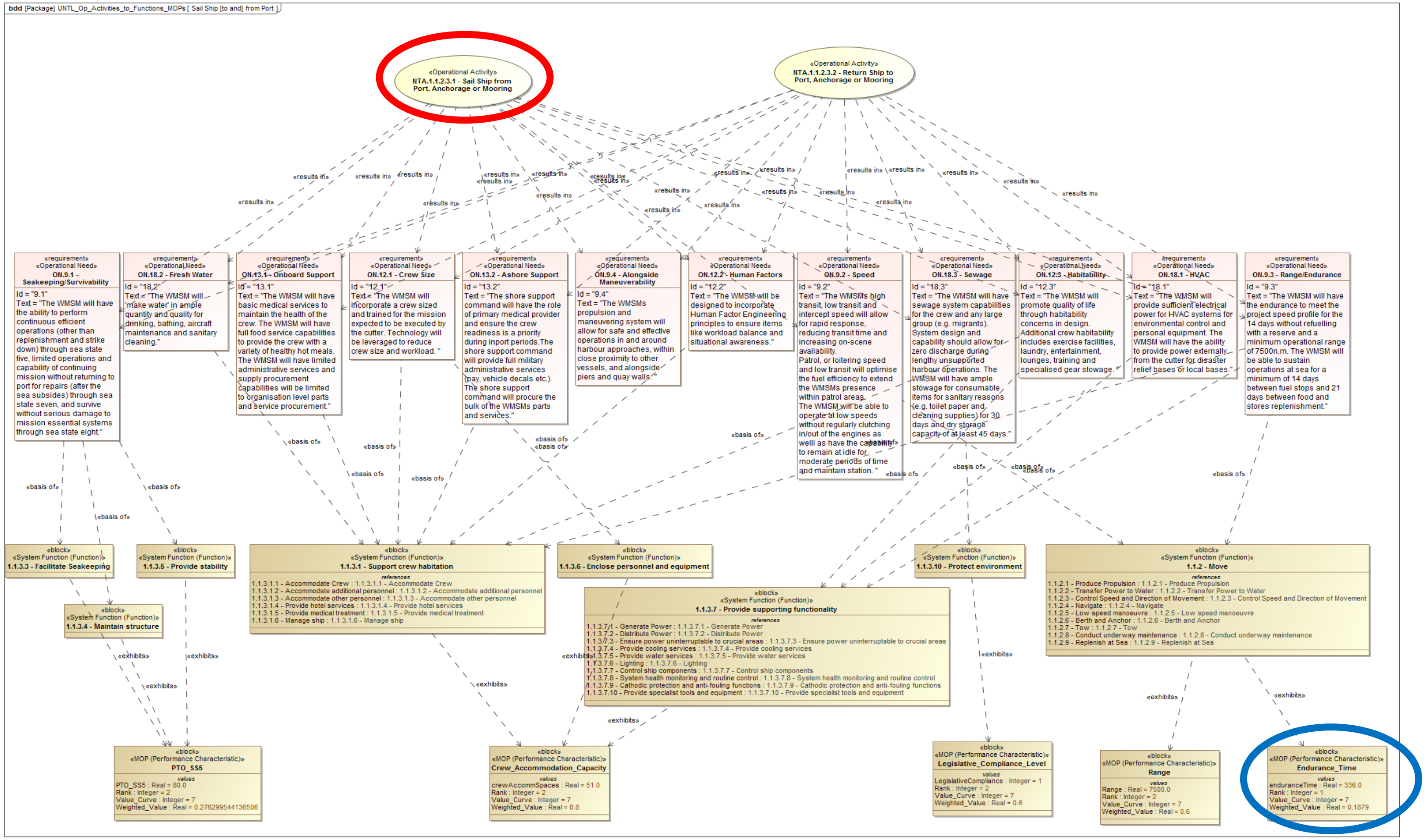


Figure 51: Traceability from the Scenario to the Operational Activities for the 'Conduct Maritime Counterdrug Operations' Scenario in the USCG WMSM test implementation (DAF OV-5a part two). The red oval highlights the 'Sail Ship from Port, Anchorage or Mooring' Operational Activity that is decomposed further in the following figures.



«Operational Activity»
NTA.1.1.2.3.1 - Sail Ship from Port, Anchorage or Mooring

«Operational Activity»
NTA.1.1.2.3.2 - Return Ship to Port, Anchorage or Mooring

«requirement»
«Operational Need»
ON.9.1 - Seakeeping/Survivability
Id = "9.1"
Text = "The WMSM will have the ability to perform continuous efficient operations (other than replenishment and strike down) through sea state five, limited operations and capability of continuing mission without returning to port for repairs (after the sea subsides) through sea state seven, and survive without serious damage to mission essential systems through sea state eight."

«requirement»
«Operational Need»
ON.18.2 - Fresh Water
Id = "18.2"
Text = "The WMSM will 'make water' in ample quantity and quality for drinking, bathing, aircraft maintenance and sanitary cleaning."

«requirement»
«Operational Need»
ON.13.1 - Onboard Support
Id = "13.1"
Text = "The WMSM will have basic medical services to maintain the health of the crew. The WMSM will have full food service capabilities to provide the crew with a variety of healthy hot meals. The WMSM will have limited administrative services and supply procurement capabilities will be limited to organisation level parts and service procurement."

«requirement»
«Operational Need»
ON.12.1 - Crew Size
Id = "12.1"
Text = "The WMSM will incorporate a crew sized and trained for the mission expected to be executed by the cutter. Technology will be leveraged to reduce crew size and workload. "

«requirement»
«Operational Need»
ON.13.2 - Ashore Support
Id = "13.2"
Text = "The shore support command will have the role of primary medical provider and ensure the crew readiness is a priority during inport periods.The shore support command will provide full military administrative services (pay, vehicle decals etc.). The shore support command will procure the bulk of the WMSMs parts and services."

«requirement»
«Operational Need»
ON.9.4 - Alongside Maneuverability
Id = "9.4"
Text = "The WMSMs propulsion and maneuvering system will allow for safe and effective operations in and around harbour approaches, within close proximity to other vessels, and alongside piers and quay walls."

«requirement»
«Operational Need»
ON.12.2 - Human Factors
Id = "12.2"
Text = "The WMSM will be designed to incorporate Human Factor Engineering principles to ensure items like workload balance and situational awareness."

«requirement»
«Operational Need»
ON.9.2 - Speed
Id = "9.2"
Text = "The WMSMs high transit, low transit and intercept speed will allow for rapid response, reducing transit time and increasing on-scene availability.
Patrol, or loitering speed and low transit will optimise the fuel efficiency to extend the WMSMs presence within patrol areas.
The WMSM will be able to operate at low speeds without regularly clutching in/out of the engines as welll as have the capability to remain at idle for moderate periods of time and maintain station. "

«requirement»
«Operational Need»
ON.18.3 - Sewage
Id = "18.3"
Text = "The WMSM will have sewage system capabilities for the crew and any large group (e.g. migrants). System design and capability should allow for zero discharge during lengthy unsupported harbour operations. The WMSM will have ample stowage for consumable items for sanitary reasons (e.g. toilet paper and cleaning supplies) for 30 days and dry storage capacity of at least 45 days."

«requirement»
«Operational Need»
ON.12.3 - Habitability
Id = "12.3"
Text = "The WMSM will promote quality of life through habitability concerns in design. Additional crew habitability includes exercise facilities, laundry, entertainment, lounges, training and specialised gear stowage. "

«requirement»
«Operational Need»
ON.18.1 - HVAC
Id = "18.1"
Text = "The WMSM will provide sufficient electrical power for HVAC systems for environmental control and personal equipment. The WMSM will have the ability to provide power externally from the cutter for disaster relief bases or local bases."

«requirement»
«Operational Need»
ON.9.3 - Range/Endurance
Id = "9.3"
Text = "The WMSM will have the endurance to meet the project speed profile for the 14 days without refuelling with a reserve and a minimum operational range of 7500n.m. The WMSM will be able to sustain operations at sea for a minimum of 14 days between fuel stops and 21 days between food and stores replenishment."

«block»
«System Function (Function)»
1.1.3.3 - Facilitate Seakeeping

«block»
«System Function (Function)»
1.1.3.5 - Provide stability

«block»
«System Function (Function)»
1.1.3.4 - Maintain structure

«block»
«System Function (Function)»
1.1.3.1 - Support crew habitation
references
1.1.3.1.1 - Accommodate Crew : 1.1.3.1.1 - Accommodate Crew
1.1.3.1.2 - Accommodate additional personnel : 1.1.3.1.2 - Accommodate additional personnel
1.1.3.1.3 - Accommodate other personnel : 1.1.3.1.3 - Accommodate other personnel
1.1.3.1.4 - Provide hotel services : 1.1.3.1.4 - Provide hotel services
1.1.3.1.5 - Provide medical treatment : 1.1.3.1.5 - Provide medical treatment
1.1.3.1.6 - Manage ship : 1.1.3.1.6 - Manage ship

«block»
«System Function (Function)»
1.1.3.6 - Enclose personnel and equipment

«block»
«System Function (Function)»
1.1.3.7 - Provide supporting functionality
references
1.1.3.7.1 - Generate Power : 1.1.3.7.1 - Generate Power
1.1.3.7.2 - Distribute Power : 1.1.3.7.2 - Distribute Power
1.1.3.7.3 - Ensure power uninterruptable to crucial areas : 1.1.3.7.3 - Ensure power uninterruptable to crucial areas
1.1.3.7.4 - Provide cooling services : 1.1.3.7.4 - Provide cooling services
1.1.3.7.5 - Provide water services : 1.1.3.7.5 - Provide water services
1.1.3.7.6 - Lighting : 1.1.3.7.6 - Lighting
1.1.3.7.7 - Control ship components : 1.1.3.7.7 - Control ship components
1.1.3.7.8 - System health monitoring and routine control : 1.1.3.7.8 - System health monitoring and routine control
1.1.3.7.9 - Cathodic protection and anti-fouling functions : 1.1.3.7.9 - Cathodic protection and anti-fouling functions
1.1.3.7.10 - Provide specialist tools and equipment : 1.1.3.7.10 - Provide specialist tools and equipment

«block»
«System Function (Function)»
1.1.3.10 - Protect environment

«block»
«System Function (Function)»
1.1.2 - Move
references
1.1.2.1 - Produce Propulsion : 1.1.2.1 - Produce Propulsion
1.1.2.2 - Transfer Power to Water : 1.1.2.2 - Transfer Power to Water
1.1.2.3 - Control Speed and Direction of Movement : 1.1.2.3 - Control Speed and Direction of Movement
1.1.2.4 - Navigate : 1.1.2.4 - Navigate
1.1.2.5 - Low speed manoeuvre : 1.1.2.5 - Low speed manoeuvre
1.1.2.6 - Berth and Anchor : 1.1.2.6 - Berth and Anchor
1.1.2.7 - Tow : 1.1.2.7 - Tow
1.1.2.8 - Conduct underway maintenance : 1.1.2.8 - Conduct underway maintenance
1.1.2.9 - Replenish at Sea : 1.1.2.9 - Replenish at Sea

«block»
«MOP (Performance Characteristic)»
PTO_SS5
values
PTO_SS5 : Real = 80.0
Rank : Integer = 2
Value_Curve : Integer = 7
Weighted_Value : Real = 0.276299544136506

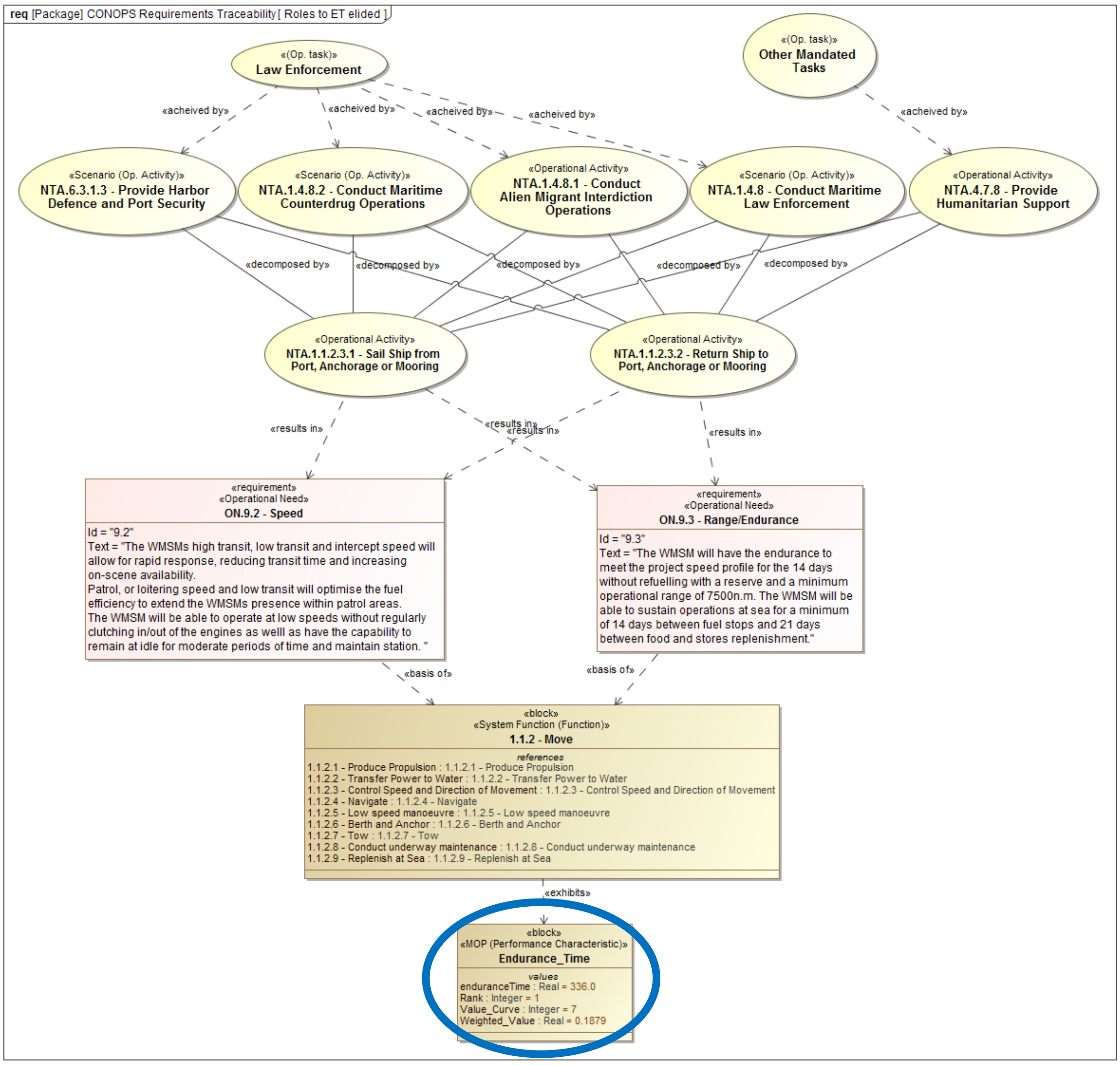
«block»
«MOP (Performance Characteristic)»
Crew_Accommodation_Capacity
values
crewAccommSpaces : Real = 51.0
Rank : Integer = 2
Value_Curve : Integer = 7
Weighted_Value : Real = 0.8

«block»
«MOP (Performance Characteristic)»
Legislative_Compliance_Level
values
LegislativeCompliance : Integer = 1
Rank : Integer = 2
Value_Curve : Integer = 7
Weighted_Value : Real = 0.6

«block»
«MOP (Performance Characteristic)»
Range
values
Range : Real = 7500.0
Rank : Integer = 2
Value_Curve : Integer = 7
Weighted_Value : Real = 0.6

«block»
«MOP (Performance Characteristic)»
Endurance_Time
values
enduranceTime : Real = 336.0
Rank : Integer = 1
Value_Curve : Integer = 7
Weighted_Value : Real = 0.1879

Figure 52: Traceability from 'Sail ship from Port, Anchorage or Mooring' Operational Activity (inside red oval), through Operational Needs and System Functions to the relevant Measures of Performance/Key Performance Parameters (partial SV-5a).



Id = "9.2"
Text = "The WMSMs high transit, low transit and intercept speed will allow for rapid response, reducing transit time and increasing on-scene availability.
Patrol, or loitering speed and low transit will optimise the fuel efficiency to extend the WMSMs presence within patrol areas.
The WMSM will be able to operate at low speeds without regularly clutching in/out of the engines as welll as have the capability to remain at idle for moderate periods of time and maintain station. "

Id = "9.3"
Text = "The WMSM will have the endurance to meet the project speed profile for the 14 days without refuelling with a reserve and a minimum operational range of 7500n.m. The WMSM will be able to sustain operations at sea for a minimum of 14 days between fuel stops and 21 days between food and stores replenishment."

1.1.2.1 - Produce Propulsion : 1.1.2.1 - Produce Propulsion
1.1.2.2 - Transfer Power to Water : 1.1.2.2 - Transfer Power to Water
1.1.2.3 - Control Speed and Direction of Movement : 1.1.2.3 - Control Speed and Direction of Movement
1.1.2.4 - Navigate : 1.1.2.4 - Navigate
1.1.2.5 - Low speed manoeuvre : 1.1.2.5 - Low speed manoeuvre
1.1.2.6 - Berth and Anchor : 1.1.2.6 - Berth and Anchor
1.1.2.7 - Tow : 1.1.2.7 - Tow
1.1.2.8 - Conduct underway maintenance : 1.1.2.8 - Conduct underway maintenance
1.1.2.9 - Replenish at Sea : 1.1.2.9 - Replenish at Sea

enduranceTime : Real = 336.0
Rank : Integer = 1
Value_Curve : Integer = 7
Weighted_Value : Real = 0.1879

Figure 53: Summary of traceability from top-level roles through to the Endurance Time KPP with elements that are not linked elided for clarity.

8.3.1.2 Step 2 – Design Space Exploration

The next step in the C&RE part of the MEANS MBSE methodology is to build and explore a design space for the KPPs based on suitable parent hullforms. In the WMSM test implementation, the hullform was assumed to be monohull and an upper length constraint of around 80 metres was imposed. Constraints such as these would typically be placed on a naval ship acquisition so that the ship could operate from existing wharf infrastructure, or navigate in specific operational areas.

When discussing this step in the MEANS MBSE methodology the researcher noted [31: p. 10]:

> ‘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.’

Following on from the previous step and using the Endurance Time KPP as an example, in this step, a relationship linking ship design parameters to this KPP needed to be developed. Endurance time is a calculated by dividing a ships range by its transit speed and is used by the researcher as a ships endurance because this time period will often be shorter than the period other consumables on the ship will last. To ensure the design space generated from the relationship between ship design parameters and the KPP was reflective of the OTS design space, an analysis of an existing naval ship design database was undertaken, and several parametric models developed. The parametric model for the endurance time KPP is governed by Equation 5 [13].

$$ET = 154.35 \left(\frac{V_{endurance}}{\sqrt{L}}\right)^{-2.054} \quad (5)$$

Where: ET = Endurance Time (hours);

$V_{endurance}$ = Ship endurance speed (knots);

L = Ship length (metres).

Figure 54 shows the SysML parametric diagram for the endurance time KPP parametric model in Equation 5 that is executed from within the MBSE model. The constraint element from the analysis domain in the metamodel shown in Figure 54 (in the purple oval) is linked via model integration software to executable models written in Wolfram Mathematica® code.

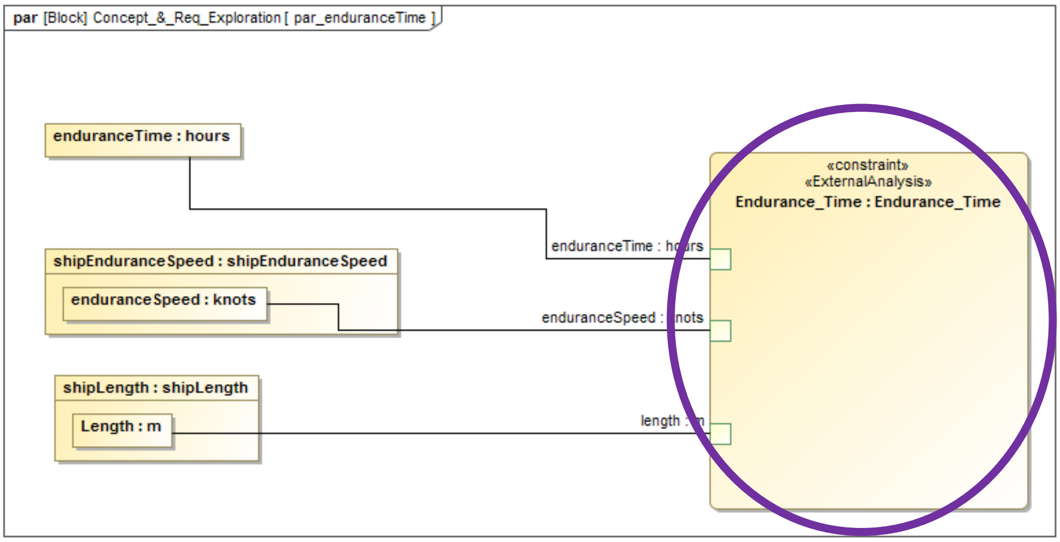


Figure 54: Parametric diagram used to calculate the Endurance Time KPP highlighted in the blue oval in the previous figures .The constraint block is highlighted in the purple oval.

Design of Experiments (DOE) can be used to generate a suitable experimental matrix comprising different combinations of ship design parameters. In turn, the experimental matrix is used as an input to the KPP model to generate a design space such as the one for the endurance time KPP shown in Figure 55. The design space shows that the designs with a combination of lower endurance speed and higher ship length are the best performing for the Endurance Time KPP. Figure 56 shows the results of an analysis of the sensitivities of the ship design parameters used in the Endurance Time KPP. From Figure 56, it can be seen that the most sensitive ship design parameter for Endurance Time in the model developed for this test implementation is the endurance speed. As the endurance speed increases, it has an increasingly negative impact on the endurance time. Conversely, as ship length increases, so does the endurance time, but to a lesser extent than the endurance speed.

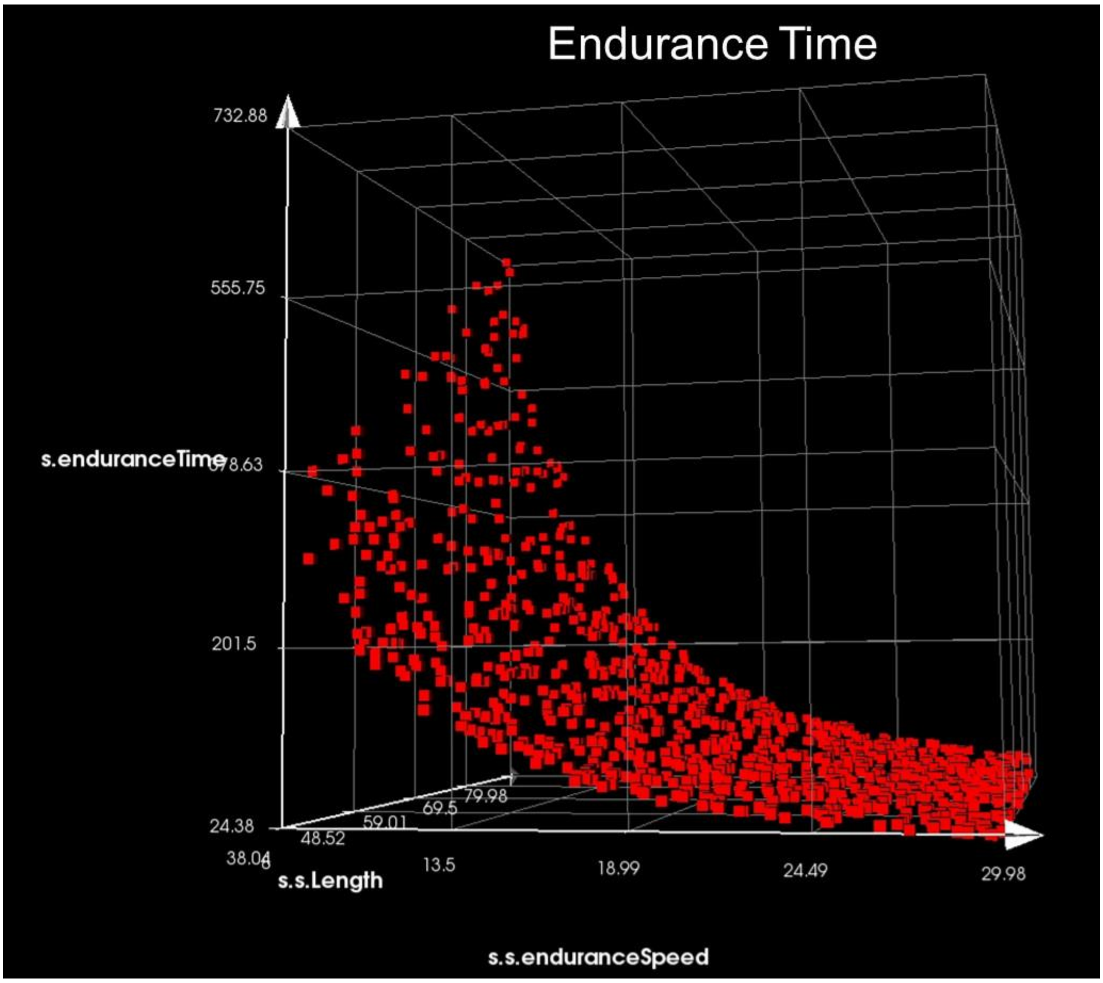


Figure 55: Design space for the Endurance Time KPP generated using a 1000 run Monte Carlo Experiment.

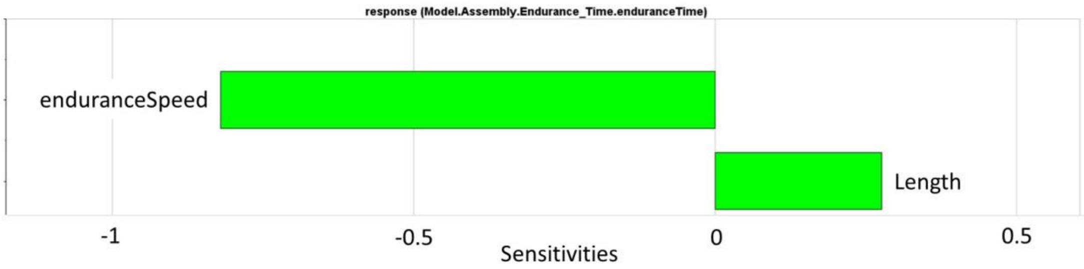


Figure 56: Ship design parameter sensitivities for the Endurance Time KPP.

8.3.1.3 Step 3 – Market Survey

This step in the C&RE part of the MEANS MBSE methodology takes the knowledge gained from the Design Space Exploration in the previous step and applies to a screening of the OTS naval ship marketplace. The researcher previously noted [31: p. 13]:

> ‘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.’

In the WMSM test implementation, the OTS naval ship marketplace was represented by the patrol vessel designs available in the Janes’ Fighting Ships database [160]. Using the results from the previous step of the MEANS MBSE methodology for the Endurance Time KPP, vessels in the database were ranked firstly by endurance speed (a lower transit speed increases the endurance time as shown in Figure 55) and secondly by length (larger vessels have longer endurance time as shown in Figure 55). The approach and tool set up to do this interrogation of the vessel database is described in Morris, Cook *et al.* [31]. Table 7 shows the general particulars of the top ten OTS naval ship designs from the vessel database for the Endurance Time KPP. When considering all of the KPPs for a naval ship acquisition, a similar process of ranking the designs in the marketplace by the most sensitive ship design parameters overall can be used.

Table 7: Top ten ranked designs from the existing vessel database for the Endurance Time KPP.

Rank	Displacement (tonnes)	Length (m)	Beam (m)	Sprint Speed (knots)	Range (nm)	Crew
1	1828	80.6	13	21	8600	64
2	1880	80	13	21	8600	30
3	1756	80.6	13	22	8600	36
4	1219	80.5	9.8	22	7000	69
5	1676	75	14	22	6500	57
6	1727	78.9	14	23	6000	44
7	1083	71	10.4	24	6000	25
8	1321	75	10.8	22	5000	70
9	1350	74.1	11.4	22	5000	79
10	1453	79.9	11.5	22	4000	34

From Table 7, it can be seen that most of the vessels have combinations of design parameters that are near optimal for the Endurance Time KPP (i.e. their length is around 80 metres and they have high ranges). This means there is unlikely to be any capability risk arising from the OTS acquisition constraint. Furthermore, the lack of any capability risk indicates that there is no need to go back to the start of the MEANS MBSE methodology C&RE process to revisit the capability needs. The researcher noted [31: p. 14]:

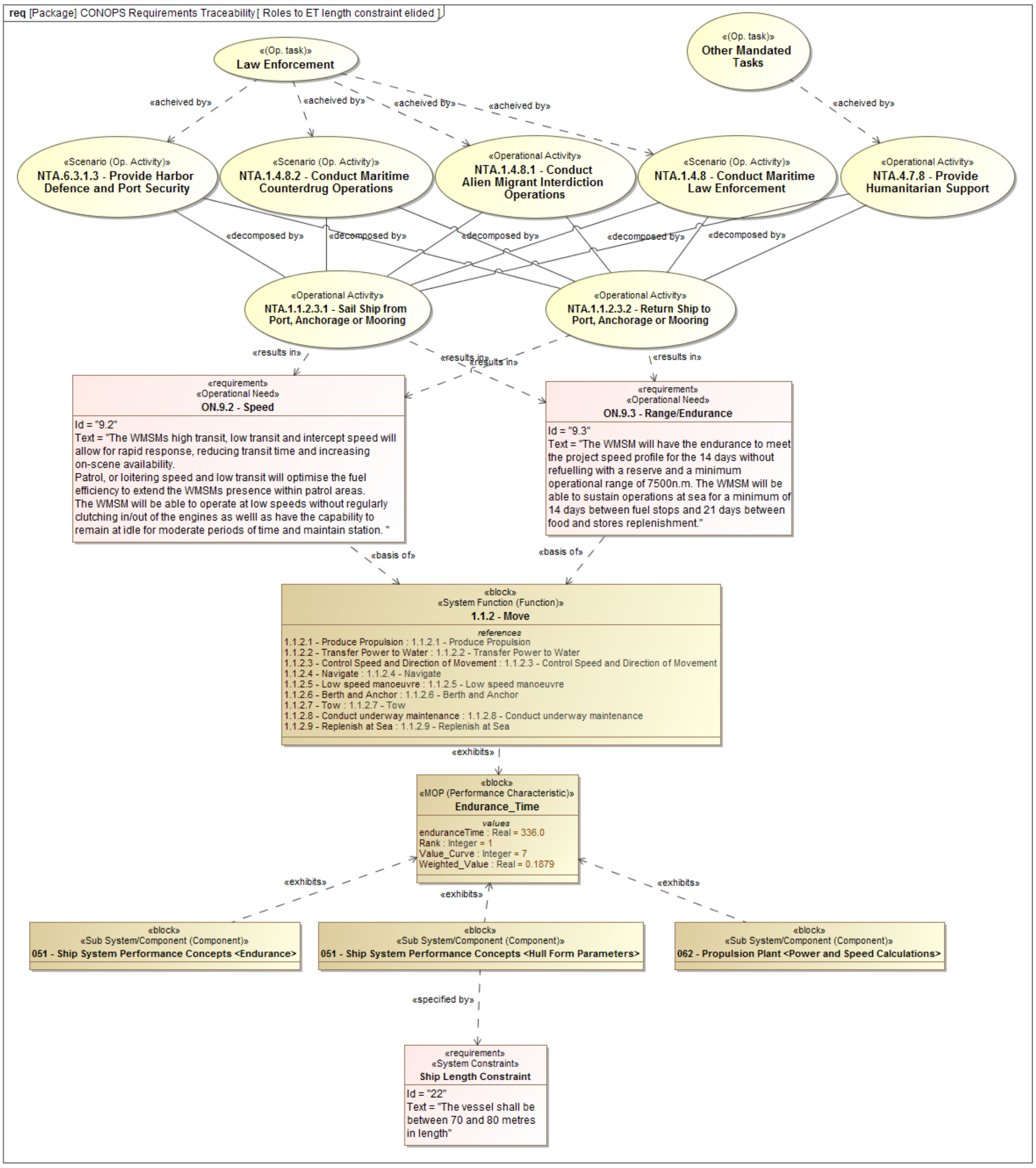
> ‘The top-ranked designs from the database can be investigated further to establish their suitability for the capability needs. In this stage of the investigation, aspects such as the operating navy, year of design and country of origin of the designer can be established, as well as refinement of the top-ranking vessels based on any key criteria, such as the range and crew size.’

These considerations may be important in the broader strategic sense if the operating navy or the designers are from countries the government wishes to strengthen relationships with. The year of design of the vessel is important due to technology obsolescence issues and the currency of the standards to which the vessel was designed.

8.3.1.4 Step 4 – Set Request for Tender Requirements

This step in the C&RE part of the MEANS MBSE methodology uses the knowledge gained from both the design space exploration (step two) and market survey (step three). This knowledge can be used to constrain the responses to a request for tender (RFT) to designs the acquirer can be confident will meet the capability needs. The responses to the RFT are constrained by setting requirements and constraints in the RFT that limit responses to suitable OTS naval ship designs.

For the WMSM test implementation, step two and step three of the C&RE showed that we can be reasonably confident OTS naval ship designs exist in the marketplace that have been designed to meet similar capability needs. The field of potential respondents to an RFT can be narrowed by placing a constraint on the ship length in the RFT to between 70 and 80 metres. The design space exploration in step two showed that vessels of this size are the most suitable for the endurance time KPP (as well as several other KPPs not covered in this section). The market survey activity in step three identified that there are many OTS naval ship designs within this size range. The ship length constraint can be included in the RFT requirements in a traceable manner within the MBSE model by continuing the traceability from the KPPs shown in Figure 53, through the ship systems that exhibit the KPPs, to the system constraint or requirement. As an example, the ship length constraint can be included in the MBSE model as shown in Figure 57. Other constraints and requirements can be set and included in the RFT in a similar manner.



ON.9.2 - Speed
Id = "9.2"
Text = "The WMSMs high transit, low transit and intercept speed will allow for rapid response, reducing transit time and increasing on-scene availability.
Patrol, or loitering speed and low transit will optimise the fuel efficiency to extend the WMSMs presence within patrol areas.
The WMSM will be able to operate at low speeds without regularly clutching in/out of the engines as welll as have the capability to remain at idle for moderate periods of time and maintain station. "

ON.9.3 - Range/Endurance
Id = "9.3"
Text = "The WMSM will have the endurance to meet the project speed profile for the 14 days without refuelling with a reserve and a minimum operational range of 7500n.m. The WMSM will be able to sustain operations at sea for a minimum of 14 days between fuel stops and 21 days between food and stores replenishment."

Ship Length Constraint
Id = "22"
Text = "The vessel shall be between 70 and 80 metres in length"

Figure 57: MBSE model view for the WMSM test implementation showing the traceability of the ship length constraint to the military roles.

8.3.2 Option Evaluation

The MEANS MBSE methodology now moves into the model-based option evaluation part to evaluate responses to an RFT. This typically occurs between Gate 1 and Gate 2 in the Australian Defence CLC.

8.3.2.1 Step 1 - Set Evaluation Scope

For this step, the researcher noted [30: p. 8]:

> ‘In scoping the option evaluation, the competing objectives need to be considered and included or deemed out of scope as appropriate… Naval platform acquisitions will generally have competing objectives of performance, costs, schedule and growth potential (margins). There may be various strategic factors that have the potential to influence the evaluation as well.’

In the WMSM test implementation, the evaluation scope was assumed to be: mission performance, economic factors, schedule and technical risks, non-functional requirements, and strategic factors. The researcher has noted that strategic factors are [30: p. 10]:

> ‘…included to capture the non-technical criteria that often accompany naval platform acquisitions. These criteria may include the preferences related to strategies associated with national interests. For example, the strategic need to strengthen ties with other countries could be a factor in the acquisition of a naval platform if a designer of an option under consideration was from a strategically important country. These factors could also include commercial aspects such as those associated with the capacity of the option designer to deliver the design.’

For this test implementation, the top-level evaluation factors were weighted during a workshop, where Subject Matter Experts (SMEs) were asked to rank the evaluation categories from their individual perspectives. The overall rank was then determined from the aggregated scores using the Rank Order Centroid method. Figure 58 shows an instance of the top-level evaluation factors as blocks containing value properties of their rank, value function and the total value of each top-level evaluation factor for the design under evaluation.

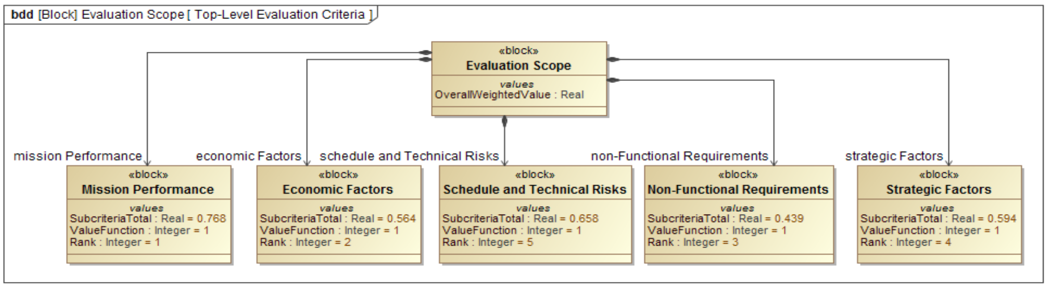


Figure 58: Top-level option evaluation factors for the WMSM test implementation.

8.3.2.2 Step 2 - Establish Evaluation Criteria

The WMSM test implementation focused on the mission performance evaluation criteria. These will be the KPPs for the WMSM that have been identified in a top-down manner as shown in Figure 50 through to Figure 52 above.

8.3.2.3 Step 3 – Determine Evaluation Criteria Value Functions and Weights

The Multi-Attribute Value Analysis (MAV) Multi-Criteria Decision Making (MCDM) method underpins the option evaluation part of the MEANS MBSE methodology. The researcher noted for the WMSM test implementation [17: p. A-28]:

> ‘The weights and value functions for the evaluation criteria were elicited from Navy and naval architecture SMEs for the (WMSM) 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 [159: p. 368]. SMEs selected a value function from the set of eight shown in Figure 59 for each evaluation criteria.’

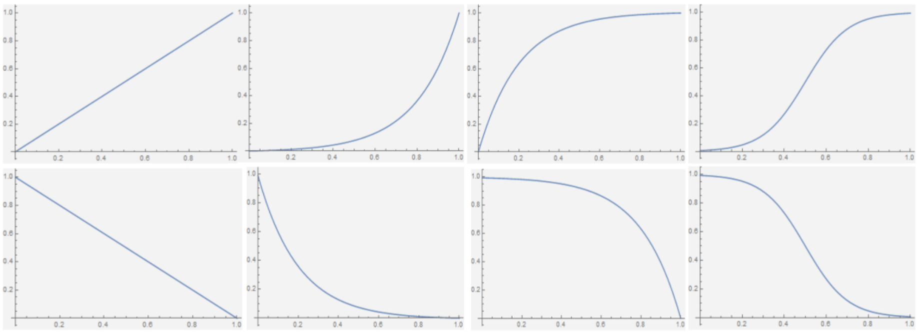


Figure 59: Common value function curves [30].

8.3.2.4 Step 4 – Estimate Evaluation Criteria Values for Each Design Option

This step requires the evaluation of criteria values for each design option under consideration to be estimated. The researcher noted [17: p. A-28]:

> '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 information. Where values for the design could not be found, they were estimated using engineering judgement or parametric relationships.'

Figure 60 shows a view from the MBSE model for the WMSM test implementation. The model view shows how the KPP values, KPP rank (for conversion to a weight via the Rank Order Centroid method), value curve and weighted value of one of the design options selected from the internet are held as value properties inside the block representing each KPP. This is also a model-based view of a DAF SV-7 systems measures matrix.

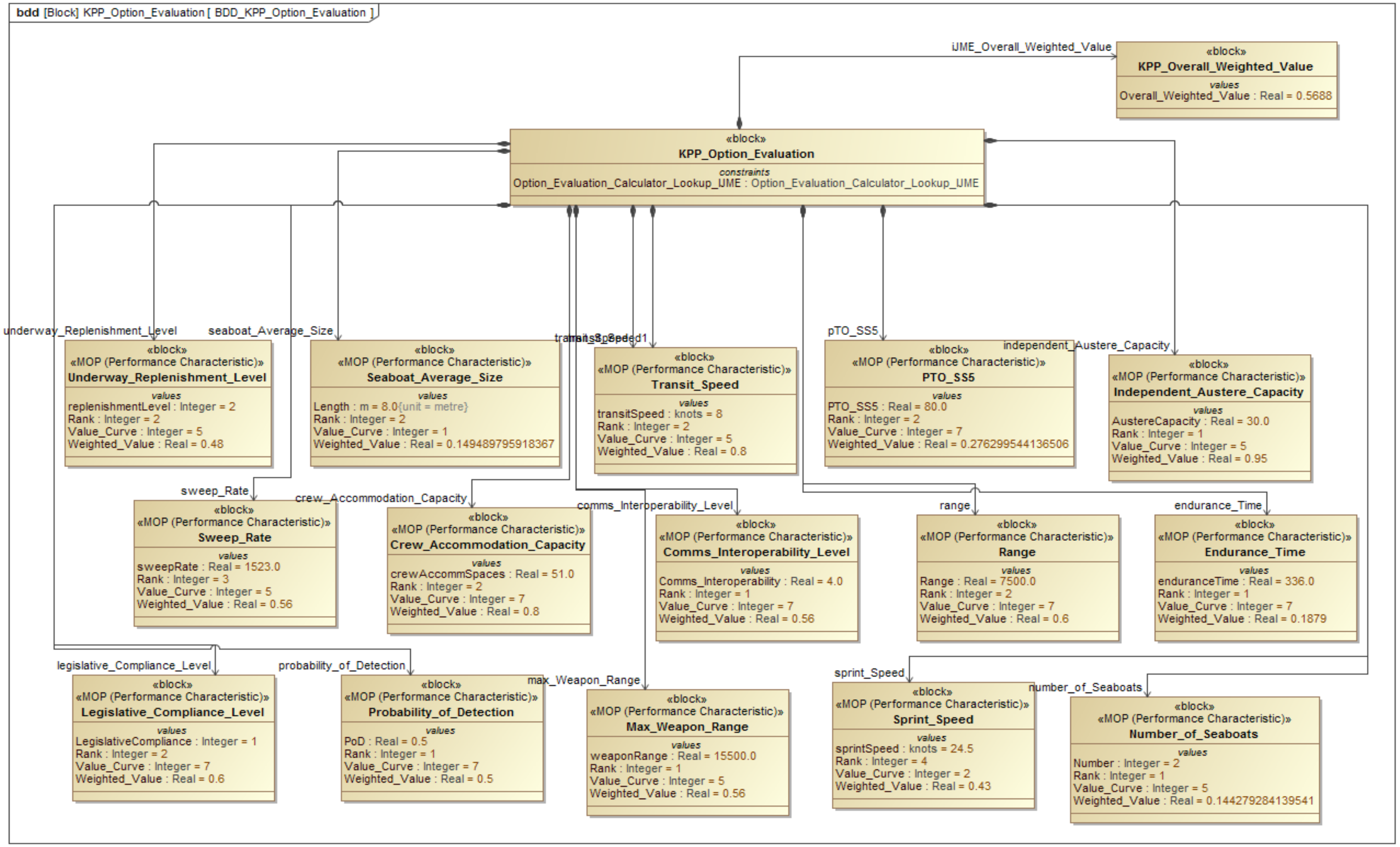


Figure 60: MBSE block diagram showing the KPPs, their rank (used in the Rank Order Centroid weight calculation), value curve and value for one of the designs being evaluated (model-based view of the SV-7).

8.3.2.5 Step 5 – Calculate Overall Value and Compare Options

This step in the option evaluation part of the MEANS MBSE methodology calculates the Overall Weighted Value (OWV) of each design option by summing the weighted values of each evaluation criterion. As for the calculation of the Endurance Time KPP discussed in Section 8.3.1.2 above, the overall weighted value for each ship design option under consideration is calculated from within the MBSE model using information contained within a parametric diagram as shown in Figure 61, which is for indicative purposes only and not intended to be readable! The parametric diagram is linked to a spreadsheet application via model integration software where the individual KPP weights, weighted criteria values, and overall weighted value for each design under evaluation are calculated.

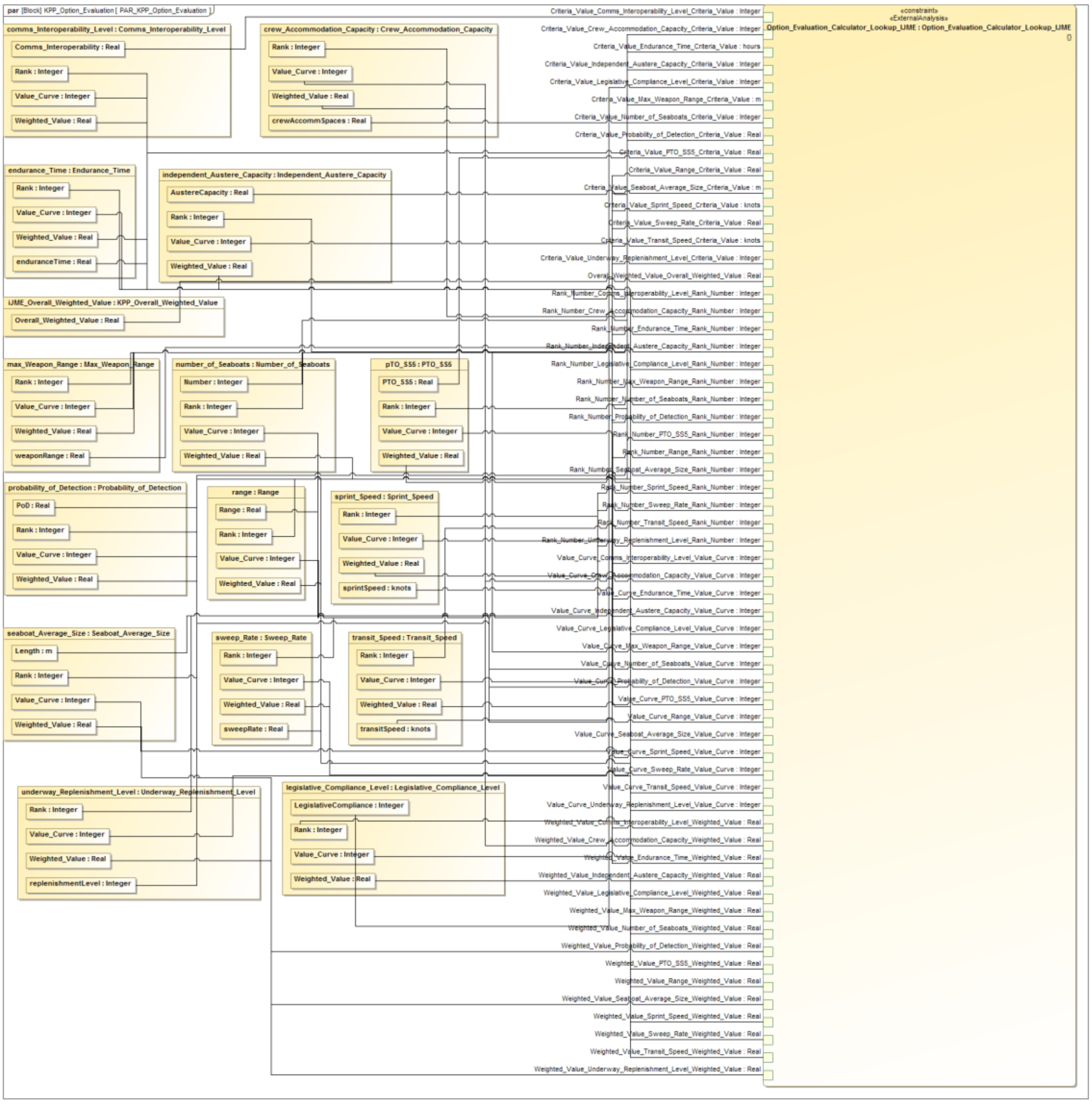
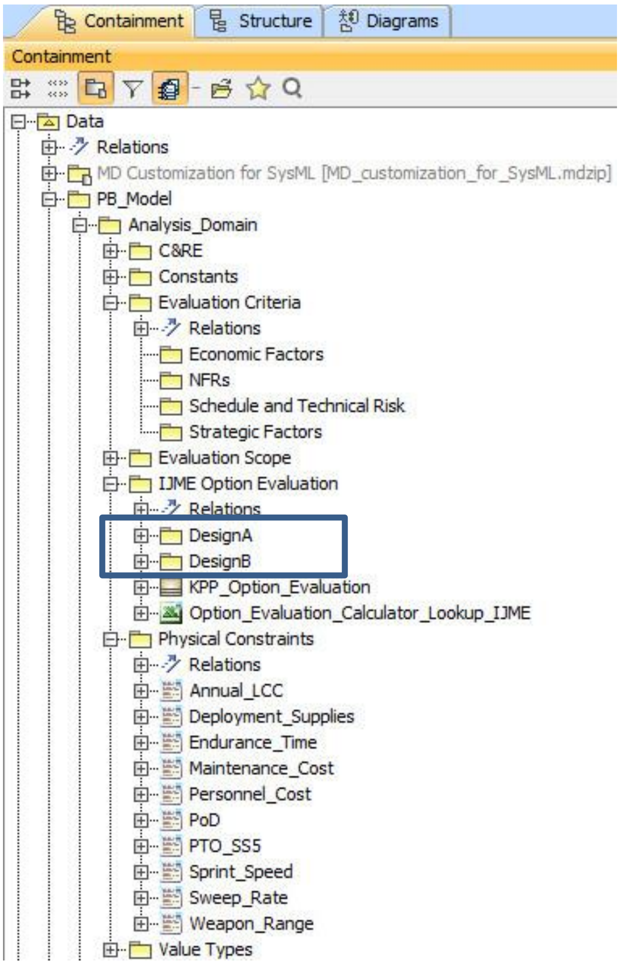


Figure 61: MBSE model parametric diagram that is linked to a spreadsheet application to calculate the individual KPP weighted values and overall weighted value for each OTS design option.

Figure 62 shows how OTS design data can be maintained within packages containing instantiations of KPP blocks and their value properties, or ship design parameters, for each design under evaluation within the MBSE model.



- Data
  - Relations
  - MD Customization for SysML [MD_customization_for_SysML.mdzip]
  - PB_Model
    - Analysis_Domain
      - C&RE
      - Constants
      - Evaluation Criteria
        - Relations
        - Economic Factors
        - NFRs
        - Schedule and Technical Risk
        - Strategic Factors
      - Evaluation Scope
      - IJME Option Evaluation
        - Relations
        - DesignA
        - DesignB
        - KPP_Option_Evaluation
        - Option_Evaluation_Calculator_Lookup_IJME
      - Physical Constraints
        - Relations
        - Annual_LCC
        - Deployment_Supplies
        - Endurance_Time
        - Maintenance_Cost
        - Personnel_Cost
        - PoD
        - PTO_SS5
        - Sprint_Speed
        - Sweep_Rate
        - Weapon_Range
      - Value Types

Figure 62: Screenshot of the MBSE model structure for the WMSM example showing how the OTS design option data can be store in model packages (highlighted in the blue rectangle).

Data from the spreadsheet application used to calculate the OWV is shown in Table 8. From the green highlighted cells in Table 8, it can be seen that design option B had a higher OWV than design option A for the mission performance evaluation criteria used in this test implementation.

Table 8: Option evaluation table for mission performance criteria.

KPP	**Rank**		**KPP**			**Option A**		**Option B**	
Name		**ROC Weight (*w*)**	**Threshold**	**Objective**	**Value Curve #**	**KPP**	***w*v(KPP') ^+***	**KPP**	***w*v(KPP') ^+***
Seaboat_Average_Size	3	0.0929	5	11	1	6	0.0155	8	0.0464
Comms_Interoperability_Level	3	0.0929	2	5	7	4	0.0781	4	0.0781
Independent_Austere_Capacity	15	0.0044	20	50	1	20	0.0000	30	0.0015
Range	3	0.0929	7500	10000	5	7500	0.0000	8600	0.0329
Crew_Accommodation_Capacity	7	0.0375	30	55	1	54	0.0360	30	0.0000
Endurance_Time	1	0.1879	336	672	7	504	0.0939	672	0.1866
Sweep_Rate	7	0.0375	100	400	7	350	0.0362	350	0.0362
Number_of_Seaboats	3	0.0929	1	3	7	2	0.0464	2	0.0464
PTO_SS5	1	0.1879	50	90	7	80	0.1736	80	0.1736
Probability_of_Detection	7	0.0375	0.3	0.75	7	0.7	0.0367	0.7	0.0367
Transit_Speed	7	0.0375	8	12	5	12	0.0375	12	0.0375
Legislative_Compliance_Level	13	0.0118	2	5	5	4	0.0114	4	0.0114
Underway_Replenishment_Level	13	0.0118	1	5	1	4	0.0088	4	0.0088
Sprint_Speed	7	0.0375	20	30	5	20	0.0000	22	0.0238
Max_Weapon_Range	7	0.0375	6500	15500	5	13800	0.0371	15500	0.0375
						OWV	**0.6112**	**OWV**	**0.7575**

Notes:

Value curves 1, 3, 5 and 7 are the increasing utility value curves in the top row of Figure 59. Value curves 2, 4, 6 and 8 are the decreasing utility value curves in the bottom row of Figure 59.

^ *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.

8.3.2.6 Step 6 – Estimate Uncertainty and Identify Weak Spots

Errors or uncertainties in the evaluation arise from two main sources: subjective errors and procedure inherent shortcomings [36]. Subjective errors can arise due to stakeholder bias and partiality, whereas procedure inherent shortcomings can arise from the accuracy of the data upon which the evaluation criteria values are estimated [36]. For the WMSM test implementation there is likely to be a large degree of uncertainty as many of the KPP values were estimated from open source data. The researcher also conducted a sensitivity study where the evaluation criteria rankings were systematically varied, which only changed the outcome of the option evaluation in one third of the trials. This reflects the relatively large difference in the OWV of the design options as shown in Table 8. It also suggests that if the OWV of designs are close, the uncertainties need to be investigated further as they could change the result of the evaluation. The level of uncertainty was deemed to be acceptable for the test implementation as it was the MEANS MBSE methodology that was under evaluation.

With respect to weak spots in the OTS design options under consideration, the researcher previously noted [17: p. A-29]:

> ‘Weak spots in each design option can be identified by looking for relatively low values of individual evaluation criteria [36]. These are particularly important for promising design options that exhibit good overall value. Once identified, these weak spots can be addressed through design changes [36]. The yellow highlighted cells in Table 8 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.'

If design changes are allowed, and the designer agrees to undertake them in order to reduce or eliminate any weak spots, the feedback loop in the option evaluation part of the MEANS MBSE methodology allows for a re-evaluation of the designs.

The MBSE model and the analytical results generated through implementing the MEANS MBSE methodology as described above in Section 8.3 could be used as supporting data in the business cases presented to government for milestone decisions at Gate 1 and Gate 2 in the Defence lifecycle. This data provides the supporting evidence that the acquirer has developed requirements and selected a preferred OTS design option based on robust analysis. Furthermore, the MBSE model, underpinned by the metamodel built for this research project, provides the golden thread between the analysis, decisions and capability needs.

8.4 Chapter Summary

Chapter 8 provided an overview of the final refinements to the MEANS MBSE methodology to support the early phases of Australian Defence OTS naval ship acquisitions that was constructed during the research project. The three final refinements were: the use of KPPs rather than MOPs during C&RE and option evaluation, the use of pattern-based methods throughout the MBSE methodology, and the inclusion of feedback loops into the C&RE and option evaluation parts of the MEANS MBSE methodology. This chapter also provided a more extensive walk-though of the USCG WMSM test implementation of the MEANS MBSE methodology than space restrictions allowed in the papers covering the research. The walk-though gives an indication of the traceability and rigour provided by the MEANS MBSE methodology. This type of traceability is important because it can be used to support defensible decision making and in turn, defensible business cases, during the early phases of OTS naval ship acquisitions.

Chapter 9 – Thesis Conclusions

This thesis covered the design, construction, and trial applications of the Middle-out Early-phase Above-the-line Naval Ship (MEANS) Model-Based Systems Engineering (MBSE) methodology that is intended to support the early phases of Australian Off-the-Shelf (OTS) naval ship acquisitions. The research employed the Constructive Research Approach (CRA) to address a current need in Australian Defence naval ship acquisitions. The need for further support for acquisition stakeholders to enable them to make better informed, defensible decisions while developing business cases for acquisition milestones was identified through both a literature review (Chapter 2) and the author's professional experience. A second literature review (Chapter 3) subsequently identified a suite of methods and tools that provide an opportunity to address this need. MBSE was selected as the foundation of the research due to its ability to capture and represent the necessary information in a structured fashion, and its ability to facilitate communication, support traceability, and enable the reuse of model elements. The application of MBSE necessitated the development of a unique metamodel, which was achieved over several iterations (Chapter 5), that could support the representation of the problem domain and guide and manage the analytical and synthesis activities that need to be undertaken to support the acquisition activities.

Several of the methods and tools identified in the literature review were combined with an overarching process to develop an approach to conducting Concept and Requirements Exploration (C&RE) within an MBSE environment (Chapter 6). The C&RE approach was matured over several iterations. It supports acquisition activities between Gate 0 and Gate 1 in the Australian Defence Risk Mitigation and Requirements Setting Phase leading up to a release of a request for tender to OTS naval ship designers. A model-based option evaluation method was then constructed (Chapter 7) that supports acquisition activities between Gate 1 and Gate 2 in the Defence Risk Mitigation and Requirements Setting Phase. The key activity the model-based option evaluation supports is the evaluation of OTS naval ship design options submitted by designers in response to the request for tender. The method contains a Multi-Criteria Decision Making (MCDM) method and is implemented from within an MBSE model.

The inclusion of the Multi-Attribute Analysis MCDM method in the MEANS MBSE methodology, which was covered in Chapter 7, enables acquisition stakeholder preferences to be captured when comparing OTS naval ship design options. This supports the selection of a design option that most closely aligns with the capability needs and current preferences of Defence. The model-based option evaluation method can also be used to highlight weak spots in design options that could potentially be remediated through design changes.

Final refinements to the overall MEANS MBSE methodology to support the early phases of Australian OTS naval ship acquisitions included a focus on Key Performance Parameters as design discriminators during C&RE and option evaluation, increasing the use of pattern-based methods and the incorporation of explicit feedback loops into each part of the methodology (Chapter 8).

9.1 Contribution and Novelty

While not the first methodology to support the early phases of defence acquisitions, the MEANS MBSE methodology presented in this thesis demonstrates what is achievable with minimal resources and off-the-shelf software tools that are reasonably straightforward to implement. The MBSE methodology presented in this thesis also focused on OTS naval ship acquisition, rather than developmental acquisitions. The researcher has noted [17: p. 2]:

> ‘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.’

In the same paper, the author made an analogy between the ‘modified-repeat’ ship design approach, where an existing design is adapted to meet new requirements, and the OTS acquisition strategy. For the modified-repeat, and by inference the OTS acquisition strategy to realise cost and schedule benefits over the developmental approach, the operational and legislative requirements of the parent design must be virtually identical to the new design. However [17: p. 2]:

> '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.'

The MEANS MBSE methodology presented in this thesis provides a means of building this missing knowledge on an existing ship design space in a bottom-up manner, which the methodology combines with a top-down decomposition of the capability requirements to support defensible decision making. This means the MBSE methodology provides an approach to conducting 'middle-out' systems engineering in a model-based manner. Middle-out systems engineering is likely to become more prevalent as more and more defence systems are developed using OTS strategies, or by making extensive use of OTS components. There are a relatively small number of publications covering middle-out systems engineering in the open literature and even less on model-based approaches to conduct middle-out systems engineering, so this thesis provides a contribution on the topic.

A specific contribution from the research was the introduction of an 'analysis domain' into the extended WSAF metamodel to enable analytical activities to be executed, managed and stored within an MBSE model. Using MBSE as the foundation of the MEANS MBSE methodology also facilitates the reuse of models that have been constructed for previous acquisitions. This means the MBSE modeller will be able to build upon the knowledge captured in earlier models.

The novelty in the MEANS MBSE methodology presented in this thesis arises from a bespoke synthesis of proven methods and approaches for robust systems development targeted at the early phases of Australian Defence OTS naval ship acquisitions. The research covered a broad range of methods and their amalgamation into a methodology, rather than being a deep dive into a single topic. Each of the methods needed to be investigated sufficiently to allow an assessment of their utility and whether they adhered to the guiding principles for inclusion in the MBSE methodology. Combining the suitable methods into an MBSE methodology that implements a middle-out systems engineering approach was shown to be useful in supporting defensible stakeholder decision-making through the test implementations covered in this thesis and the researcher’s publications.

9.2 Further Work

There are several areas for further research that could enhance the MEANS MBSE methodology. Firstly, the methodology could be packaged into a software tool in the manner of the Framework for Assessing Cost and Technology (FACT) [90] or the Whole Systems Trade Analysis (WSTA) [89] methodology in the US. These software tools are tailored for the US Defence acquisition environment and a similar software tool could be used to support Australian Defence acquisition professionals to implement the MEANS methodology in a guided manner. The FACT tool is underpinned by SysML, which suggests it would be possible to build standalone software to implement the MEANS MBSE methodology, which also utilises SysML. Doing this is beyond both the software development skills of the researcher and the scope of the research. Nonetheless, the current approach of implementing the MEANS MBSE methodology by integrating standalone Off-the-Shelf software tools using model integration software makes the approach flexible. This flexibility allows for the integration of newer and higher-fidelity ship performance models into the methodology and is a focus in ongoing research led by the author, an example of which has been published in Dwyer and Morris [37].

Another suggestion for further work is to explicitly integrate the non-materiel Fundamental Inputs to Capability into the C&RE. An initial effort to do this was undertaken during the second iteration of the research to construct the MEANS MBSE approach to C&RE, however, the researcher believes there is still more work required to ensure the non-materiel aspects of defence capability are considered during the early phases of acquisitions.

A final suggestion for further work is to implement the MBSE methodology for an Australian Defence OTS naval ship acquisition project, perhaps initially alongside the typical, document-based approach. While the test implementations covered in this thesis provided insights and iterative refinements, a full implementation would constitute a ‘holistic market test’ of the MBSE methodology. This could be used to quantitatively ascertain the MEANS MBSE methodology’s utility and gather more data on its strengths and weaknesses.

9.3 Final Remarks

The research to construct the MEANS MBSE methodology has been driven by the opening problem statement that the researcher identified early in his career and has been reinforced by various reviews of Defence. The research sub-questions were addressed through the knowledge gained and the construction of the MEANS MBSE methodology constructed. Addressing each of the sub-questions in turn:

How are the activities between Gate 0 and Gate 2 presently performed? What processes and tools are currently employed to support this class of activity?

The review of defence acquisition manuals covered in Chapter 2 found that the recent acquisition guidance provided to acquisition professionals within Australian Defence lacks detail and consistency on the processes to develop business cases for government decision gates compared to other nations. The training and required competencies of staff involved in Defence acquisition are not addressed in the guidance either. The three key activities within the Risk Mitigation and Requirements Setting Phase of the Defence capability lifecycle were identified as: requirements definition, requirements setting and options refinement. The relative lack of detail within the Australian Defence acquisition guidance provides an opportunity for methods and tools to be developed that can support Australian Defence acquirers. The acquisition guidance of the United States Department of Defense ([40] and [46]) and the Systems Engineering standard, ISO/IEC/IEEE 15288:2015 [18] provide examples of the tools and processes that can support Defence acquisition activities between Gate 0 and Gate 2 in the Defence capability lifecycle. Overarching these processes is the OTS acquisition strategy that Australian Defence naval ship acquisition projects now adopt as the default approach. The OTS acquisition strategy requires adjustments to the existing processes and tools that can support the early phases of Defence naval ship acquisitions.

What approaches can be used to support the early phases of naval ship acquisitions that can enable and enhance rigour and traceability between strategic objectives and capability development?

The literature review covered in Chapter 3 identified several suitable approaches to support defensible business case development in the early phases of OTS naval ship acquisitions. These suitable approaches were identified based on three guiding principles derived from recurring themes of Australian Defence reviews highlighted in the First Principles Review of Defence [2]. Model-Based Conceptual Design, Modelling and Simulation, Design Space Exploration, Resilient Systems, Pattern-Based Methods and Multi-Criteria Decision Making appear to have the most potential to support OTS naval ship acquisition due to their adherence to the guiding principles and their previous use in naval ship acquisitions.

How can MBSE-based approaches enhance the current process and what is their utility?

The MEANS MBSE methodology that was constructed during the research project has demonstrated that MBSE-based approaches can support the acquisition process by maintaining the “golden thread” that links strategic goals to ship requirements. Furthermore, support for a defensible business case is provided through the evidence generated when implementing the MEANS MBSE methodology, which builds knowledge of the existing naval ship design space and enables requirement trades-off and option evaluation based on proven analytical techniques and methods. The MEANS MBSE methodology also explicitly links analytical activities and the requirements these generate, to the originating capability needs for the acquisition project. This means the MEANS MBSE methodology constructed for the research project certainly has the capability to enhance the current Australian Defence naval ship acquisition process.

While the utility of the MEANS MBSE methodology is yet to be ascertained under ‘holistic market test’ conditions (i.e. applied to Australian Defence OTS naval ship acquisition projects), market testing of the MEANS MBSE methodology has been undertaken by regularly publishing papers in the open literature. Reviewer feedback on these papers covering the MEANS MBSE methodology has included:

- “This paper provides a useful description of the application of a model-based methodology to the traceability of system requirements back to strategic guidance, as well as an example of how requirements might be elicited using a model-based methodology.”
- “The paper presents an interesting topic on MBSE practice, extending traceability ‘far-left’ from system requirements all the way to Government strategic objectives. The paper will be of great interest to SETE defence audience.”
- “I like the paper as it is informative and the methodology is sound. It is an easy read and presents how to combine OA, MBSE and Conceptual design of naval ships in a logical and straightforward way.”
- “Paper is directly relevant to the conference audience on a subject of importance.”
- “Nice example of leveraging MBSE to drive robust SE execution.”
- “This topic is completely in line with the direction Systems Engineering is heading presents a contemporary approach to making decisions by reuse of data and models in a more integrated and traceable environment. This is the type of work, paper and talk that the community needs to be exposed to. It will help to push the state of practice forward.”

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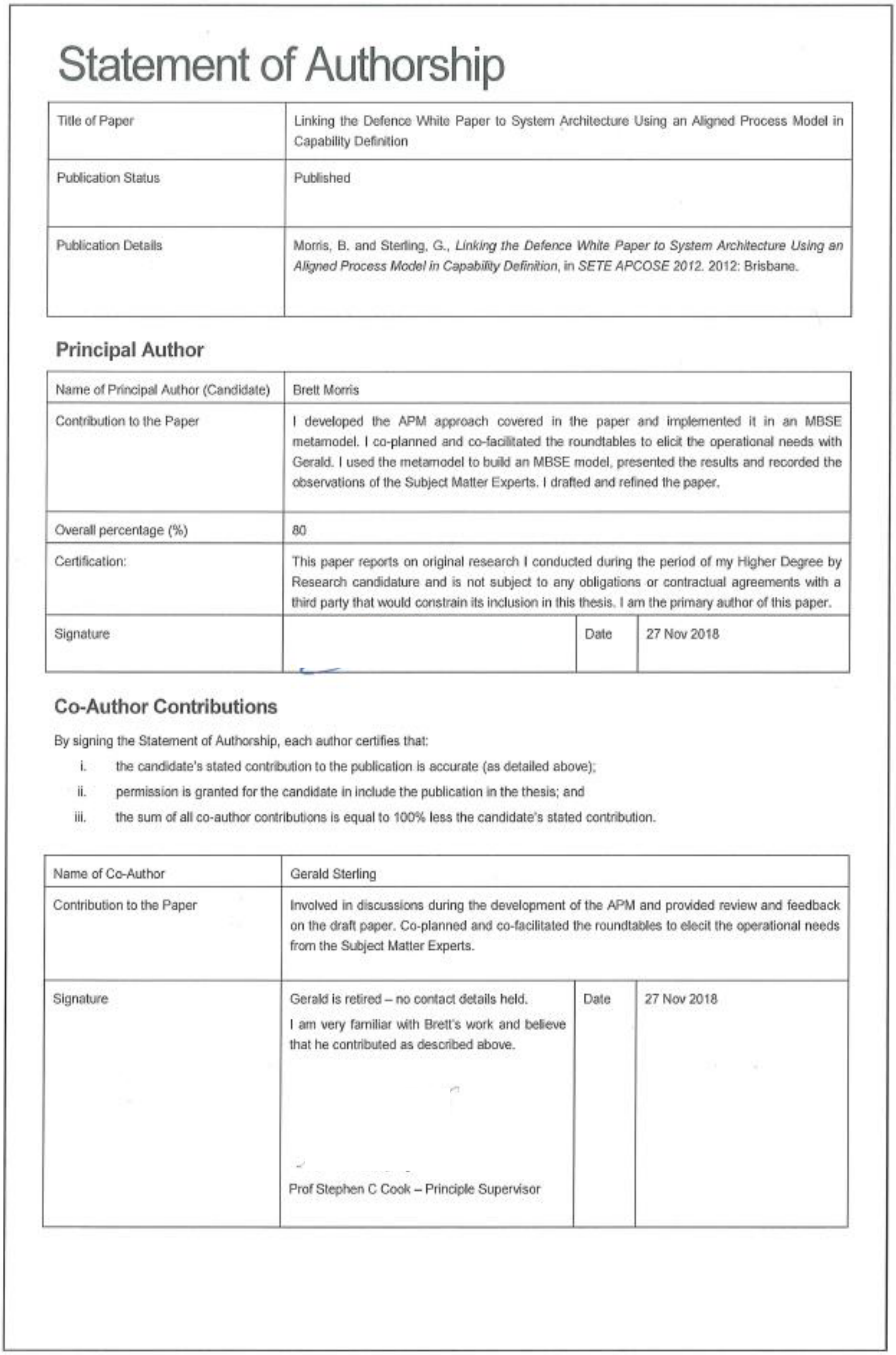
Appendix A: Linking the Defence White Paper to System Architecture Using an Aligned Process Model in Capability Definition



Statement of Authorship

Title of Paper	Linking the Defence White Paper to System Architecture Using an Aligned Process Model in Capability Definition
Publication Status	Published
Publication Details	Morris, B. and Sterling, G., *Linking the Defence White Paper to System Architecture Using an Aligned Process Model in Capability Definition*, in *SETE APCOSE 2012*. 2012: Brisbane.

Principal Author

Name of Principal Author (Candidate)	Brett Morris		
Contribution to the Paper	I developed the APM approach covered in the paper and implemented it in an MBSE metamodel. I co-planned and co-facilitated the roundtables to elicit the operational needs with Gerald. I used the metamodel to build an MBSE model, presented the results and recorded the observations of the Subject Matter Experts. I drafted and refined the paper.		
Overall percentage (%)	80		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	27 Nov 2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Gerald Sterling		
Contribution to the Paper	Involved in discussions during the development of the APM and provided review and feedback on the draft paper. Co-planned and co-facilitated the roundtables to elecit the operational needs from the Subject Matter Experts.		
Signature	Gerald is retired – no contact details held. I am very familiar with Brett's work and believe that he contributed as described above. Prof Stephen C Cook – Principle Supervisor	Date	27 Nov 2018

Linking the Defence White Paper to System Architecture Using an Aligned Process Model in Capability Definition

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Abstract.

This paper outlines an approach that has been developed in order to provide traceability between the strategic priorities set out in the Defence White Paper and the systems that will carry them out. The approach is given in the form of an Aligned Process Model (APM) that is not domain specific (within a Defence context), is based on existing theory and can be tailored for a given application. The APM is created by aligning frameworks for system development that are found in the Australian Defence context with the Strategy-to-Task technique. Merging the APM with the Whole-of-System Analytical Framework (WSAF) metamodel facilitates a Model-Based Systems Engineering (MBSE) approach to capability definition. The use of the MBSE language SysML, allows the traceability that is established within the APM to be visualised and maintained, as well as a repository for the relevant information to be set up.

In the paper, brief overviews of each of the frameworks used in the creation of the APM are given. Their amalgamation into the APM and use of the MBSE language, SysML is discussed and the merging of the APM and WSAF metamodel detailed. Following this, an example of how the merged APM and WSAF metamodel has been tailored and used to identify the operational needs of a system is stepped through. Finally, some of the initial feedback from the Subject Matter Experts (SMEs) that participated in the generation of the operational needs is discussed, along with some of the lessons learnt.

INTRODUCTION

Background

According to ISO/IEC 15288:2008 (ISO/IEC 2008), the purpose of the capability (or stakeholder requirements) definition process “is to define the requirements for a system that can provide the services needed by users and other stakeholders in a defined environment”. The INCOSE Systems Engineering Handbook (Haskins 2010) adds that “there is near unanimous agreement that successful projects depend on meeting the needs and requirements of the stakeholder/customer”. These two sentiments highlight the importance of establishing a set of needs for a system that accurately reflect the intended use of the system during capability definition. While the intended uses of the system of interest may alter over time, in the first steps of capability definition, a set of needs that are traceable to the initial guidance that formed the genesis of the project could realise several benefits. These benefits may include a reduction of the risks associated with requirements creep and the flow on risks to project cost and schedule. A traceable set of needs will also facilitate the retention of a clearer vision of the use for which the system was originally intended, which will be particularly important when the system is integrated as part of a larger system-of-systems.

In the Australian Defence context, the initial guidance that forms the origins of an acquisition project are the capability priorities set out in the Defence White Paper (DWP) (Defence 2010). The most recent DWP, DWP09 (Defence 2009) appears to support the above assertion that a capability's traceability to this initial guidance is important as it states; "...Defence planning needs to be done in a 'whole of enterprise' way, with clear links between strategy, priorities and resources". This clear declaration of the Government's objective of being a "strategy-led" organisation was reinforced by the Mortimer (Mortimer 2008) and Pappas (Pappas 2008) reviews. Both of these reviews highlighted the need for traceability between Defence's strategy and its capability decisions (Defence 2010). However, authors such as Hodge (Hodge 2010) have been researching approaches to strategy and capability planning for several years and the theme of linking strategy to capability has been a recurring one in the strategic planning space.

The Missing Link

With the need for traceability between Defence strategy and the capabilities that will implement it established, the seemingly unresolved question is; how can this traceability be realised? A systems engineering process, which in classical form begins with a need and transforms it into a system (see for example Blanchard and Fabrycky (Blanchard and Fabrycky 2006) or DAU (DAU 2001)) appears to partly answer to this question. A precedent for this type of solution is provided in the work of Hodge (Hodge 2010) where systems engineering approaches were utilised to create an integrated approach to strategy and execution. A more complete answer to the unresolved question at the present point in time may be a Model-Based Systems Engineering (MBSE) process. This is due to the result of this process being a system model that comprises elements representing requirements (or needs), design elements and their interrelationships (Friedenthal, Moore et al. 2009).

A Potential Connection

The purpose of this paper is to describe the first cycle of a body of research that has been undertaken to answer the question of how to establish traceability in capability definition using an action research methodology. Firstly the planning phase (Riding, Fowell et al. 1995) of the research is described, where an approach is given for establishing the traceability between the strategic capability priorities set out in the Defence White Paper and the systems that will carry them out. The approach is termed the Aligned Process Model (APM) due to its development being a result of aligning frameworks for system development found in the Australian Defence context with the Strategy-to-Task (StT) technique. (Thaler 1993) The APM is embedded in MBSE through its merger with the Whole-of-System Analytical Framework (WSAF) metamodel.

Secondly, the action phase (Riding, Fowell et al. 1995) of the first research cycle is described. This is where the APM is applied to the establishment of a set of operational needs of an organic Unmanned Aerial System (UAS) for a naval ship acquisition. Finally, the initial observation and reflection phase is described, where some of feedback and lessons learned during the action phase are detailed. Some potential methods of incorporating these improvements into the APM for further cycles of research are also discussed.

PLANNING

Strategy-to-Task

Several authors have developed StT methodologies since the 1980's (Davis 1991), with the RAND Corporation being involved in several of the publications. These publications are all small variations on the central premise of tracing national strategies to operational tasks in a top-down manner. Authors such as Thaler (Thaler 1993), extend this hierarchy to the systems that perform these tasks as shown in Figure 1.

The StT framework was principally designed to provide an audit trail from the highest level national objectives, to the operational activities that achieve them (Thaler 1993). Thaler (Thaler 1993) also asserts that the StT framework can give visibility to the interrelationships between elements, assist in force planning, along with helping stakeholders make informed choices at the concept stage of a systems lifecycle. The framework also appears to be suitable as a baseline to generate a system's Concept of Operations (CONOPS) from the operational tasks.

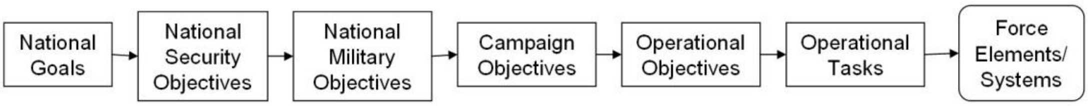


Figure 1: Strategy to task hierarchy of objectives (Thaler 1993)

The StT framework appears to be flexible, scaleable and able to be tailored to particular operational domains, as it has been used in a wide range of applications. This flexibility implies that aligning the StT framework with the ADO acquisition framework will be possible.

The Strategy Framework

The most recent edition of The Strategy Framework (TSF) (Defence 2010) results from the Government objective, given in DWP09 (Defence 2009), of ensuring defence is a strategy-led organisation. TSF appears to mirror the StT framework in that it uses the terminology of identifying "ends" and the "ways" and "means" to achieve them, but does not expressly call this approach StT. Chapter 7 of TSF gives an overview of capability development and states: "A key outcome of the Needs Phase is a transparent and auditable logic trail between government direction and Defence capability development decisions" (Defence 2010). This seems to be at variance with the work of authors such as Baker (Baker 2000) and Hodge (Hodge 2010), who identify a "gap in explination" between strategy and force structure options

Chapter 4 of TSF contains a section on strategic planning for operations that provides a framework for ensuring "that Defence is prepared for directed, possible, and anticipated military operations" (Defence 2010). This framework appears to provide a basis for not only high-level strategic planning for operations, but also a useful method for eliciting a set of needs that are traceable to strategic guidance. This is because the strategic planning approach is based on wargaming, where scenarios provide the context for missions and tasks that must be undertaken. Such an approach could conceivably be utilised to establish the needs of the systems that will perform the missions, as ISO 15288:2008 states that as part of the define stakeholder requirements activity: "scenarios are used to analyse the operation of the system in its intended environment"

(ISO/IEC 2008). The strategic planning for operations process is shown in Figure 2.

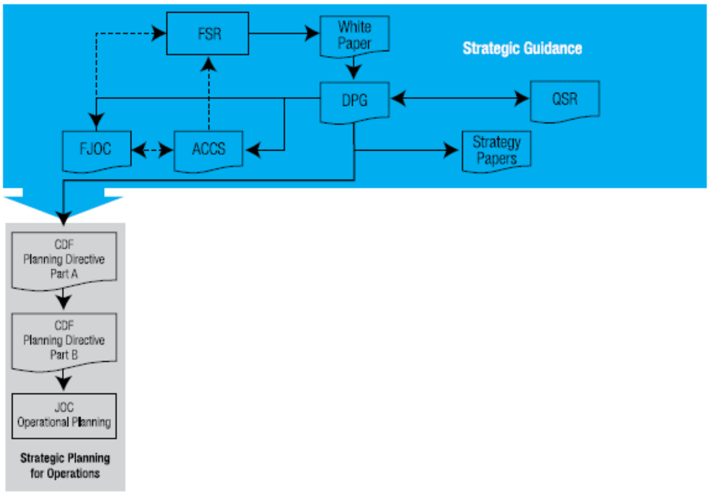


Figure 2: Strategic planning for operations (Defence 2010)

TSF document also gives the intent of each of the documents shown in Figure 2 and those relevant to the idea of aligning the StT framework with the Australian Defence Organisation (ADO) acquisition framework include (Defence 2010):

1. White Paper
   - Articulates the strategic priorities that guide Defence
2. Defence Planning Guidance (DPG)
   - Outlines Australia's Military Strategy
3. Australian Capability Context Scenarios (ACCS)
   - Provides a strategic testing tool for capability and concept development
4. Chief of the Defence Force (CDF) Planning Directive Part A
   - Strategic interests, priorities and objectives
5. CDF Planning Directive Part B
   - Planning direction including proposed mission and key tasks

From Figure 2 the flowdown from the White Paper to campaign objectives, which are given in the CDF planning directive part B, can be seen, which also mirrors the StT framework. This implies that the two approaches can be aligned and also, that the strategic planning for operations process can be extended to provide traceability down to the systems that will perform the operations, as for the StT framework in Figure 1. Furthermore, this traceability will also feedback up from the systems, to Defence's strategic priorities, which will inform subsequent iterations of these priorities.

Whole-of-System Analytical Framework

The Whole-of-System Analytical Framework (WSAF) was initially developed to provide an architectural method for defining capability analysis (Robinson and Graham 2010). It has since been expanded into the capability definition domain (Robinson, Tramoundanis et al. 2010) whilst maintaining Department of Defense Architecture Framework (DoDAF) compliance. The WSAF also has the advantages of previously being extended for use with Model-Based Systems Engineering (MBSE) tools and is underpinned by MBSE principles and methods (Robinson, Tramoundanis et al. 2010). The WSAF is also gaining increasing acceptance within the ADO from repeated usage. The key benefit that will be gained from the using the WSAF in the present work is that it can form the basis of a metamodel that will ensure consistency in a model developed using MBSE. The metamodel represents the underlying description of the system model that encapsulates the elements and the relationships between them (Robinson, Tramoundanis et al. 2010). The WSAF metamodel is shown in Figure 3 in order to give the reader an overview of the groups of elements included (the reader is not expected to read all of the element names in the metamodel!).

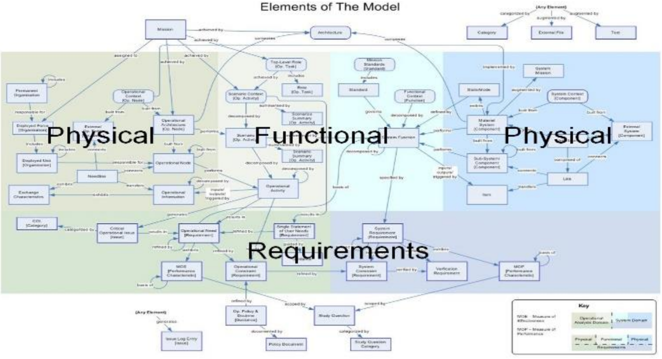


Figure 3: Overall WSAF metamodel (Robinson 2011)

While the WSAF metamodel appears multifaceted at this level, tailoring will be used to adapt it for APM applications, meaning only relevant elements and relationships will be implemented. However, by using such an extensive metamodel as the basis for the APM, the capacity to expand the model developed at a later time exists. Further expansion could include preparation of Capability Definition Documents (CDDs) that are used in the Australian Defence context, such as an Operational Concept Document (OCD), along with relevant DoDAF views.

Model-Based Systems Engineering

Model-Based Systems Engineering (MBSE) is an emerging discipline that uses a central electronic model rather than, or alongside, a set of documents, as a means of describing a system of interest (Robinson, Tramoundanis et al. 2010). MBSE is implemented through the use of a methodology, which is a collection of related processes, methods and tools (Estefan 2008). According to Estefan (Estefan 2008), a process defines *what* is to be done, a method defines *how* it will be done and a tool will facilitate the *what* and *how*. Power *et al* (Power, Do et al. 2011), identify two MBSE methodologies that are suitable for capability definition purposes. These are the WSAF, which has been discussed in the preceeding section, and the Object-Oriented Systems Methodology (OOSEM). The OOSEM encapsulates the contemporary top-down SE approach to system development and utilises the Systems Modelling Language (SysML) (Power, Do et al. 2011). The WSAF methodology utilises the CORE® software tool, which is based on the Integration Definition (IDEF) language (Power, Do et al. 2011).

A top-level comparison of the methodologies performed by Power *et al* (Power, Do et al. 2011) found that the WSAF methodology is preferred in the early stages of capability development. This is due to the creative freedom encouraged when not restrained by the OOSEM class structure (Power, Do et al. 2011). However, the SysML based OOSEM was preferred for system design and synthesis phases and it was recommended that a method of transitioning the WSAF model to an OOSEM environment at some milestone in the capability development lifecycle (Power, Do et al. 2011).

Since the present work is concerned with capability definition, an approach that aims to emulate the WSAF methodology by implementing the WSAF metamodel in a SysML based tool is used. This implementation is achieved through the use of profiles to extend the SysML. The approach has been adopted for several other reasons:

1. ADO familiarity with WSAF
2. Avoid being limited to the use of the CORE® software tool
3. Desire to include SysML Use Case and Activity diagrams in modelling
4. Potential to link with DSTO platform systems modelling work that utilises SysML related codes

The overarching reason for using any metamodel in MBSE is that it will create consistency in the modelling by providing a standard set of elements and relationships that modellers can use (Holt and Perry 2008). Inconsistency between the models developed by different MBSE users for models of the same system has been highlighted as an issue when using SysML by authors such as Yamada (Yamada 2011).

The SysML tool utilised for the work undertaken in this paper is the Sparx Systems software, Enterprise Architect (EA)™. The approach adopted to implement the WSAF metamodel in EA™ was to create profiles that utilised SysML metaclasses, which contained new stereotypes with the names of each element in the WSAF metamodel. Stereotypes provide a method of extending the SysML to specific domains (Friedenthal, Moore et al. 2009) and applications. These stereotypes are grouped into a special type of package called a profile, which extend the modelling language itself (Friedenthal, Moore et al. 2009). This is due to the new profiles, which contain their own properties, rules and relationships, allowing the SysML metamodel to be augmented with concepts from other domains (Friedenthal, Moore et al. 2009). When the SysML is extended using profiles, a metamodel is created, so by creating profiles for each of the elements in the WSAF, a WSAF metamodel is formed. Each of the profiles in this new metamodel utilises a SysML metaclass, so that the diagrams using the stereotype of each WSAF element can be readily understood

Overarching Systems Engineering Standard

The activities that will be undertaken in the present work represent a stakeholder needs definition process. In general language, the stakeholder needs can be termed stakeholder requirements and there is an international standard, ISO 15288:2008 – Systems and Software Engineering, that covers systems lifecycle processes (ISO/IEC 2008). This standard has a section (6.4.1) covering the activities that should be performed in such a needs/requirements definition process and the recommended activities are (ISO/IEC 2008):

1. Elicit Stakeholder Requirements (Needs)
    a. Identify relevant stakeholders
    b. Elicit requirements
2. Define Stakeholder Requirements (Needs)
    a. Define system constraints
    b. Define a representative set of system activity sequences
    c. Identify the interaction between users and the system
    d. Specify stakeholder requirements and functions that relate to critical qualities (e.g. health, safety, environment etc.)
3. Analyse and maintain stakeholder requirements (Needs)
    a. Analyse the complete set of elicited requirements
    b. Resolve requirements problems
    c. Feed back the analysed requirements to applicable stakeholders to ensure that the needs and expectations have been adequately captured and

expressed

d. Establish with stakeholders that their requirements are expressed correctly
e. Record the stakeholder requirements in a form suitable for requirements management through the life cycle and beyond
f. Maintain stakeholder requirements traceability to the sources of stakeholder need

It is envisaged that the procedure developed in the following sections, will include most of the recommended activities.

Aligning StT, TSF and WSAF into a Single APM

While there appears to be some inherent relationships between the elements in the StT process shown in Figure 1 and the Strategy Framework process shown in Figure 2, the relationships between these and the WSAF elements are less evident. However, the traceability that will be established within capability definition by incorporating the WSAF in the alignment of the frameworks is valuable. Aligning the three frameworks resulted in some uncomfortable fits, where the definitions need to be stretched. The two main stretches in the alignment were for the StT Campaign Objectives and Operational Objectives elements. This appears to be primarily due to the origins of WSAF as a method for defining capability analysis within CORE®. The StT elements and the associated TSF and WSAF elements, along with a short explanation of the association is given in Table 1.

StT Element	TSF Document	WSAF Element	Explanation
National Goals	N/A	N/A	This level is beyond the Defence context
National Security Objectives	White Paper (WP)	None – need to create	The WP articulates the strategic priorities that guide Defence (Defence 2010). As such, the "strategic priorities" can be interpreted as security objectives.
National Military Objectives	Defence Planning Guidance (DPG)	None – need to create	The DPG outlines Australia's military strategy and amplifies the WP policy guidance (Defence 2010). This military strategy can be interpreted as military objectives.
Campaign Objectives	Australian Capability Context Scenarios (ACCS)	Mission	The WSAF Mission element is defined as; "A mission identifies a task, together with its purpose, that clearly indicates the action to be taken and the reason therefore." This aligns with TSF which states: "Each ACCS consists of a scenario leading to a planning directive, operational plan and operational level effects to achieve…" (Defence 2010).
None – this level refines the campaign	CDF Planning Directive Part A (CDF PD PtA)	Scenario Context	This element in the TSF provides further direction to the campaign objectives set out in the ACCS by giving strategic level objectives and end-states (Defence 2010). These strategic

objectives			objectives and interests give a strategic context to the scenario being considered, which aligns it with the WSAF scenario context element.
Operational Objectives	CDF Planning Directive Part B (CDF PD PtB)	Scenario	While the WSAF scenario element's name can be misleading when discussing ACCS etc, from the perspective of a StT framework, the WSAF scenario aligns with the operational objectives provided by the proposed mission given in the CDF planning directive Part B (Defence 2010).
Operational Tasks	Operational Plan (OPLAN) Key Tasks/Activities	Operational Activity	The WSAF operational activity element is described as "an action or process needed to fulfil a mission, task or role." This reflects the nature of the Key Tasks that are given in the CDF Planning Directive Key Tasks.

Table 1: Aligned StT, TSF and WSAF elements and explanation

In summary, the alignment of the StT, TSF and WSAF can be seen in Figure 4 and the relevant aligned elements are highlighted inside the green border in Figure 5.

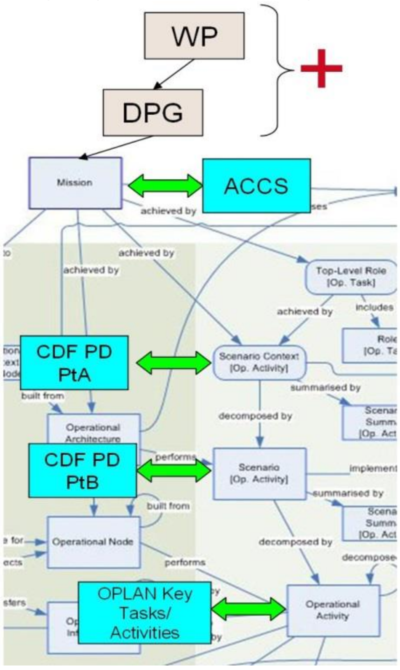


Figure 4: Merger of StT, TSF and WSAF elements showing how WP and DPG elements are added and the ACCS, CDF PDs and OPLAN elements are exchanged with the equivalent WSAF elements

One of the keys to establishing robust metamodels for use in MBSE is the relationships between the elements. Neither the StT framework nor TSF provide defined relationships between their elements. However, relationships between elements are given for the WSAF that utilise the CORE® schema relations, which for the sake of alignment between frameworks, would be prudent to utilise. The overall WSAF merged with the APM can be seen in Figure 5.

ACTION

Tailoring the Merged Metamodel for Operational Needs

During 2011, an opportunity to implement the APM arose when the operational needs for a naval ship platform’s Unmanned Aerial System (UAS) needed to be established and captured. The opportunity marked the initiation of the first action phase for the research, which began with the tailoring of the merged WSAF - APM metamodel. The aim of the tailoring was to create a metamodel that results in a set of operational needs and constraints. Tailoring involved carving out the relevant (i.e. the elements that trace from the White Paper to the operational needs and constraints) elements and relationships from the overall merged metamodel. The tailored metamodel elements are shown as the elements inside the red border in Figure 5.

Tailoring of the way that the OPLAN Key Tasks were decomposed was also implemented in the metamodel for this application. This was due to the aim of capturing not only the activities that the UAS would perform, but also the ship platform activities that these UAS activities were decomposing. The decomposition used for the OPLAN key tasks can be seen in Figure 6a. Further tailoring, which is shown in Figure 6b, was undertaken by creating groups for the operational needs and constraints that were likely to be generated. This grouping was performed in order to facilitate the MBSE modelling of the generated needs and constraints.

It is worth noting from Figure 6 that the operational activities, needs and constraints are only decomposed one or two levels. This corresponds with the system’s development being in the early stages of its acquisition lifecycle.

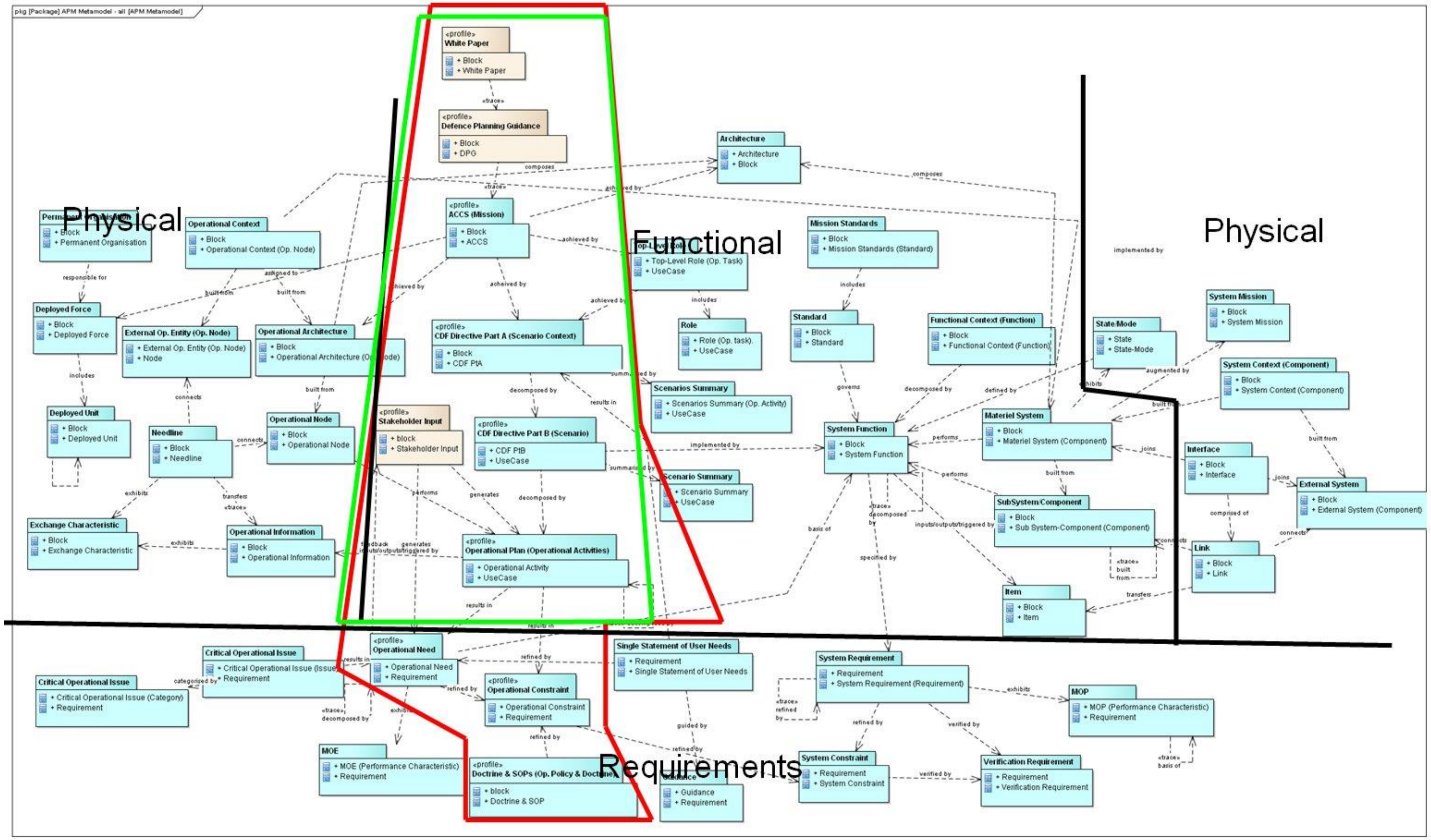
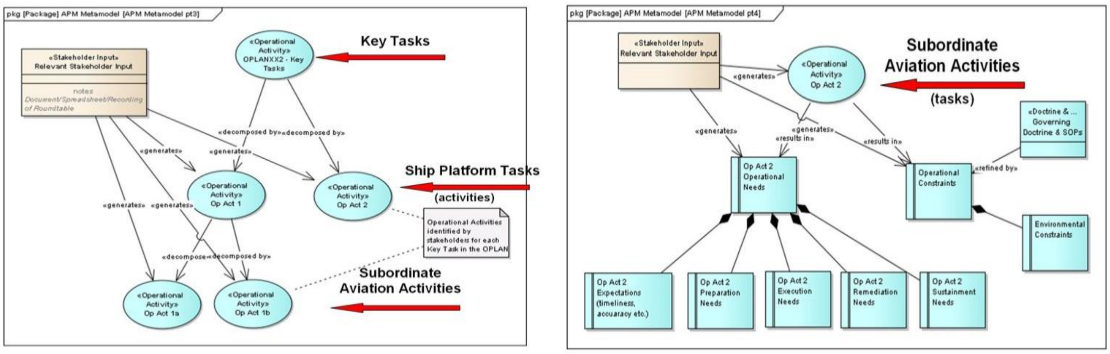


Figure 5: Overall WSAF merged with the APM. Note that the blue elements are WSAF aligned and the elements inside the red border are the elements of the tailored merged metamodel used in the generation of operational needs. Elements inside the green border are those that were aligned for the APM.



(a) (b)

Figure 6: Tailored decomposition of the OPLAN element (a) and grouping of operational needs and constraints (b).

ADO Documents and Relevant Information

Following the metamodel tailoring, the relevant information from the ADO documents needed to be identified for use in the APM. In doing this, the Initial Capability Description (ICD) of the ship platform was treated as the prevailing definitive document. The ICD was published by Defence and endorsed by the Chief of Navy and Capability Development Group. It provides a background for the project, along with forming a vision for the early stages of the project's capability definition. The ICD does this by providing a set of aggregated primary roles, which could be utilised in the development of capability requirements. The ICD also gives concepts of employment, an operations profile and some key platform characteristics that guided selection of the relevant information for the ship platform from the ADO documents.

The content within most of the ADO documents is classified, so remaining cognisant of this, the documents, along with the type of information that will be extracted and stored in the APM for the OCV aviation needs is given in Table 2.

ADO Document	Pertinent Information
White Paper	Defence Priorities given in relevant paragraphs covering the proposed ship platform
Defence Planning Guidance	Defence Contingencies and Military Response Options (MROs) relevant to the ship platform and its aviation capability
ACCS	The context and mission within the Defence Contingency relevant to the ship platform and its aviation capability
CDF Planning Directive Pt A	Military context and objectives relevant to the ship platform and its aviation capability
CDF Planning Directive Pt B	Methods, CONOPS and constraints relevant to the ship platform and its aviation capability
Operational Plan (OPLAN)	Key Tasks and Effects relevant to the ship platform and its aviation capability

Table 2: ADO documents and the pertinent information that may be encapsulated in the APM (dependent on classification level)

It is also worth noting that the content within these high-level planning documents is very broad as it encompasses the entire ADF. This means that not all of the scenarios and other information will be relevant to the ship platform under consideration. Whilst selecting only relevant information from the ADO documents is not conventional for the purposes of wargaming and operational planning, it ensures that the traceability through the documents is set up in capability definition. This approach is not without weaknesses, which were highlighted during discussions with stakeholders and will be covered in the Observation and Reflection section.

Stakeholders

Selection of relevant stakeholders to provide input was shaped by the desire to have SMEs with recent seagoing command experience in the domains covered by the ICD for the ship platform. The need for this type of SMEs was identified as being important as they would be capable of providing informed input into the types of activities the ship platform and subsequently its air capability, would be expected to undertake within the context of the scenario, where the platform would be operating as part of a system-of-systems. Furthermore, these SMEs would be aware of current Royal Australian Navy (RAN) doctrine and operating procedures that will influence the performance of the operational activities they identify as being relevant to the ship platform and its aviation capability. As such, SMEs with the applicable experience from the relevant RAN Force Commands were selected, along with stakeholders from the Fleet Air Arm (FAA), Navy Strategy and the CDG, to participate in the generation of the UAS's operational needs and constraints.

Focused Round Table

From the tailored metamodel in Figure 5, it can be seen that stakeholder, or SME input generates the system's operational needs and constraints. The method for generating this input had to be developed for a scenario based approach due to both the nature of the information contained in the ADO documents and the preference for more structured, traceable SME data. In this instance, such an approach could be seen as mission, or operations analysis, since it is being performed to take the customers needs statement (i.e. the RAN/CDG ICD) and expand this by studying how the system of interest will be utilised, within a specified context, to meet this need statement (Grady 1993). On the other hand, scenarios are a widely used tool in requirements elicitiation (Zowghi and Coulin 2005) and they provide an ideal means of eliciting and validating stakeholder needs (Pohl and Haumer 1997).

The method of undertaking the scenario based approach to operational need and constraint elicitation, along with the way that the SME data was captured, was carefully considered. The use of MBSE in the APM process gave the authors the mindset of obtaining more structured data that would facilitate the building of a knowledge model of the system. Having this mindset may not have been completely ideal in practice and some of the implications are discussed in the Observation and Reflection section. The method developed for the need elicitation process was termed the Focused Round Table (FRT). The key purpose of the FRT is for the SMEs to essentially decompose the CDF PD Key Tasks in line with the merged WSAF – APM metamodel. The FRT comprised three main themes that had the corresponding activities given in Table 3.

Theme	Activities
1. Placing SMEs in the scenario context	Overview presentation on FRT purpose and process
	Presentations on the ADO documents with a focus on the ACCS
	Background presentation on the ship platform
2. Data Capture	Example usage of the data capture tool
	Identification of Key Tasks relevant to the ship platform
	Identification of the operational activities that decompose relevant Key Tasks
	Identify the operational needs and constraints that decompose the operational activities
3. Feedback	Provide SMEs with an opportunity to comment on the data captured
	Present example MBSE diagrams back to SMEs for comment to ensure they accurately reflect the data captured
	Provide an opportunity for FRT participants to comment on FRT process in order to facilitate FRT refinement

Table 3: FRT themes and associated activities

By placing the SMEs in the scenario context in the first theme's activities, a boundary is essentially being imposed on their thinking before they generate the operational needs and constraints for the system of interest. These constraints include relevant aspects such as the size of the ship platform they are commanding, the location where they are operating and the tasks they are being given to perform. However, as well as providing the SMEs with a boundary, the situational context facilitates the elicitation of the general uses of the system, but also issues that may not have arisen if only the general uses were explored (Benner, Feather et al. 1993). The issues/data that were hoped to be captured in this instance are the doctrine and standard operating procedures that govern the operational activities. This data helps to scope the operational imperatives that would need to be satisfied in the preparation and execution of the Key Tasks and provides further context in the system's capability definition.

In developing the data capture tool, the primary considerations were having a tool that was both easy for the SMEs to use and to provide a structure that reflected the merged WSAF – APM metamodel to facilitate modelling. Initially, work developing a database tool was undertaken, however time constraints and database complexity led to a Microsoft Excel ® spreadsheet *pro forma* being developed. After performing the FRTs the use of Microsoft Excel ® software did not turn out to be an issue, however, further refinement of the spreadsheet *pro forma* could be undertaken, which is discussed further in the Observation and Reflection Section.

The aim of the FRT in this first action research cycle was to embrace the scenario based approach provided by the ADO documents and avoid a workshop type approach to need elicitation. It was felt that a smaller group of SMEs would be able to provide a more focused set of data that decomposed the Key Tasks more effectively than a larger group of SMEs. In the authors' experience, a larger group has the potential to adopt a workshop type approach in which concepts and ideas were explored rather than specific needs being developed. This led to the development of a strategy where each of the relevant SME domain groups would undertake FRTs in small numbers of people (i.e. 2-4) over a single day. However, this strategy proved to be unfeasible as arranging access to single domain SME groups was difficult and a compromise was made whereby two domain groups would undertake FRTs in a single day. Again, this strategy has scope for refinement in future research cycles, which is discussed in the Observation and Reflection section.

Modelling the FRT Data

Modelling of the SME FRT data was a time consuming process. The data capture spreadsheet contained 33 fields for the ship platform's organic UAS operational activities, needs and constraints. It also asked the SMEs to identify relevant ICD role tasks for the ship platform and textual comments were able to be entered. Overall, the SMEs identified 67 aviation activities for the UAS to perform in the scenario context provided in the FRTs. Not all fields were completed however, with those missing generally being the platform expectations and environmental constraints for an operational activity that the SME had identified.

While time consuming, the modelling was found to be greatly facilitated by the alignment of the data capture tool's structure with the merged WSAF – APM metamodel. Modelling was also facilitated by utilising a process within the EA™ tool that allows the profiles of the metamodel elements to be exported as a UML profile. Each of these profiles can be imported back into EA™ as a resource, then dragged and dropped into diagrams and named as the desired activity/need/etc.

The author conducting the modelling also remained cognisant of two main considerations while carrying out the modelling. First and foremost, the modeller had to focus on not interpreting the SME data when modelling it. This was difficult at times as there were cases where it was tempting to tweak what was in the spreadsheet to facilitate modelling. For example, one of the cells in the spreadsheet was a drop down box with a yes/no selection for a stealth service expectation for the UAS platform. One SME left this cell empty, but put in the comment cell that stealth would be needed when conducting the activity in a hostile environment. It was tempting to simply model this as a stealth service expectation operational need element, which was utilised in modelling all other SME data, however, to accurately reflect the SME data, a new element was created with this service expectation.

The other aspect that was considered throughout the modelling was looking out for potential groupings of the elements. This was found to be achievable for the platform expectation operational needs of nominal speed whereby they were grouped into low (30-60 knots), Medium (60-120knots) and high (120+ knots). The overall ratings of importance that the SMEs assigned to the operational activities they identified were also able to be grouped in a similar manner.

Some examples of the model diagrams that were developed from the SME data can be seen in Figure 7, Figure 8 and Figure 9. In Figure 7 the decomposition of Key Task 08 can be seen, whilst in Figure 8, the use case diagram of the Beach Survey operational activity (the element second from the left in the bottom row of Figure 7) is shown. In Figure 9, the operational needs that trace from the Beach survey operational activity can be seen.

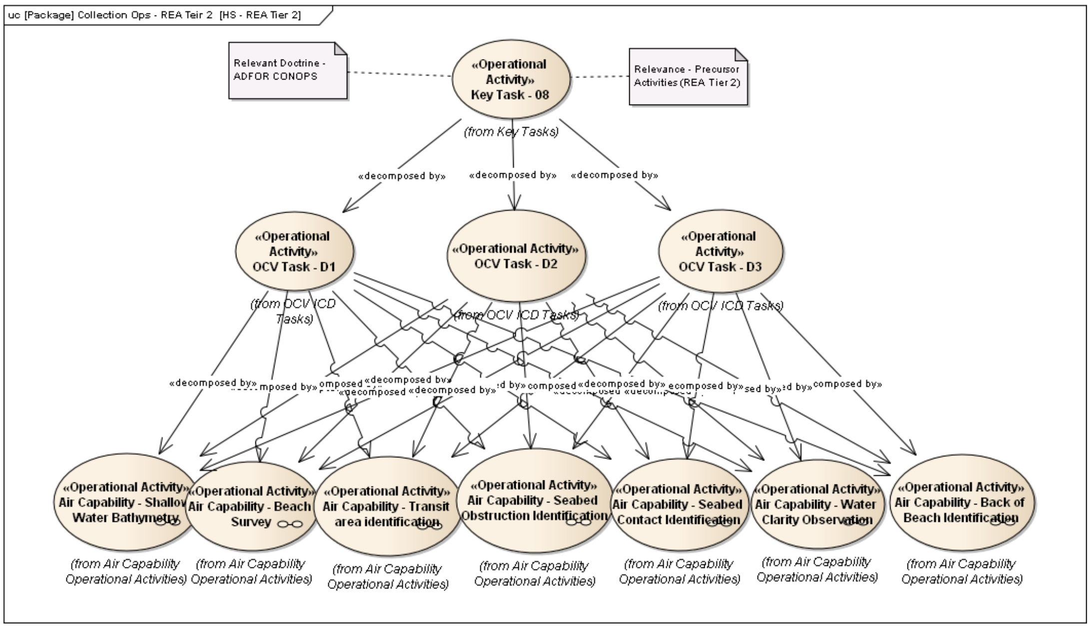


Figure 7: Decomposition of an SMEs Key Task 08 data showing the operational activities modelled as use cases

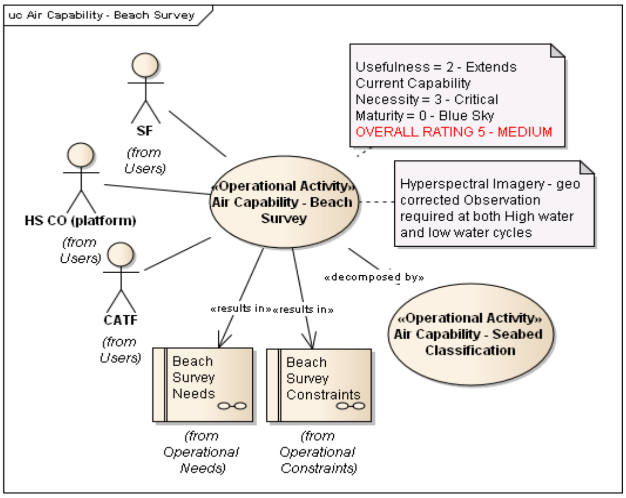


Figure 8: Use case diagram of the Beach Survey operational activity showing the users of the activity, SME importance ratings and comment

Feedback of Data to SMEs

The approach adopted for the feedback theme of the FRT involved a two step process. Firstly, a half day meeting was held two days after the data capture sessions with the available SMEs present, where some of the initial MBSE modelling (such as Figure 7, Figure 8 and Figure 9) and data observations were presented. As part of the meeting, a classified slide that showed (in an MBSE-like way) how the operational needs and constraints the SMEs developed for the Beach Survey operational activity could be traced all the way back through the ADO documents to the White Paper using the merged WSAF – APM metamodel. An unclassified version of this traceability slide is shown in Figure 10.

After the SMEs were shown these diagrams, they were asked for feedback on both the content and whether the diagrams were a useful method of presenting the data from the workshop. It was interesting to note that whilst all of the diagrams were positively received, the “PowerPoint engineering” slide (Figure 10) was described by one SME as the “money shot” due to the way it showed the traceability of the operational needs to the White Paper. It is unfortunate, but completely understandable, that the additional contextual data cannot be incorporated into the MBSE model for general publication as the contextual information certainly adds to the validity of the needs and constraints.

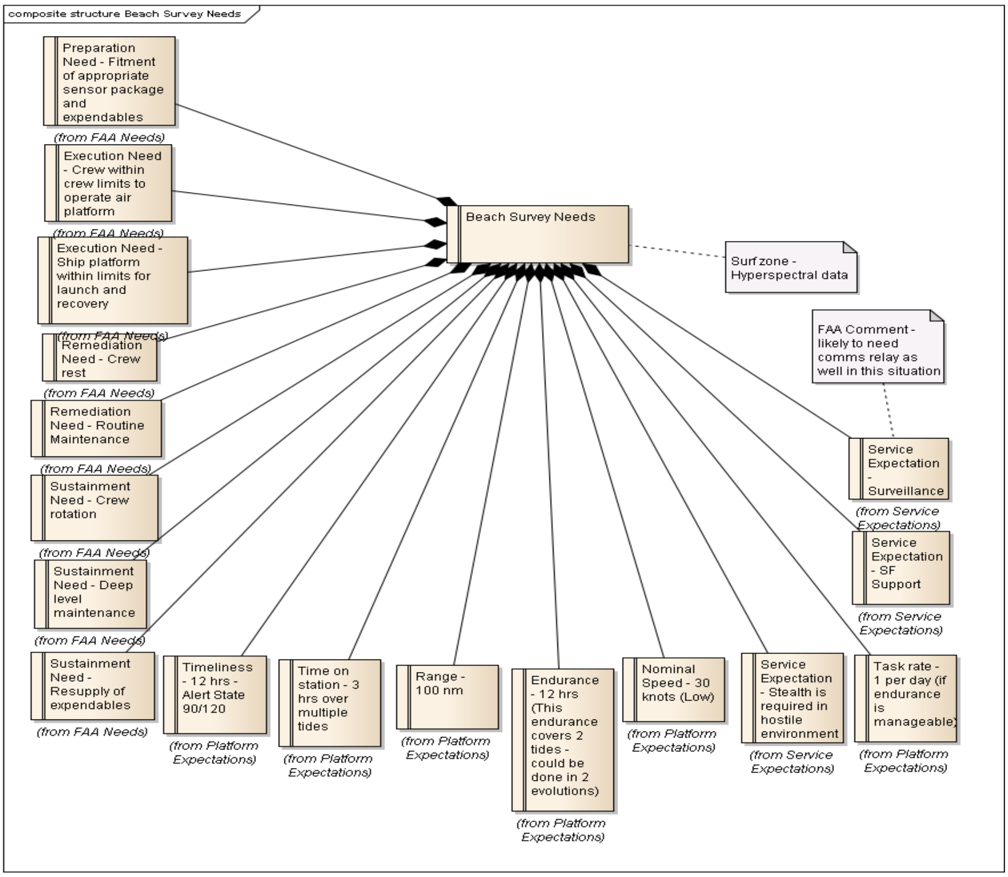


Figure 9: Operational needs for the Beach Survey operational activity

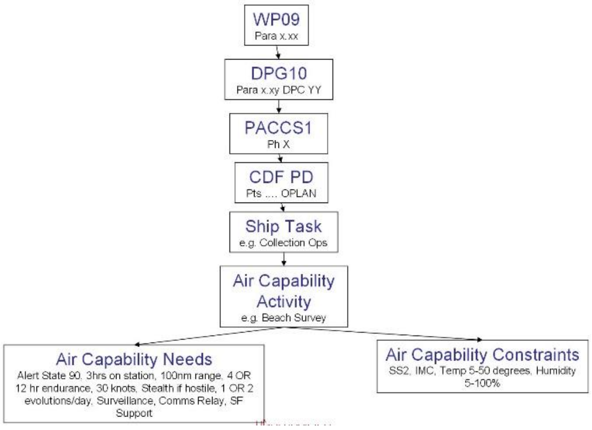


Figure 10: Example of the high-level traceability of the SME operational needs for the Beach Survey operational activity

Also during the SME feedback session, they were also asked for feedback on the overall APM and FRT processes. This feedback is covered in the Observation and Reflection section. The second part of the feedback theme of the FRT occurred after the MBSE modelling was completed, when the SMEs were sent copies of the diagrams that were developed and asked to comment on whether they accurately reflected the data they had entered into the spreadsheet *pro forma*.

OBSERVATION AND REFLECTION

During the first action research cycle described in the previous sections, several observations and reflections have been noted that could be used to refine the process and activities in future cycles of the research. Firstly, the data capture spreadsheet didn't entirely capture the freeform concepts and ideas that were generated by the SMEs during their discussions during the FRT. This can be put down to the data capture tool being structured to facilitate knowledge model building in the MBSE tool. This arrangement did facilitate easier modelling in the MBSE tool and in this first research cycle, this failure to capture the SMEs freeform ideas and concepts in the spreadsheet was accounted for by the authors making notes during the FRT and later incorporating these into the modelling as note elements. There may be better, more efficient ways of doing this that find a middle ground that allows for the structure desired to facilitate model building, whilst encouraging freeform ideas to be generated and captured at the same time.

It is likely that if another opportunity arises to implement the APM, thereby facilitating another action research cycle, the process of the FRT and data capture tool will be further developed to account for these shortcomings. The suggestion of having the SMEs do their own modelling has been made by peers in the MBSE fraternity. This approach may not be entirely feasible due to the time required to familiarise the SME with the tool, but an arrangement whereby the SME directs a proficient user of the tool to implement their ideas could be possible

Several SMEs observed during the FRT that the scenarios set out in the ACCS seemed to be aimed at the high end (i.e. major system) warfighting capabilities. This resulted in the SMEs identifying that many of the OPLAN key tasks would be undertaken by a major fleet unit rather than the ship platform of interest. This poses an interesting problem as the traceability to Defence's strategic priorities set up in the APM is reliant on the ACCS being relevant to the system of interest. If other (i.e. non ACCS) scenarios are used in capability definition, this traceability is lost, which is contradictory to the recommendations set out in the recent reviews of Defence acquisition. A potential solution may be for ACCS to be created that cover different levels of capability, however, maintaining a systems-of-systems perspective will remain vital.

Another SME observation relevant to the ACCS used in the FRT was that the ship platform's peacetime activities were neglected. However, there was agreement that the operational activities undertaken during peacetime would be the same as those conducted within the ACCS context. There would be differences in the operational tempo and fidelity with which these activities would be undertaken depending on the situation, but essentially the operational activities remain the same. This could have implications on the operational needs of the system of interest as the resulting performance requirements for sub systems such as sensors are likely to depend on the situation. This begs the question; do you design for wartime conditions, where the system is only likely to operate rarely, if at all, or for peacetime tasking?

Other valuable reflections on the process were provided by the SMEs during the FRT feedback sessions. These included a need for a briefing on the state of the technology of the system-of-interest to be given as part of the FRT. This may be a good inclusion for any application where the technology of the system-of-interest is not widely appreciated. Another SME felt that the process "stove piped" the SME input within their domain streams and that perhaps cross pollination of SMEs ideas from different domains could result in some interesting concepts. It was also suggested that the amount of information (i.e. the number of fields the SMEs were asked to fill) that was being collected was too much for the capability definition phase of system development.

During the MBSE modelling, it became apparent that MBSE enabled the repeated operational activities, along with the repeated operational needs and constraints to be highlighted. Feedback from the SMEs regarding the MBSE diagrams was also generally positive and the traceability through the ADO documents to the White Paper that was shown in Figure 10 was extremely well received. Further traceability through the merged WSAF – APM metamodel to requirements, systems and components was identified as being other valuable work that could be undertaken by the SMEs. There is also the potential for this work to inform development of the system's CONOPS and Preliminary Capability Definition Documents.

Overall, a very useful set of operational needs and constraints for a ship platform's organic UAS that are traceable to Defence's strategic priorities have been established. Therefore, the APM provides a good approach for developing operational needs that are contextualised within these priorities. It is hoped that the opportunity for further cycles of action research involving the application of the work described in this paper will arise. These cycles would focus on refining the FRT/data capture process that utilises the observations and reflections from this first cycle of research, along with expanding the MBSE aspects further throughout the capability development lifecycle. This work will be dependent on receiving approval to participate in other capability acquisition projects.

ACKNOWLEDGEMENTS

The authors wish to acknowledge all of the SMEs that contributed to the FRTs, as well as Kurt Brinschwitz, Stuart Cannon, Bryan Jessup, Karl Brinkmann and Neil Davenport.

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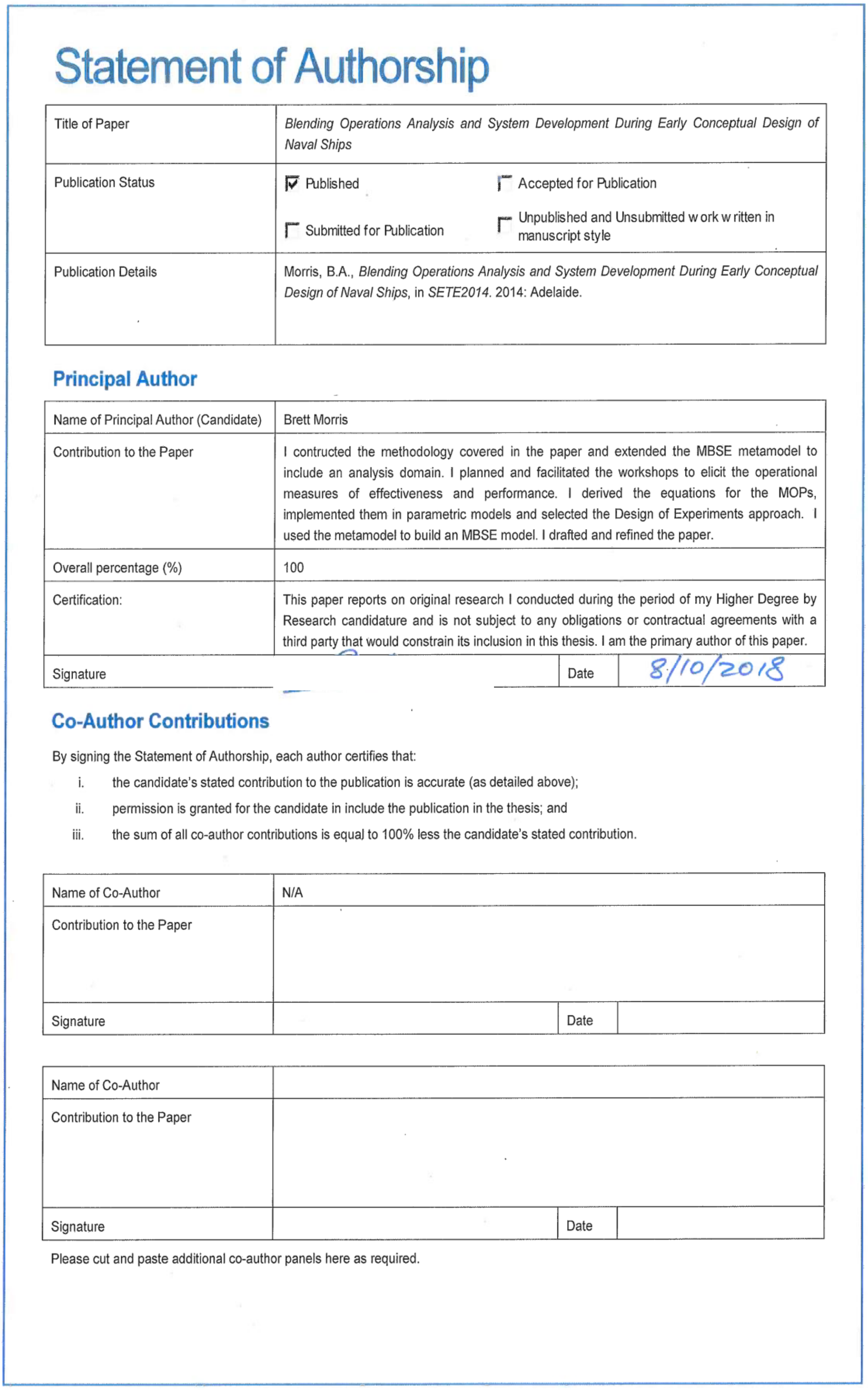
BIOGRAPHIES

Brett Morris is a Naval Architect/Systems Engineer who joined DSTO in 2007. He has previously worked for the RAN in the Directorate of Navy Platform Systems and is interested in the fields of Naval ship concept design, structures and hydrodynamics, along with Systems Engineering applications to Naval Architecture. Brett has a Grad. Dip. in Systems Engineering, a BE (Nav. Arch.) and is currently undertaking part-time research towards a PhD.

Gerald Sterling joined DSTO in 1988. He is in the Air Operations Division. His current research interests address the conceptual analysis and effectiveness aspects of unmanned aerial systems. He has also worked extensively in systems engineering for flight simulation systems and in control system design and development for aircraft and gas turbine control systems in Australia and the UK. He has a PhD (Comp Sc), BE (Aero) and a Dip Ed

Appendix B: Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships



Statement of Authorship

Title of Paper	*Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships*
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted w ork w ritten in manuscript style
Publication Details	Morris, B.A., *Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships*, in *SETE2014*. 2014: Adelaide.

Principal Author

Name of Principal Author (Candidate)	Brett Morris		
Contribution to the Paper	I contructed the methodology covered in the paper and extended the MBSE metamodel to include an analysis domain. I planned and facilitated the workshops to elicit the operational measures of effectiveness and performance. I derived the equations for the MOPs, implemented them in parametric models and selected the Design of Experiments approach. I used the metamodel to build an MBSE model. I drafted and refined the paper.		
Overall percentage (%)	100		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	8/10/2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	N/A		
Contribution to the Paper			
Signature		Date	

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

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Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships

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INTRODUCTION

This paper is the third in a series covering ongoing research to construct a Model-Based Systems Engineering (MBSE) methodology for performing conceptual design in Australian Defence acquisition projects. The first paper (Morris and Sterling 2012) covered the development of an approach to establish linkages between Defence's strategic objectives and system operational requirements using an MBSE metamodel. The metamodel comprised requirements, functional and physical domains. In the second paper, the linkages were made at the strategic planning level and the operational requirements were traced through to physical systems that could potentially perform them.

This paper introduces an analysis domain into the MBSE metamodel in order to provide a means of blending performance analysis with conceptual design activities, in an integrated environment. Typically, performance analysis has been carried out in a separate environment to system development activities. It is proposed that by integrating these two activities during conceptual design, acquisition project stakeholders will gain a rough order of magnitude (ROM) view of the effect on performance that the physical design of a major system will have. This outcome has the potential to help inform Australian Defence Organisation (ADO) stakeholders during conceptual design activities, of the implications of decisions on the capability being developed.

The research covered in this paper focuses on the initial stages of conceptual design. Conceptual design comprises the exploratory research and concept lifecycle stages given in the INCOSE Handbook (Haskins 2010). The purpose of these stages is to explore ideas and create an understanding amongst stakeholders of a system-of-interest's design space. Furthermore, these stages align with the latter stages of the needs phase and the initial stages of the requirements phase within the ADO capability lifecycle (Defence 2011). It is within these stages that an identified capability need is transformed into a set of capability definition documents (Defence 2011). This transformation needs to be done with consideration of all of the "*fundamental inputs to capability*" (FICs) (Defence 2011). However, the research within this paper focuses on the major system's performance as a starting point for an MBSE methodology for conceptual design, since this is arguably the most important aspect for the end user during this lifecycle phase.

The author has previously highlighted the importance of performing the transformation from need into a defined capability in a manner that retains a clear view of the intended use of the system (Morris and Sterling 2012) since having "clearly defined goals" has been identified as the most significant success factor in system development projects (Jiang, Klein et al. 1996). An equally important aspect linked to retaining a clear view of the intended use of the capability, is that the transformation should be performed with a connection to the measures of effectiveness (MOEs) for the missions that the system-of-interest will perform. In the case where the system-of-interest is a naval surface ship, Hockberger (Hockberger 1996) notes that:

> *"It is valuable for the designers to have the MOEs in mind when they are conceiving alternative concepts, because the MOEs provide significant illumination for recognizing what ship subsystems may be required or whether a particular concept is likely to achieve those MOEs."*

In the following sections, a brief background on current approaches to connect MOEs to ship design parameters is given and an argument made for the need to develop a methodology specifically for the ADO context. An overview of the foundations of this methodology is given, followed by an outline of how these foundations were built upon in the construction the methodology. An exemplar implementation of the methodology for a simplified Anti-Submarine Warfare (ASW) mission is then given. Finally, a discussion of some of the key aspects identified during the implementation of the methodology and some conclusions are presented.

BACKGROUND

Several approaches to link performance analysis with naval surface ship concept design are currently in various stages of development (see for example, (Kerns, Brown et al. 2011), (Fox 2011) and (McKeown 2012)). In addition to this a NATO evaluation team (AVT-ET-132) has been established to support research into the approaches used by the member nations. However, some of these approaches can be seen as overly rigorous and excessively labour intensive for the initial stages of a ship design from the ADO viewpoint. This is primarily due to the need to build and execute complex operational and ship synthesis (architecture) models that require significant effort (Kerns, Brown et al. 2011). Furthermore, many of these methodologies have been developed in the context of the United States (US) Department of Defence (DoD) acquisition system.

In terms of naval ship acquisition strategy, the US DoD generally conducts most of its conceptual design activities in-house, prior to setting up Integrated Project Teams with DoD and industry members to perform preliminary and detailed design (Keane, McIntire et al. 2009). This approach differs from the ADO, which has recently adopted a Military Off-The-Shelf acquisition strategy for the design and construction of its warships (Saunders 2013). As such, the US has a vested interest in generating a more detailed concept design, since this design will likely become the basis for the final design. On the other hand, ADO in-house concept design activities are more likely to be focused on conducting capability and feasibility studies that inform capability definition prior to industry engagement and the fielding of concepts during the options development phase.

The existing methodologies to link performance analysis with ship concept design methodologies typically comprise separate operational performance and ship architecture models from the domains of Operations Analysis (OA) and Naval Architecture (NA) (McKeown 2012). The evolution of these separate domain models appears to be a result of their complexity and relatively high level of fidelity. The intent of linking these models is to give acquisition stakeholders an early and thorough understanding of the influence of ship design parameters on the ship's military effectiveness (McKeown 2012). The key benefits of stakeholders having an earlier understanding of the influence of the design on the mission effectiveness is that the likelihood of costly changes in later stages of design could be decreased (Fox 2011). Furthermore, the impact of design changes on mission effectiveness can be explored (Fox 2011).

A key assertion of the present research is that the high-fidelity US DoD based approaches, whilst complex, are extremely valuable for conceptual design due to the positive downstream effects of performing these early stage project activities well (e.g. see the increasing costs of changes as system design progresses in Figure 2-4 of (Haskins 2010)). However, these approaches are not suited to the current ADO acquisition system due to the differences between the level of resources available and the prevailing acquisition strategies outlined above. This leads to the assumption that coarse fidelity OA and NA models will suffice in the initial stages of ADO conceptual design. Coarse fidelity models are also likely to be more suited to integration with each other due to the possibility of using a less disparate set of modelling and analysis tools. As a result, there is a need to develop an integrated methodology for providing a rapid ROM view of the effect on performance that the design of a major system will have for ADO naval ship acquisition projects. This approach could be used to inform the stakeholders involved in conceptual design, as well as identify areas of concern related to mission performance that need more detailed analysis.

MBSE METHODOLOGY FOUNDATIONS

Estefan (Estefan 2008) defines a methodology as "*a collection of related processes, methods and tools*" where the process describes *what* is done, the method defines *how* it will be done and the *tool* facilitates the method. In this section, the process, methods and tools utilised as the underlying foundations and guiding principles of the MBSE methodology for linking mission performance to conceptual design are briefly described.

Linking Performance Analysis to an MBSE model using Executable Parametrics

The ongoing research covered in this paper utilises the Systems Modelling Language (SysML) at its core. Along with structure, behaviour and requirements, parametrics have been described as one of the four pillars of SysML (Bajaj, Zwemer et al. 2011). Parametric diagrams can be used to build systems of equations that constrain the properties of block elements (Friedenthal, Moore et al. 2009). Typically, SysML based MBSE tools have not had the capability to execute, or mathematically solve parametric diagrams. However, recently commercial software developers have released add-ins, for these tools, such as Solvea™ for Enterprise Architect®, that provide the capability to solve systems of equations built in parametric models.

The development of this capability provides a key benefit for blending performance analysis with system development within conceptual design arise. The constraint parameters can be used to represent system properties, such as physical characteristics. This provides a means of linking the MBSE system model, to a simulation built in parametric diagrams, or views of the system model. Therefore, if an MBSE model is being developed during conceptual design, it can be linked to performance analyses via the system-of-interests physical characteristics, using parametric diagrams.

Metamodel

The metamodel is the method by which the underlying structure is embedded into the methodology. A metamodel defines the classes of elements and the permissible relationships between these classes in a system model (Logan, Morris et al. 2013). Several architecture frameworks are suitable, with some modifications and extensions, for use as MBSE metamodels for Defence systems development (Logan, Morris et al. 2013). These include the Department of Defense Architecture Framework (DoDAF), the Ministry of Defence Architecture Framework (MODAF) and the Australian Defence Architecture Framework (AusDAF). In the ADO context however, the AusDAF compliant Whole-of-System Analytical Framework (WSAF) (Robinson 2011) has been endorsed for MBSE practice within the Capability Development Group (CDG) (Plenty 2012).

Since CDG typically performs conceptual design activities for ADO acquisition projects, it makes sense to utilise the WSAF metamodel in the present research. Previous research by the author (Morris and Sterling 2012) extended the WSAF to link Defence strategic guidance through to system requirements. However, the need to link performance analysis to system development necessitates the introduction of an analysis domain into the extended WSAF metamodel. The analysis domain can be seen inside the red border in Figure 1. Within the analysis domain are the ship representation, physical constraints and simulation classes. The ship representation class contains the ship design parameters that are used in the governing equations of the simulations. The physical constraint class contains the equations that govern both the simulations (contained in the simulation class elements) and ship representation class elements. In SysML modelling terms, the ship representation class elements are blocks, the physical constraint class elements are constraint blocks and the simulations are parametric diagrams.

Also from Figure 1, the relationships between the simulation and ship representation class elements to classes within the operational behaviour, functional design and requirements domains of the metamodel can be seen.

Set Based Design

Set Based Design (SBD) is an emerging paradigm in engineering design, particularly in the USA, where its principles are being adopted for naval ship design (Singer, Doerry 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). These sets of design parameters are narrowed as the design progresses and more knowledge is gained about the system being developed. 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 with more information available as the decisions are purposely delayed in the SBD approach.

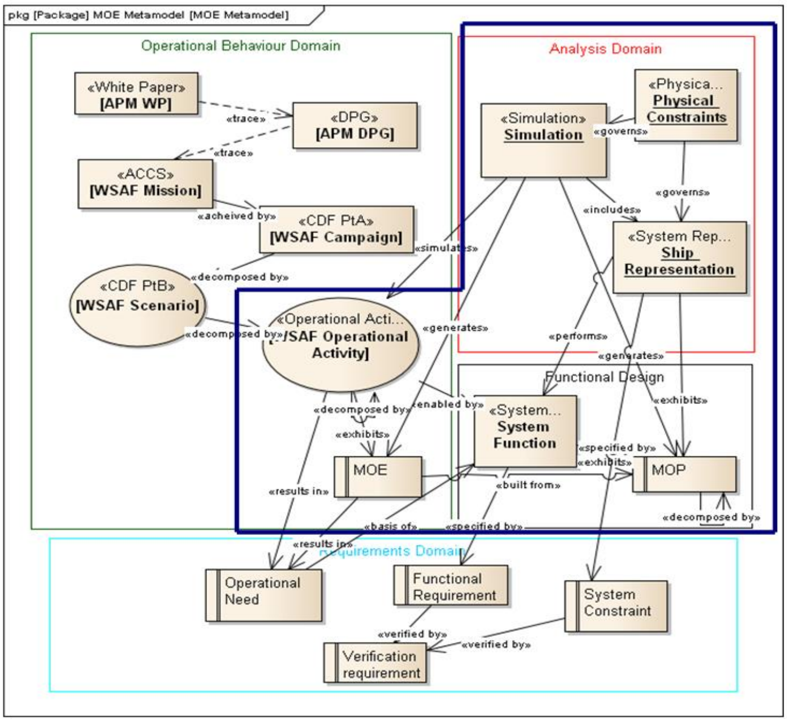


Figure 1: Part of the metamodel being used in the ongoing research that utilises the extended WSAF metamodel. The elements within the dark blue border are those used in the ASW exemplar implementation covered later in this paper

SBD principles are a foundation of the methodology being constructed in the research covered in this paper. It provides a means of presenting sets of ship design parameters to build a conceptual design space, rather than a single point conceptual design. By developing a design space of sets of ship design parameters that is linked to mission performance, stakeholders will gain an understanding of the ranges and combinations of design parameters that will have higher performance levels during the missions for which the ship is being developed. This understanding would be very useful for stakeholders to have during conceptual design as it can be used to inform decision making

The Overarching Process

The overarching process that forms a key part of foundation of the methodology being constructed for the research comprises six main steps:

1. Establish the mission scenario and the associated MOEs/MOPs.
2. Determine the governing equations for mission performance and the relationships between performance and design parameters.
3. Develop a simple numerical model of the mission.
4. Conduct a range of experiments/simulations using the simple numerical model.
5. Post-process the results from the experiments.
6. Develop a conceptual design space for the mission that is linked to performance.

Each of these steps will be covered in more detail in the following section.

CONSTRUCTING A METHODOLOGY TO BLEND OPERATIONS ANALYSIS AND SYSTEM DEVELOPMENT

The research methodology being utilised in the ongoing research covered in this paper is the constructive research approach (CRA). This research methodology comprises the features as translated by Piirainen and Gonzalez (Piirainen and Gonzalez 2013): 1. a focus 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. This paper is aimed at covering features 1, 2 and 3 in order to step into features 4 through 6. In this section of the paper the construction, or deliberate design (Piirainen and Gonzalez 2013), of the methodology for blending OA and NA in an MBSE environment during conceptual design is discussed for each of the steps involved in the overarching process given in the previous section.

Establish Mission Scenario and MOEs/MOPs

This step commences the process and as such, it is extremely important that the mission accurately reflects the intended use of the system-of-interest. The mission scenario can be seen as a design reference mission (DRM), since it will need to represent the anticipated threats, operational activities and environment within which the proposed capability system is expected to perform (Skolnick and Wilkins 2000). This research focuses on two approaches for establishing the mission scenario along with the associated MOEs and Measures of Performance (MOPs). The first is to utilise a “library” of DRMs and associated measures for common warfare areas. The second is to consult with subject matter experts (SMEs) and if required, utilise a structured method of weighting the importance of competing measures such as the analytical hierarchy process, or weighted sum method (Fox 2011).

When establishing MOEs and MOPs with SMEs it is worth noting that MOEs are concerned with the systems level and should be traceable and justifiable. Sproles (Sproles 2002) asserts that MOEs should be limited to essential Critical Operational Issues, or the “showstoppers” for a mission. MOPs can be used to quantify the performance and measure the attributes of a systems behaviour (Green 2001). Generally, an aggregation of MOPs will constitute the system’s MOE (Green 2001). This implies that MOPs are chiefly concerned with the subsystem aspects within phases of a mission, such as sensor performance during the search phase of an ASW mission.

Utilising a library of DRMs, MOEs and MOPs to establish the mission scenario and associated measures is the approach that authors such as Fox (Fox 2011) and Kerns et al. (Kerns, Brown et al. 2011) have adopted. In their approach, they have used the library of measures for Naval tactical level tasks provided in the US Navy Tactical Task List (CNO 2008). In the ADO context, a similar “library” of missions is referred to as the Australian Joint Essential Tasks in (Defence 2010), however, no associated MOEs/MOPs could be found in the open literature. This makes the SME consulting approach the remaining alternative. A positive aspect of this approach may be that the SMEs and stakeholders that are consulted during the development of the reference mission and MOEs/MOPs are likely to feel more engaged in the overall process.

It is worth noting that mission scenarios are typically developed during conceptual design in the ADO as they will become part of Chapter 5 within the capability’s Operational Concept Document (Defence 2009). It would be beneficial if these could be collected into an ADO endorsed library of missions at some point in the future. This would facilitate the re-use of the scenarios in numerical modelling for performance analysis and provide traceability to endorsed guidance in the analysis, in a similar manner to the US DoD.

Determine Relationships between Performance and Design Parameters

This is the critical step in the process that allows OA and early conceptual design to be linked. Since the aim of the current research is to provide a ROM view of the effect on mission performance of a range of system design parameters, OA textbooks can be a useful source of simple equations for estimating mission performance aspects. Mission performance aspects such as detection rates and reliability have been studied extensively and equations are in widespread use in the OA domain. These equations will generally contain terms that are influenced by system design parameters either directly or indirectly. Engineering judgement must be used to identify the terms that system design parameters will influence.

Relationships between performance and design parameters can be developed using parametric or surrogate modelling. Parametric modelling is a commonly used method in engineering and architectural 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 that are typically generated using linear regression or other curve fitting techniques from the historical data of similar systems (Lamb 2003). This approach is particularly useful during conceptual design since the system designer has a lack of knowledge and data regarding the intervention system being developed (Mavris and Pinon 2011).

Naval surface ships are well suited to the parametric modelling method due to their relatively long lifecycle. As a result of this the evolution of individual hull form types (not necessarily new hull forms) is inherently slow. 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 (Lamb 2003). Together these circumstances have encouraged the use of parametric design. Notwithstanding this, there is uncertainty associated with parametric modelling due to two key aspects: firstly, the historical data that is often normalised or non-dimensionalised to facilitate the generation of relationships between parameters needs to be accurate and reliable; secondly, the correlation of the relationship between two parameters and the historical data points must be addressed. In the case where curve fitting is used to generate relationships, statistical techniques can be utilised to quantify the level of correlation (Lamb 2003).

In many instances, such as system/sub-system performance data, a sufficient set of historical data is unavailable for use in 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. However, conducting these analyses generally requires significant time and effort. In contrast, surrogate modelling techniques take the results of a set of simulations across a design space and constructs an approximate relationship between design parameters and responses (Mavris and Pinon 2012). This technique is well suited to conceptual design and design space exploration since the relationships between design parameters and responses (performance) facilitate an understanding of the design problem (Mavris and Pinon 2012). Surrogate models can be developed using either new simulation data or the data from previous analyses.

As with parametric modelling, there is a degree of uncertainty associated with the use of surrogate models. However, provided the surrogate is generated from a validated physics based model the level of uncertainty is acceptable for a ROM view of the design space during conceptual design.

Develop Simple Numerical Model of Mission

Leite and Mensh (Leite and Mensh 1999) provide a framework for model development, part of which is shown in Figure 2. The framework highlights the importance of linking MOEs to high-level system requirements (Leite and Mensh 1999). Furthermore, Leite and Mensh (Leite and Mensh 1999) emphasise the importance of establishing the mission MOEs and MOPs prior to commencing any model development. An important element of their framework shown in Figure 2, particularly for naval platforms, is to account for the environmental conditions. These will have a significant impact on the effectiveness of a naval platform for any operational mission.

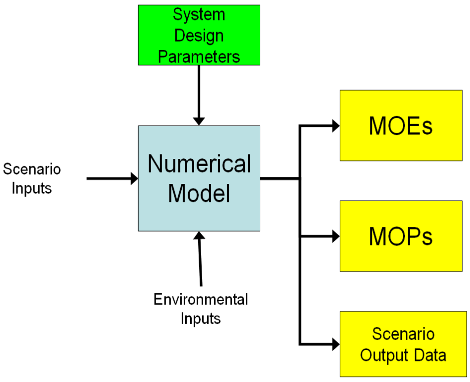


Figure 2: Model development

Conduct Experiments/Simulations

To build a conceptual design space using the relationships between mission performance and ship design parameters in the simple numerical model, a range of experiments, or simulations, needs to be performed. The relationships between mission performance and ship design parameters will contain a number of independent variables. In conducting the experiments using the simple numerical model, the full range of each variable needs to be included in the set of experiments. This can entail a significant number of experiments. For example, a full factorial experimental matrix for k variables, for three values of each variable (i.e. minimum, average and maximum value of each design parameter), would comprise n experiments, where:

$$n = 3^k$$

In cases where a full factorial experiment is infeasible due to a large number of simulations being required, Design of Experiments (DOE) is a useful method for reducing the computational effort involved in this step of the process. DOE involves conducting a screening experiment in order to examine a number of variables and quantitatively understand their effect on the result of the simulations (Fox 2011). Analysis of the results of a screening experiment determines the statistical significance of each design parameter. From the screening experiment, the statistically significant parameters influencing mission performance can be identified and a Monte Carlo approach to the simulations can be implemented. Monte Carlo simulations utilise an experimental matrix that has been developed using random samples from the applicable probability distributions of the variables involved in the simulation (Wagner, Mylander et al. 1999). Where the statistically significant variables, or in this case, ship design parameters have been identified, the experimental matrix for a Monte Carlo simulation can be developed with a focus on ensuring all possible combinations are captured.

Post-Process Results/ Present Conceptual Design Space

Inevitably, with a range of simulations being performed in order to develop a ship design space that is linked to performance, there will be a large amount of data that will need to be translated into a form that is useful for stakeholders. Statistical and graphical methods will need to be implemented within this step of the overarching process to ensure this happens. This will not be an overly complex step in the process, since software for statistical analysis and generation of graphical views of the experiment results is in common use.

Methodology Summary

The methodology covered in this section is summarised in Figure 3.

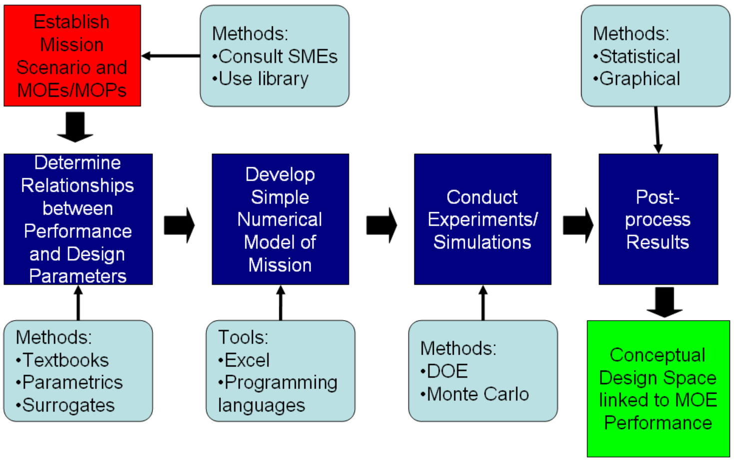


Figure 3: Methodology summary showing the process, along with the methods and tools that could be used

TESTING THE METHODOLOGY

In this section, the methodology described in the previous section is tested through its implementation for an ASW mission. ASW was selected as the exemplar mission for two main reasons. Firstly, ASW is an important naval mission that is typically performed by surface warships in collaboration with organic and inorganic off-board systems. Secondly, the testing was undertaken while the author was on a Defence Science Fellowship at the Center for Innovation in Ship Design (CISD) within the US Naval Surface Warfare Center Carderock Division. Colleagues at CISD included both serving and former naval officers with ASW operational experience. These colleagues acted as stakeholders and SME consultants during the implementation.

Establish Mission Scenario and MOEs/MOPs

The method used to establish the ASW mission scenario, MOE and MOPs was to consult SMEs. This approach was adopted to test the methodology in an environment where no endorsed library of missions and measures exist; similar to the ADO acquisition space. The ASW mission was developed during a roundtable under the assumption that: the ASW ship is a monohull vessel; it is operating as part of a task force; and that it has been sent to a position at a distance from the task force to set up a barrier between a suspected hostile submarine choke point and the task force. The operational activities that comprise this typical ASW mission were identified as mobility (transit from the task force to the barrier), search, detect, track and prosecute. However, the track and prosecute operational activities were neglected for the present implementation due to the complexity associated with modelling these activities. Furthermore, the performance levels of these activities will be more highly influenced by factors other than ship design parameters, such as sensor and weapon performance.

During the roundtable, MBSE modelling was conducted and Figure 4 shows a mindmap that was developed “on-the-fly” to capture aspects that the CISD staff with ASW operational experience identified as important for each of the activities within the ASW mission. This proved to be useful both during and after the roundtable as the staff were able see what was being captured live and it was also able to be used when determining suitable relationships between performance and design parameters.

Following the establishment of the ASW mission activities, the overarching MOE for the mission was established:

The percentage of hostile submarines that do not breach the barrier

The following MOPs were elicited during the roundtable for each of the three operational activities within the simplified ASW mission:

- Mobility - The ability to assume the barrier position; and operational availability
- Search – Sweep width
- Detect – Probability of Detection

Determining Relationships between Performance and Design Parameters

All three of the methods shown in Figure 3 were utilised in the test implementation: equations from textbooks, along with surrogate and parametric modelling. Since modelling and simulation was to be used to rank the effectiveness of different combinations of ship design parameters, the MOE for the simplified ASW mission was determined to be a product of the three MOPs for each of the mission activities. This aggregation of MOPs into a single MOE is not unusual (Green 2001).

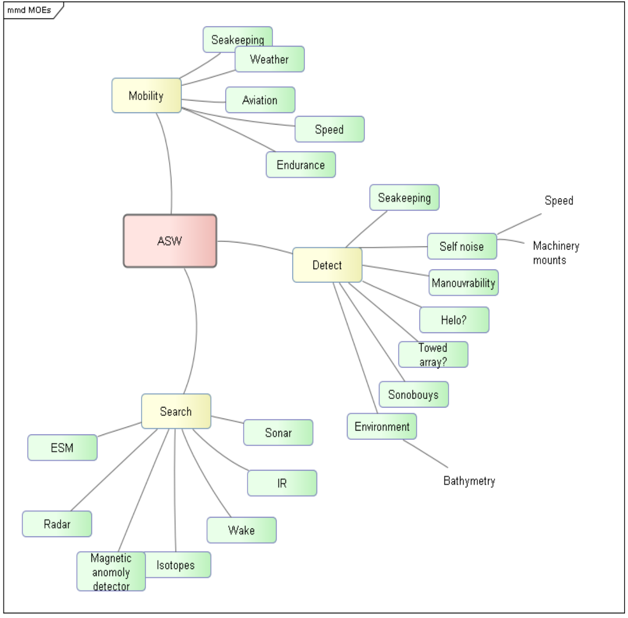


Figure 4: Mindmap used to capture aspects stakeholders considered important for each mission activity

Mobility Phase: MOP_M – Percent Time Operable

The platform's seakeeping performance was highlighted during the roundtable as an important aspect of the mobility stage of the ASW mission. A study of transit mission operational availability for a range of monohull surface warships was identified (Smith and ThomasIII 1990). Linear regression was used to generate a surrogate model from the simulations presented in the study. The regression based model (equation (1)) correlates well with the originating data (coefficient of determination, $R^2 = 0.76$).

$$MOP_M = PTO = 14.932 \ln (R_e) + 8.074 \qquad (1)$$

Where:

- MOP_M = Measure of Performance – Mobility
- PTO = Percent Time Operable (operational availability)
- R_e = Extended Bales Index

The Extended Bales Index (R_e) is a ranking factor of the estimation of the seakeeping performance of surface warships (Smith and ThomasIII 1990). The equation used to calculate the Extended Bales Index contains several ship design parameters that are useful in conceptual ship design. This provides a useful relationship between tangible ship design parameters and the mobility MOP.

Search Phase: MOP_S – Sweep Width

The method adopted to determine a relationship for the search activity MOP of the ASW mission was to review textbooks on naval operations analysis pertaining to ASW as this topic has been extensively studied in the OA domain and is well documented (Wagner, Mylander et al. 1999). Using several assumptions that were deemed suitable for a ROM analysis within conceptual design by the SMEs, including the use of passive sonar only and that the hostile submarine does not alter speed or course when approaching the barrier, the sweep width for a barrier patrol can be determined using equation (2) (Wagner, Mylander et al. 1999).

$$w = 2 \times \left(10^{FOM/k} \right) \qquad (2)$$

Where:

- w = Sweep width
- FOM = Figure of Merit
- k = Spherical spreading loss factor (i.e. the loss in sound wave intensity as it travels from its source)

It was anticipated that equation (2) can be linked to ship design parameters via the equation for FOM using parametric modelling of ship noise data. The equation for passive sonar FOM contains terms for the slope of self-noise radiated into the sea by the ASW ship versus ship speed, along with the ASW ship's search speed. These noise and speed aspects are related to ship design aspects such as hullform coefficients (for flow noise), the installation of engine isolating mounts (for machinery noise) and so on.

Significant effort was expended attempting to develop a parametric model relating several ship design parameters to the self-noise versus speed slope term in the FOM equation using data collected from a sensor in a shipping lane as part of a study covered in (McKenna, Ross et al. 2012). Unfortunately, the equation developed for the parametric model using linear regression of the data from the study in (McKenna, Ross et al. 2012) only yielded a R^2 value of 0.57. In order to expedite the testing assumptions were made for minimum, average and maximum self-noise slopes based on the data from the study in (McKenna, Ross et al. 2012) for cases where the ASW ship had either hull mounted or towed array sonar systems. If the ASW ship had an aviation capability to facilitate the use of dipping sonar, the (assumed) range of the dipping sonar was added to the sweep width calculated using (2).

Detect Phase: MOP_D – Probability of Detection

The method initially used to determine an equation for the detect phase MOP identified by the CISD SMEs in the roundtable was to consult naval OA textbooks. This was a suitable approach for the ASW mission due to it having been studied and reported on extensively. The probability of detection for a ship conducting a barrier patrol is given by (Wagner, Mylander et al. 1999) in equation (3):

$$P(D)_{Ship} = \frac{w}{l}\sqrt{1+\frac{v_{search}^2}{u^2}} \qquad (3)$$

Where:

- $P(D)$ = Probability of Detection
- w = Sweep width (calculated in (2))
- l = Barrier length
- v_{search} = ASW ship search speed
- u = Hostile submarine speed (constant in all cases)

It is worth noting that the MOP for the search phase (sweep width) is included in (3). This means that the link between the ship design parameters that govern the ship self-noise versus speed slope relationship to sweep width covered in the previous section, will also be carried through into the relationship for P (D). The statistical significance of these design parameters will be consequently influenced as they will be accounted for more than once in the overall mission MOE calculation. However, the decision was made to proceed with the analysis using separate equations for the search and detect ASW mission phases. These separate phases were identified by the acting stakeholders during the MOE/MOP formulation roundtable and adhering to the knowledge captured from the acting stakeholders was given precedence over analytical concerns. If the ASW ship has an aviation capability available for dipping sonar the P(D) can also be calculated from an equation given in (Wagner, Mylander et al. 1999) and added to the P(D) for the ship given by (3).

MOE versus Acquisition Cost

Obtaining a ROM estimate of the cost of a system that is linked to effectiveness as early in the system's lifecycle as possible in order to develop an understanding of the price of performance. Work undertaken by the US Congressional Budget Office (CBO) (Elmendorf 2010) presented the lifecycle costs for a range of US warships. Using parametric modelling and linear regression, a simple relationship between a monohull warship's full load displacement and procurement cost was identified (equation (4)). The regression equation has an R^2 value of 0.93.

$$PC = 0.1695 \times \Delta + 99.65 \qquad (4)$$

Where:

- PC = Procurement Cost (2010 US\$M)

- Δ = Full load displacement (tons)

It should be noted that cost estimation is not a focus of this research, however, it does highlight the need for subsequent research to incorporate all of the FICs into an MBSE methodology for performing conceptual design.

Development of a Simple Numerical Model

The desire to minimise the complexity of the numerical model, combined with the methodology making use of an MBSE approach, led to the selection of Solvea® and Microsoft Excel® as the basis of the numerical model for the ASW mission implementation. The general approach when utilising Solvea® for performing parametric execution within an MBSE environment consists of the following six steps (Intercax 2013):

1. Create a MBSE model
2. Create a structural model of the physical parameters to be used in the analysis
3. Define the constraints: the governing equations of the simulation
4. Create a parametric model
5. Create an instance
6. Solve the instance

The top-level view of the MBSE model that was built for the ASW mission, which utilises the part within the bold dark blue border of the underlying metamodel shown in Figure 1, is shown in Figure 5.

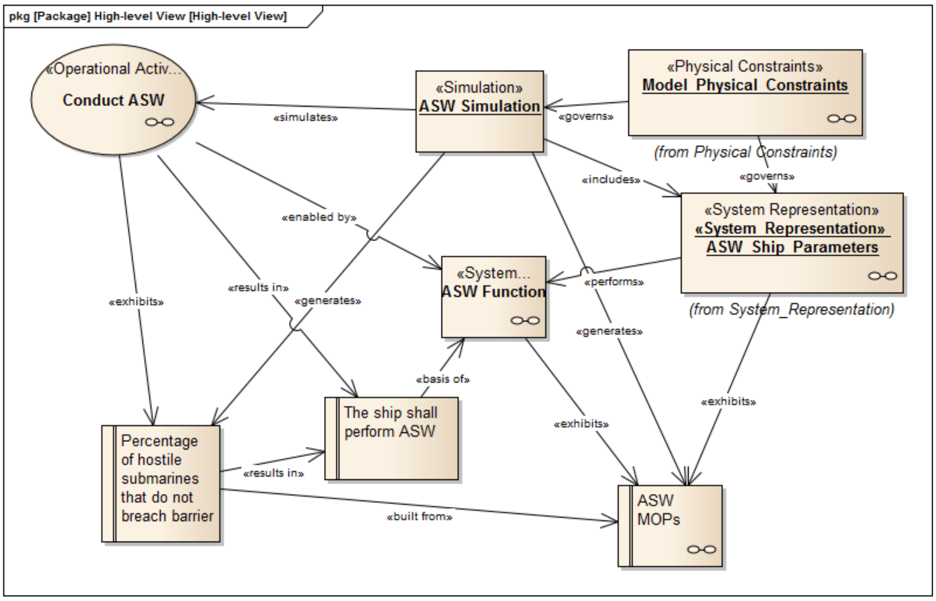
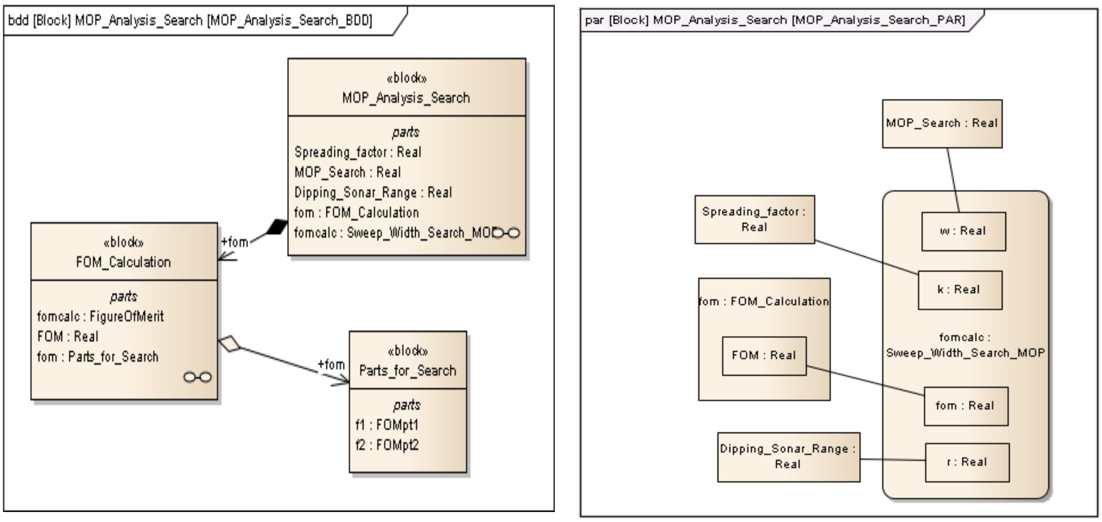


Figure 5: Top-level view of the MBSE model for the ASW mission

To illustrate the MBSE model that was developed in the ASW mission test implementation, some model views are given in Figure 6. The block definition diagram of the ASW ship parameters that are used in the calculation of the search phase MOP, sweep width (equation (2)), is shown in Figure 6(a). Figure 6(b) shows the parametric diagram for the search phase MOP calculation.



(a) (b)

Figure 6: Block definition (a) and parametric (b) diagrams of the MBSE model for the search phase MOP calculation of the ASW mission

The block definition diagram in Figure 6(a) shows how the simulation stereotype elements of the metamodel are structured for the search phase MOP analysis. From Figure 6(a), it can be seen that the MOP analysis element comprises parts used for sonar performance prediction (i.e. the parts appended with the “Real” value type). Figure 6(a) also shows the link between the MOP analysis element and the FOM calculation element that was calculated in separate parts due to the large number of terms in the equation. Figure 6(b) shows how the constraint (the fomcalc element) is linked to the various parts used in the calculation of the search phase MOP (sweep width) using equation (2).

The Solvea® software has the ability to import data from and export data to Microsoft Excel®. This prompted the decision to calculate the combined ASW mission MOE within Excel® using data exported from Solvea®, which also meant that the graphing capabilities of Excel® could be utilised to present the results of the experiments visually.

Conducting the Experiments/Simulations

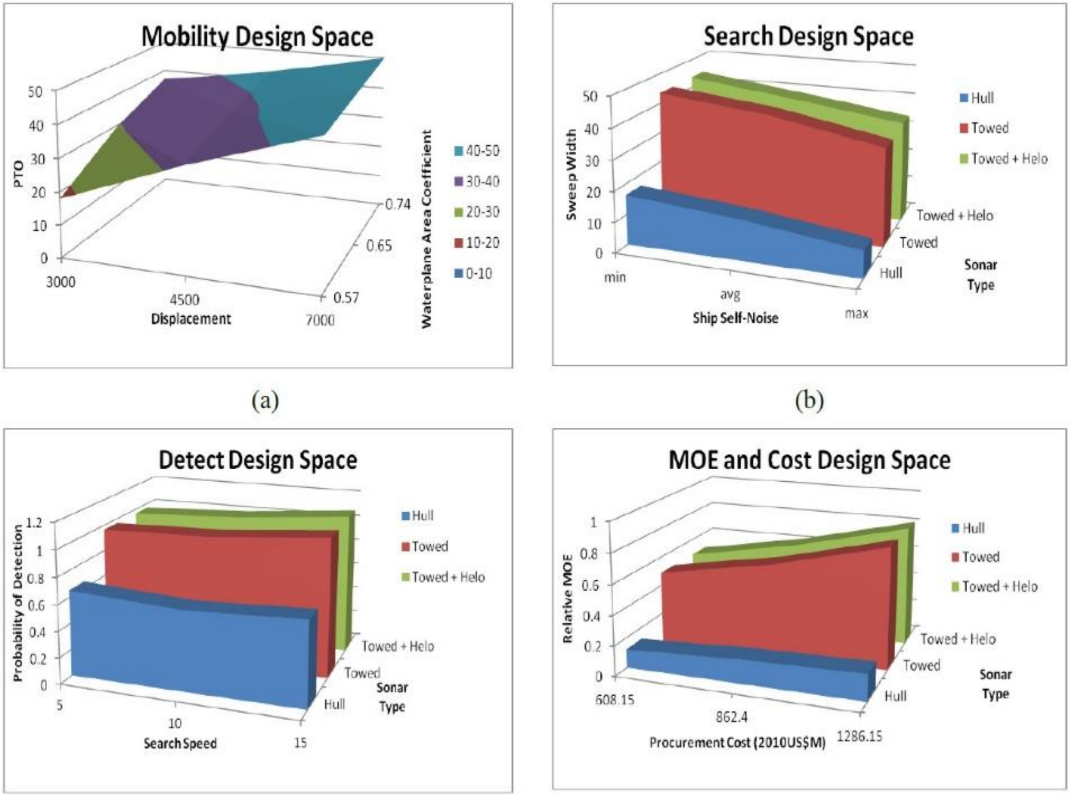
In the equations for linking ASW mission performance to ship design parameters there were 10 ship design parameters that can be varied to calculate the MOPs and, subsequently, the MOE. In order to create a realistic range of values for these 10 variables, which become the inputs for the experiments, ship particulars data was gathered from Jane’s Fighting Ships (Moore 1987) for ships that have been previously designed with ASW capabilities. Histograms of the ship design parameter data were plotted to determine the probability distributions of each parameter. Where design parameter information was not available (for example the hullform coefficients), ranges of values were identified from other analyses and a normal probability distribution assumed.

To avoid conducting the nearly 60000 simulations that would be required to conduct a three level full factorial experiment for the 10 ship design parameters (i.e. 3^{10}), DOE was utilised to conduct a screening experiment. A Taguchi L27 array was used to generate the input matrix for the screening experiment and the results analysed to determine the statistical significance of the design parameters in each phase of the ASW mission. The most statistically significant design parameters for the mobility phase of the mission were identified as the displacement and the hullform waterplane coefficient. The most statistically significant parameters for the search and detect phases, as well as for the overall mission, were the sonar type used by the ship and the ship's self-noise. This meant that significantly less than 60000 simulations would be needed to explore all combinations of the statistically significant design parameters.

For the experiment to develop the design space, Monte Carlo simulation was utilised and a 729 (i.e. a three level six parameter experiment) simulation experimental matrix was created in order to maintain a short simulation time. This number of simulations would also allow for a sufficient number of experiments for all possible statistically significant parameter combinations to be simulated.

Post-Processing the Results and Presenting the Conceptual Design Space

Statistical post-processing of the results of the ASW simulations was performed in Microsoft Excel®. In keeping with the methodology foundation of adhering to the principles of SBD, the graphing capabilities of Microsoft Excel® were utilised to generate charts for the different sets of relationships between the statistically significant ship design parameters and ASW mission performance. The graphs are in Figure 7.



(a) (b)

(c) (d)

Figure 7: Graphs of the analysis results showing the MOPs versus the significant ship design parameters for the mobility phase (a), search phase (b), detect phase (c) and the MOE versus procurement cost and sonar type (d)

Some points of note from Figure 7 regarding the links between ship design parameters and ASW mission performance that have been established via the methodology proposed in this paper include the considerable impact of the sonar type on performance. This is shown in Figure 7(b), (c) and (d) where the ships with towed array sonar and a towed array in combination with helicopter had significantly higher performance and effectiveness levels than the hull mounted sonar ships. Figure 7(b) highlights the influence that ship self-noise has on performance, since this parameter affects the performance of the installed sonar system. Figure 7(a) shows the positive impact that larger ship displacement has on the performance of the mobility phase of the ASW mission. This aspect of performance is carried though into Figure 7(d) where the MOE is higher for the more expensive ships, since procurement cost is a function of displacement (see equation (4)).

DISCUSSION

The MBSE methodology that was developed during the research appears to be useful for linking performance analysis and a naval ships physical design parameters during conceptual design activities. However, in order to ascertain the level of usefulness of the methodology, there is a clear need to test this methodology within an ADO acquisition project and in consultation with ADO in order to satisfy the conditions of the “market test” phase of the CRA approach (Piirainen and Gonzalez 2013). This phase will help determine whether the constructed methodology (which is the artefact) can be generalised and remain useful (Piirainen and Gonzalez 2013).

The use of parametric and surrogate modelling to generate equations linking design parameters to mission performance, suggests that the applicability of the MBSE methodology developed and presented in this paper may be broader than naval surface warships. This applicability could extend to other complex systems for which relationships between performance and physical design parameters can be established.

The amount of effort involved in developing the relationships between performance and design parameters can be significant; however, once a relationship is established and proven it can then be reused. Hence, the methodology facilitates the building of a “library” of missions and relationships between performance and design parameters that could be updated or modified and held in a repository in order to facilitate rapid design space exploration. This exploration could be useful perhaps even during strategic planning or needs phase activities.

It can be argued that the numerical model could have been entirely built using Microsoft Excel®, which was done in initial testing of the methodology. However, the use of MBSE parametric diagrams facilitates a modular approach to the analysis and an additional level of re-use. This means that if a more suitable equation is developed for a phase of the ASW mission, new block definition and parametric diagrams for the new equation, or module, could simply be imported into the MBSE model. Furthermore, the use of the MBSE environment also facilitates traceability for requirements development activities, since the underlying WSAF metamodel already contains these elements.

The method of presenting the results of the simulations graphically, as shown in Figure 7, is useful for highlighting the “knees”, or optimal combinations of design parameters for mission performance and effectiveness. Highlighting these aspects of performance and linking them to ship design via the methodology proposed in this paper will help to inform ADO acquisition project stakeholders during conceptual design activities.

A key benefit of the methodology uncovered during the ASW mission implementation was that ship design aspects, which are intuitive to an experienced naval architect (e.g. a larger ship having better seakeeping abilities, which leads to the ship being operationally available in a larger range of sea-states), can be demonstrated to non-naval architects with a degree of rigour.

The research covered in this paper is ongoing and along with the need to further test the MBSE methodology for conceptual design within an ADO acquisition project, future work will focus on incorporating other FIC elements. Other planned future work includes the introduction of other missions combined with an approach such as the Analytical Hierarchy Process to weight MOEs/MOPs, since naval vessels are typically designed for more than one mission. Also, it would be useful to have design feasibility checking performed during the experimental step of the methodology, as it could be possible to generate a combination of design parameters that is infeasible in reality. During the simplified ASW mission implementation, a rudimentary feasibility check was performed by linking combinations of design parameters.

CONCLUSIONS

This paper presented an MBSE methodology that was developed as a starting point for ongoing research into an approach for conducting ADO naval ship conceptual design in an integrated environment. The methodology presented focused on linking the major system's mission performance, to sets of physical design parameters, in order to provide stakeholders with a ROM view of a potential design space for the capability being developed. This view could aid stakeholder decision making during conceptual design activities.

The use of an integrated MBSE environment appears to facilitate reuse of the analytical steps of the methodology process, along with providing a means of establishing traceability between requirements, functional, physical and analysis domains during conceptual design.

ACKNOWLEDGEMENTS

The author would like to acknowledge: Dr. Colen Kennell for being a sounding board and providing the costing material used in this research, NREIP interns Turner Meeks and Scott McHenry for their work in helping to demonstrate that the methodology was useful during the testing phase of the research and developing the Excel tools utilised in this paper. The author is would also like to acknowledge LCDR Robert D'Eon (RCN) and David Ruley for their ASW insights. Finally, the author would like to acknowledge the Maritime Division of DSTO, who supported the research that was undertaken while the author was on a Defence Science Fellowship at NSWCCD.

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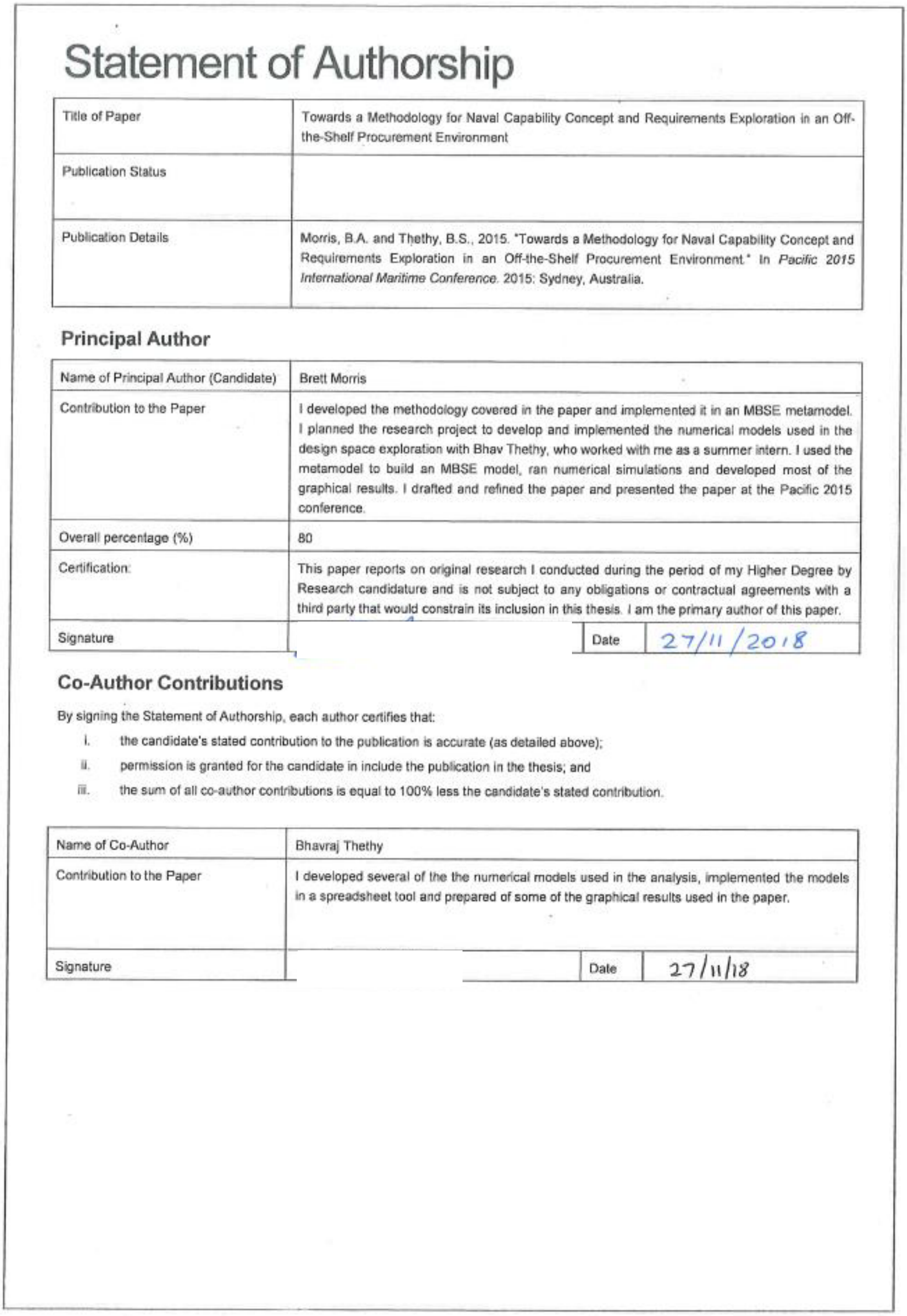
BIOGRAPHY

Brett Morris is a Naval Architect/Systems Engineer who joined DSTO in 2007. He has previously worked for the RAN in the Directorate of Navy Platform Systems and is interested in the fields of Naval ship concept design, structures and hydrodynamics, along with Systems Engineering applications to Naval Architecture. Brett has a Grad. Dip. in Systems Engineering, a BE (Nav. Arch.) and is currently undertaking part-time research towards a PhD.

Appendix C: Towards a Methodology for Naval Capability Concept and Requirements Exploration in an Off-the-Shelf Procurement Environment



Statement of Authorship

Title of Paper	Towards a Methodology for Naval Capability Concept and Requirements Exploration in an Off-the-Shelf Procurement Environment
Publication Status	
Publication Details	Morris, B.A. and Thethy, B.S., 2015. "Towards a Methodology for Naval Capability Concept and Requirements Exploration in an Off-the-Shelf Procurement Environment." In *Pacific 2015 International Maritime Conference*. 2015: Sydney, Australia.

Principal Author

Name of Principal Author (Candidate)	Brett Morris		
Contribution to the Paper	I developed the methodology covered in the paper and implemented it in an MBSE metamodel. I planned the research project to develop and implemented the numerical models used in the design space exploration with Bhav Thethy, who worked with me as a summer intern. I used the metamodel to build an MBSE model, ran numerical simulations and developed most of the graphical results. I drafted and refined the paper and presented the paper at the Pacific 2015 conference.		
Overall percentage (%)	80		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	27/11/2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Bhavraj Thethy		
Contribution to the Paper	I developed several of the the numerical models used in the analysis, implemented the models in a spreadsheet tool and prepared of some of the graphical results used in the paper.		
Signature		Date	27/11/18

Towards a Methodology for Naval Capability Concept and Requirements Exploration in an Off-the-Shelf Procurement Environment

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ABSTRACT

Royal Australian Navy platforms, along with their associated Fundamental Inputs to Capability (FIC), provide Defence with the ability to achieve a desired operational effect. When an existing or future operational effect is identified and cannot be achieved, a “capability gap”, or user need exists. In response, Defence commences a capability development process underpinned by the “Capability Systems Life Cycle” (CSLC).

Recently, there has been a focus on developing Royal Australian Navy capability using an “Off-The-Shelf” (OTS) procurement strategy. The perceived benefits of this strategy include the reduction of cost and schedule risks, typically gained through stakeholders trading-off the capability’s operational needs. Consequently, a capability will be acquired that addresses the originating capability gap to varying degrees.

Concept and Requirements Exploration (C&RE) methods provide a means for capability development stakeholders to explore a rough order of magnitude design space as they undertake capability trade-offs. This design space can link design parameters (such as ship length, displacement and crew numbers) to operational performance, thereby providing stakeholders with more information on which to base trade-off decisions. The Maritime Division of the Defence Science and Technology (DST) Group is constructing a C&RE methodology specifically for OTS procurement environments to assist stakeholders performing capability trade-offs early in the CSLC. This paper describes refinements to part of the methodology being constructed with an emphasis on the use of parametric and surrogate models to link capability design parameters to performance for all FIC. A test implementation of the methodology for an indicative patrol vessel capability is covered, along with a discussion on the utility of the methodology. Finally, suggestions for further research are proposed.

INTRODUCTION

In the Australian Defence Organisation (ADO) context, capability is defined as the “ability to achieve an operational effect” that is “provided by a ‘system’ of interlocking and interdependent Fundamental Inputs to Capability (FIC)” [1]. The FIC are shown in Figure 1. When an existing or future operational effect is identified and cannot be achieved, a "capability gap", or user need exists. In response, Defence commences a capability development process underpinned by the "Capability Systems Life Cycle" (CSLC).

Figure 1: ADO Fundamental Inputs to Capability. Colours correspond to the FIC in Figure 3.

Recently, there has been a focus on developing Royal Australian Navy (RAN) capability, particularly the major system FIC, using an "Off-The-Shelf" (OTS) procurement strategy [2]. The perceived benefits of this strategy include the reduction of cost and schedule risks, typically gained through stakeholders trading-off the capability's operational needs during requirements development. Consequently, a capability option will be acquired that may not meet the user's operational needs, may not integrate with other in-service capabilities and may not suit the local geographic and strategic circumstances [3].

DST Group is undertaking research to construct a naval vessel Concept and Requirements Exploration (C&RE) methodology for use within an OTS procurement environment. In contrast to a developmental procurement environment, an OTS procurement environment imposes constraints on the major system FIC from the outset [4]. The intent of the C&RE methodology is to help inform stakeholders performing requirements development and operational need trade-offs, of risks associated with the OTS constraint. Having this information during requirements development could assist procurement stakeholders in early assessment of the feasibility of addressing a capability gap with exemplar OTS solutions. This feasibility assessment could be used to trade-off operational needs accordingly to reduce capability risk, and develop a set of requirements that can be feasibly satisfied by OTS solutions. Otherwise, it could form the basis of a case for pursuing a developmental procurement strategy instead.

In terms of the ADO CSLC, requirements development and operational need trade-offs will be undertaken during the late needs and early requirements phases [1]. In general system development terms, these activities are performed during conceptual design [5]. The significance of conceptual design is highlighted by multiple researchers, with a succinct summary given by: "one of the most influencing factors determining the success and longevity of any developed system is the quality of its underlying conceptual design" [6].

This paper builds on the research previously described by Morris [7] by further refining and testing the analysis domain within the C&RE methodology being constructed. In the previous research, the C&RE methodology was constructed based on a Model-Based Systems Engineering (MBSE) metamodel comprising requirements, operational behaviour and analysis domains. The output of the C&RE methodology is a rough order of magnitude (ROM) design space that links capability Measures of Performance (MOPs) to ship design parameters. The ROM design space was shown to assist in highlighting optimal combinations of design parameters and how these could inform requirements development [7].

The refinements covered in this paper focus on incorporating FIC other than the major system into the analysis domain of the C&RE methodology and methods of presenting the information within the ROM design space. Testing of the C&RE methodology is undertaken through application of the C&RE methodology to the conceptual design of a Patrol Vessel capability. The paper concludes with a discussion on some of the key aspects uncovered during the testing, along with suggestions for further research.

BACKGOUND

Naval Vessel Conceptual Design and C&RE

Within developmental procurement environments, C&RE and requirements elucidation have been used to describe the activities performed in the conceptual design of naval vessels (see Brown [8] and Andrews [9]). In general system development terms, Pahl and Beitz [10] describe at a high-level the activities within conceptual design as:

- Collecting the information about the requirements to be embodied in the solution, along with information about the constraints.
- Establishment of functional structures and a search for suitable system principles and their combination into concept variants.

For naval vessel conceptual design, Brown states: “C&RE responds to a stated mission need with an early high-level assessment of a broad range of ship design options and technologies” [8]. A recent feature of naval vessel C&RE methodologies is linked operational and ship synthesis (architecture) models (see for example, [11], [12] and [13]).

Another recent feature in the literature covering naval vessel conceptual design, particularly amongst US researchers is the emergence of Set-Based Design (SBD). The features of the SBD design process have been identified as [14]:

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.

The C&RE methodologies highlighted in this section are typically focused on exploring optimal concept designs for the operational missions the vessel will perform and ensuring the emergent requirements are “elucidated” [15]. In a developmental procurement environment, these optimal designs can be developed further to address any capability shortcomings and translated into preliminary, then eventually final designs.

A Methodology for C&RE in an Off-the-Shelf Procurement Environment

The key difference between OTS and developmental procurement environments, alluded to in the introductory section, is the need for stakeholders to have an early understanding of the capability, technical and other risks imposed by the OTS constraint. Early in the CSLC, procurement information on which to develop this understanding of these risks is sparse. Another difference, is that OTS acquirers, such as the ADO typically lack the resources, both in terms of personnel and access to numerical prediction tools, to perform rigorous, high fidelity modelling during conceptual design. These two aspects highlight key drivers of the research presented in this paper. That is; the importance of early understanding of capability, technical and other risks, along with insights into issues surrounding fitness-for-purpose is increased in OTS procurements. When combined with a lack of resources in OTS procurement environments, there is a need to construct a lean C&RE methodology that can be implemented using a minimal set of operational needs.

In constructing a methodology for C&RE within an OTS procurement environment, it is pertinent to include the two recent features from developmental procurement environments described in the previous section. Particularly useful, will be linked operational and ship architecture models. This linkage facilitates development of a design space that illustrates the influence of ship design parameters on mission performance. However, the approaches covered in the previous section have been described as labour intensive [7]. This is mainly due to the need to build and execute relatively complex operational and ship architecture models, which both require significant effort and software resources [16].

The first iteration of the C&RE methodology for an OTS procurement environment constructed by Morris [7], avoided the need to use complex ship operational models. This was achieved by applying the techniques of parametric and surrogate modelling to the operational models, along with applying SBD principles to ship architecture modelling. Parametric modelling can be used for making initial estimates of system design parameters [17]. The estimates are based upon relationships between design parameters that are typically generated using linear regression from the historical data of similar systems [18]. Surrogate modelling techniques take the results of a set of simulations across a design space and constructs an approximate relationship between design parameters and responses [19]. This negates the need to construct a model and perform the simulations, provided that a suitable set of analysis results can be found.

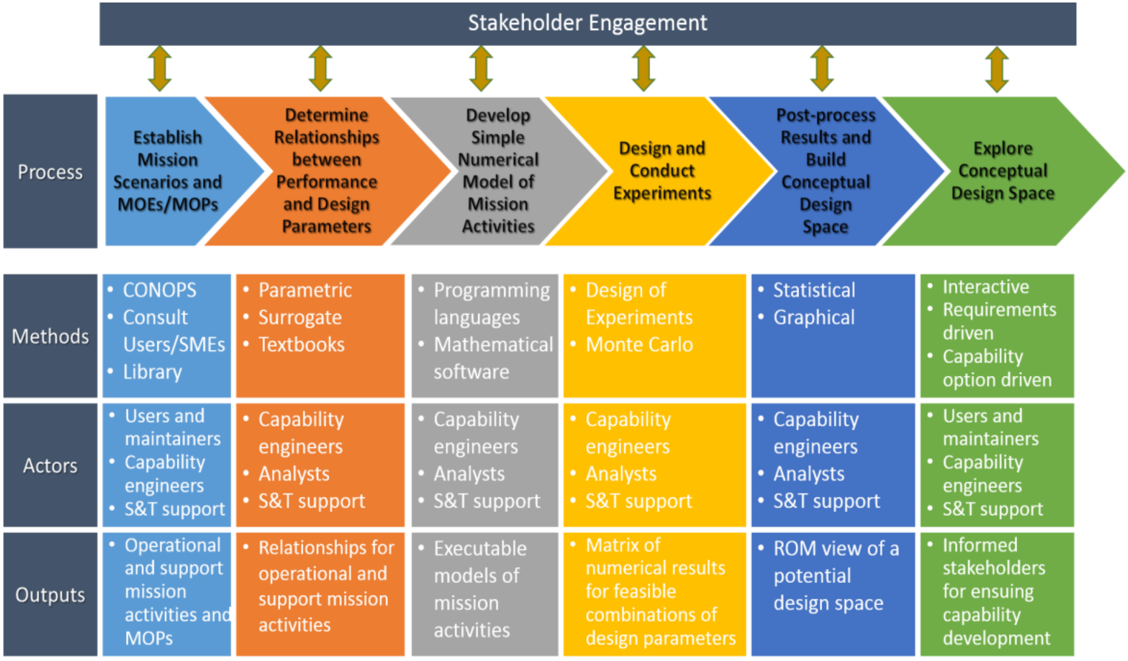
Both parametric and surrogate modelling are well suited to conceptual design since the relationships between design parameters and responses (performance) facilitate an understanding of the design problem [19]. Nonetheless, there are uncertainties associated with the use of parametric and surrogate models due to the curve fitting techniques used to approximate relationships between large amounts of data. The authors contend that the level of uncertainty associated with these techniques, is acceptable during conceptual design in an OTS procurement environment, provided appropriate boundaries of applicability are set.

The application of SBD principles provides a means of presenting sets of ship design parameters to build a conceptual design space. This requires less effort to implement than the C&RE methodologies referenced in the previous section, which utilise ship architecture models to synthesise multiple single point conceptual designs.

Refining the C&RE Methodology for an OTS Procurement Environment

The major refinement to the C&RE methodology constructed by Morris in [7], is the inclusion of a support scenario and the establishment of MOPs for the scenario activities. A support scenario represents the activities that need to be performed by FIC other than the major system to deliver the desired operational effect of the capability. The support scenario and MOPs could be generated using the same methods as for the operational scenario and are shown in Figure 2.

The other refinements to the methodology are primarily associated with the methods of presenting the ROM design space output from the C&RE methodology. These refinements have come about from the lessons learned during the first test implementation for a highly simplified Anti-Submarine Warfare scenario covered in [7]. The refined methodology, where the definition of a methodology given by Estefan [20] is used (i.e. "*a collection of related processes, methods and tools*" where the process describes *what* is done, the method defines *how* it will be done and the *tool* facilitates the method), is shown in Figure 2.



Stakeholder Engagement

Process	Establish Mission Scenarios and MOEs/MOPs	Determine Relationships between Performance and Design Parameters	Develop Simple Numerical Model of Mission Activities	Design and Conduct Experiments	Post-process Results and Build Conceptual Design Space	Explore Conceptual Design Space
Methods	• CONOPS • Consult Users/SMEs • Library	• Parametric • Surrogate • Textbooks	• Programming languages • Mathematical software	• Design of Experiments • Monte Carlo	• Statistical • Graphical	• Interactive • Requirements driven • Capability option driven
Actors	• Users and maintainers • Capability engineers • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Capability engineers • Analysts • S&T support	• Users and maintainers • Capability engineers • S&T support
Outputs	• Operational and support mission activities and MOPs	• Relationships for operational and support mission activities	• Executable models of mission activities	• Matrix of numerical results for feasible combinations of design parameters	• ROM view of a potential design space	• Informed stakeholders for ensuing capability development

Figure 2: Summary of the refined C&RE methodology for an OTS procurement environment

Figure 2 shows the process, methods, actors and outputs from each step in the process of the refined C&RE methodology. For a more detailed description of the methodology foundations see the earlier research covered in Morris [7].

TESTING THE REFINED METHODOLOGY

Testing of the refined C&RE methodology was performed by implementing it for an indicative Patrol Vessel capability. The test implementation was conducted using a

Concept of Operations (CONOPS) for a United States Coast Guard (USCG) Medium Security Cutter (MSC) [21] as a key reference for mission scenarios. The USCG MSC CONOPS [21] contained five operational scenarios and four support scenarios. The five operational scenarios and four support scenarios are given in Table 1.

A CONOPS typically describes the way a system will work from the operator's perspective and includes the user needs [4]. In the ADO context, the similar information to that contained in the USCG MSC CONOPS would be contained in an Operational Concept Document (OCD).

Table 1: Operational and support scenarios from the USCG MSC CONOPS. Note that scenarios are given in order of precedence

Operational Scenarios	Support Scenarios
Drug interdiction	In port
Living marine resources protection	Underway
Alien migration interdiction operations	Deployment port call
Port, waterways & coastal security	Dry-dock/dockside
Defence readiness	

In undertaking testing of the refined C&RE methodology, several assumptions regarding the platform to be procured were made to simplify the analysis. Firstly, a monohull displacement/semi-displacement hullform was assumed and the main machinery was assumed to be high-speed marine diesels. The patrol vessel was assumed to be of low-end warfighting capability, which restricted the weapon type to a gun (i.e. no missiles) with a maximum range of 15.5 kilometres.

Establish Mission Scenarios and MOPs

The first step in the refined C&RE 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. These scenarios were initially developed using the five operational and four support USCG MSC CONOPS [21]. As a form of peer review, the initial scenarios were reviewed in a workshop with DST Group staff experienced in naval platform capability development. The workshop attendees agreed that the missions were representative of a typical Patrol Vessel and MOPs for most of the mission activities were elicited.

Following the workshop, the five operational scenarios and four support scenario contained in the USCG MSC CONOPS [21] were distilled into a single indicative combined operational and support scenario. This decision was made due to significant commonality within the scenario activities across the operational and support missions. The single indicative scenario comprised the most common mission activities, along with the most onerous activities in terms of warfighting capability, for example destroying the target of interest. The authors note there is a need for further research into rigorous methods of developing a single indicative scenario. The distilled mission is shown in Figure 3.

Figure 3 shows that the majority of mission activities are performed by the major system FIC. This will be useful for the C&RE methodology, since this is arguably the most important FIC for the end user stakeholders during early lifecycle phases [7]. However, it can also be seen that several activities encompass other FIC and there are overarching FIC that enable all of the scenario activities (e.g. personnel and finance). The MOPs that were identified by workshop attendees for the major system FIC indicative mission activities are given in Table 2. Note that the mission activities are grouped by MOP rather than sequence in Table 2.

Table 2 shows that several activities that share the same MOP, which resulted in six MOPs for the mission activities performed by the major system FIC. The activities from the indicative mission performed by the remaining FIC and the MOPs that could be linked to design parameters are presented in Table 3 for each activity.

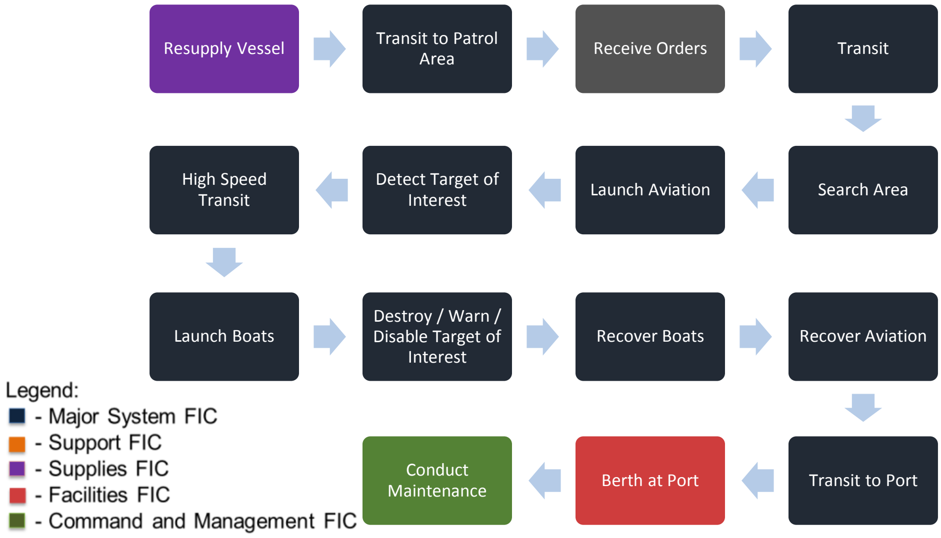


Figure 3: Distilled and combined indicative mission for the USCG MSC CONOPS. Other FICs that apply to all scenario activities above include the Organisation FIC, Finance FIC and Personnel FIC

Table 2: Major system FIC mission activities and their associated MOPs

Major System FIC Mission Activities	Measure of Performance (MOP)
Transit to patrol area	Endurance time
Transit	
Transit to port	
Search area of operation	Sweep rate
Detect target of interest	Probability of detection (PoD)
High speed transit	Sprint speed
Launch boats	Percent time operable (PTO) in Sea-State 5
Launch aviation	
Recover boats	
Recover aviation	
Destroy target of interest	Maximum weapon range

Table 3: Remaining FIC indicative mission scenario activities, MOPs and FIC responsible

Other FIC Mission Activities	Measure of Performance	FIC
Resupply Patrol Vessel	Supplies required	Supplies
Receive orders	No MOP developed	Command & Management
Berth at port	No MOP developed	Facilities
Conduct maintenance	Support cost	Support
Provide finance	Annual lifecycle cost	Finance
Provide crew	Personnel cost	Personnel

Relationships between MOPs and Design Parameters

The next step in C&RE methodology is to develop relationships between the MOPs for each of the activities in the indicative mission scenario and FIC design parameters. As indicated by Morris [7] "this is the critical step in the C&RE process that allows mission performance and an early conceptual design space to be linked". Two methods of developing relationships between mission performance and design parameters are recommended by Morris, parametric and surrogate models [7]. For the USCG MSC indicative mission, both of these methods were utilised.

The relationships between the MOPs for each mission activity and design parameters, along with their type and correlation coefficient, are given in Table 4. Where the relationship was sourced from a textbook or standard, the reference is given in square brackets.

Table 4: Summary of relationships between mission activity MOPs and design parameters

MOP (units)	Relationship	Type (R^2)
Endurance Time (hours)	$ET = 154.35 \left(\frac{V_{endurance}}{\sqrt{L}}\right)^{-2.054}$	Continuous Parametric (84%)
Sprint speed (knots)	$5.045 \frac{\Delta V_{max}}{P_p} - 1.9288 \exp\left(0.8324 * \frac{\sqrt{gL}}{V_{max}}\right) = 0$	Continuous Parametric (67%)
Percent time operable in Sea-State 5 (%)	$PTO = 18.962 \ln(\Delta) - 40.043$	Continuous Surrogate (78%)
Sweep rate km^2/hour	$SR = r * V_{endurance}$	Discrete Textbook [22]
Probability of detection	$POD = 1 - \exp(\frac{7200\, r\, V_{endurance}}{10^8})$	Discrete Textbook [22]
Max weapon range (m)	$Weapon\ Range = 0.0006\, L^{4.1133}$ (max=15.5km)	Continuous Parametric (88%)
Supplies required (tonnes)	$Supplies = 216.9 * (0.8276\, L - 6.9488) + 3.28 * L * ET$	Continuous Parametric (71%) & standard [23]

Personnel cost (2010US$M)	$Personnel\ Cost = 0.1068\Delta - 23.191$	Continuous Parametric (93%)
Support cost (2010US$M)	$Support\ Cost = 0.4514\ \Delta^{0.7186}$	Continuous Parametric (89%)
Annual lifecycle cost (2010US$M)	$Annual\ LCC = 0.1221\Delta^{0.7288}$	Continuous Parametric (99%)

For the relationships shown in Table 4, the design parameters, or variables are defined as:

$V_{endurance}$ = Endurance Speed (knots)
L = Length (m)
r = Sensor Range (m)
Δ = Displacement (full load) (tonnes)
V_{max} = Sprint Speed (knots)
P_p = Propulsive Power (kW)
g = Gravitational Constant (9.81 m/s^2)

It is worth noting that this step in the C&RE process requires significant effort and was the most time consuming step.

Numerical Model of Mission

For this implementation of the C&RE methodology, a simple numerical model of the mission activities was initially built using Microsoft Excel®. Subsequently, numerical models of the mission activities were built using Wolfram *Mathematica*®, which were integrated using Phoenix Integration's ModelCenter®. This approach was taken in order to utilise the data processing and visualisation tools available in ModelCenter®.

Design and Conduct of Experiments

This step of the C&RE 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 MOPs. For the relationships shown in Table 4, there are six design parameters, or variables that can be varied to calculate the MOPs for the mission activities. When there are more than five variables for an experiment, Schmidt and Launsby [24] recommend splitting the experiment into two parts: screening and modelling experiments. This approach was adopted for the USCG MSC mission.

A screening experiment examines a number of variables and produces a quantitative understanding of their effect on the result of the experiments [12]. A two-level factorial design (i.e. minimum and maximum value of each variable) was used for the screening experiment. The results identified the statistical significance of the design parameters, and highlighted the need to account for infeasible combinations of design parameters. Infeasible combinations included:

- Maximum propulsive power + minimum displacement or minimum length
- Minimum propulsive power + maximum displacement or maximum length
- Minimum displacement + maximum length/maximum displacement + minimum length

Initial considerations for the modelling experiment's design included using response surface methods, such as Central Composite or Box-Behnken designs to increase the efficiency of the calculations [24]. However, this approach was abandoned when the feasibility checks were likely to remove significant numbers of experiment near the minimum values of several design parameters. Subsequently, "space filling" designs (full factorial and Monte-Carlo designs), with infeasible regions calculated from the infeasible combinations above, were used for the modelling experiment.

Post-Processing and Building the ROM Design Space

Post-processing of the results from the modelling experiment for the patrol vessel test implementation was conducted using the statistical and graphical methods available in both Microsoft Excel® and the ModelCenter® software.

In terms of building the design space that links mission performance to design parameters for exploration by stakeholders, Hootman [25] describes a prediction profiler as "not the most elegant method of presenting information, but it is one of the most informative ones". ModelCenter® has the capability to produce these views of the design space, where the prediction profiler provides a matrix of graphs of the design variables versus the MOPs. The slope of the lines in the graphs represents the change in effect the design variable has on the MOP. A horizontal line implies the design parameter does not affect an MOP, whilst a steep slope means that the design parameter has a significant effect on the MOP. Prediction profilers of the ROM design space generated from a 1000 experiment Monte Carlo design are shown in Figure 4, for the major system FIC and the remaining FIC are shown in Figure 5. In the figures, the design parameters are on the horizontal axes, the MOPs are on the vertical axes and the hatched regions represent regions of infeasible designs.

Exploring the Design Space

The ROM design spaces shown in Figure 4 and Figure 5 provide several aspects that would be informative for stakeholders early in the CSLC. These include the positive influence of having a UAV available for the sweep rate and probability of detection MOPs shown in Figure 4. Also noteworthy from Figure 4, is the impact that the size of the vessel has on the PTO in sea-state 5 MOP (see the graph of PTO vs. displacement). However, this also highlights limitations of the C&RE methodology associated with using parametric and surrogate models. The infeasible region cuts off the PTO at a displacement around 1000 tonnes, whilst the relationship was generated using vessels up to roughly 1400 tonnes. The 1400 tonne vessel had a PTO in sea-state 5 of ~90%, but the curve fitting technique used (linear regression) could not reflect this at the upper end of the design space (despite the relationship having a correlation coefficient of 78%). Furthermore, the PTO MOP in Figure 4 appears to only be a function of displacement, with all other design parameters having horizontal lines. Again, this is a reflection of the parametric model used, which was only a function of displacement. Whilst generally in ship design, a ship with higher displacement will also be longer, therefore both length and displacement will affect PTO, this isn't captured in Figure 4. As with any numerical analysis, these limitations suggest that stakeholders need to interpret the design space using their experience, rather than base decisions solely on the results.

While bearing in mind the limitations, the design space does appear to provide useful insights in terms of capability, technical an integration risks associated with the patrol vessel capability. Firstly, a capability risk associated with smaller vessels (in terms of length and displacement) is highlighted with the endurance time, PTO and weapon range MOPs. This risk could be treated by specifying a minimum size vessel requirement, or a requirement of a minimum PTO. Secondly, technical and integration risks can be informed by the design space. If a UAV is specified due to the improved performance in the search and detect activities, technical risks may include the use of UAV in a maritime environment and integration risks are associated with launch, recovery, control, stowage and maintenance of a UAV from on board a patrol vessel.

Figure 5 shows the influence that the size of the vessel has on the costs associated with procuring and maintaining the vessel. This indicates that the design space could be useful for informing stakeholders when trading-off a requirement for the PTO in a given sea-state, as a larger vessel will be more capable, yet also cost more to procure and maintain.

An unintended use of the design space emerged when presented in the prediction profiler format is that data from exemplar vessel designs can be overlaid on the plots to inform questions that a procuring agency could ask tenderers. For example, if the main characteristics for an indicative patrol vessel design (taken from a designer’s brochure) given in Table 5 are overlaid on the design space shown in Figure 4 and Figure 5, interesting features related to the designer’s endurance time arises.

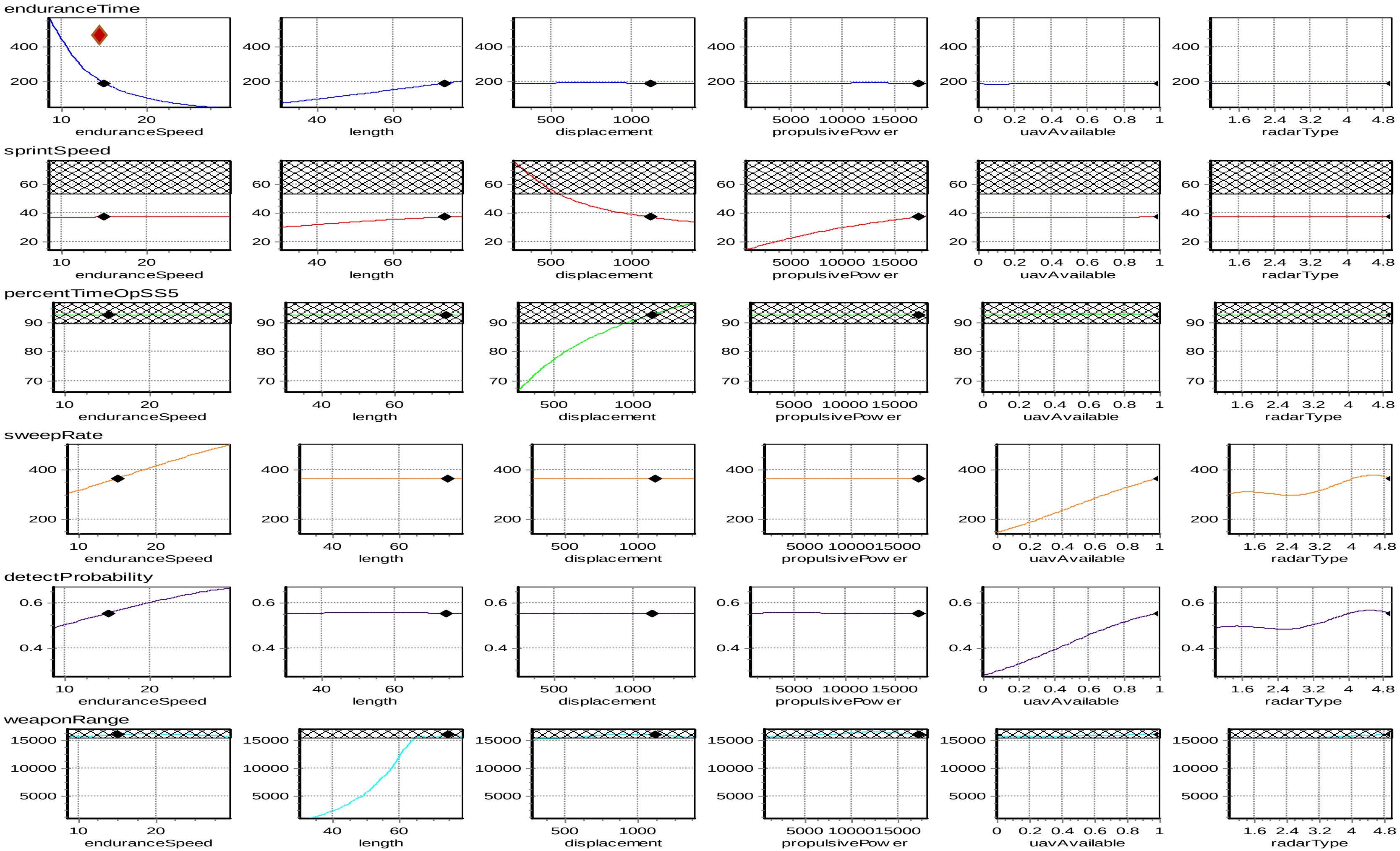


Figure 4: Design space for the major system FIC with the hatched regions indicating infeasible regions in the design space. The indicative design results are shown by the black diamonds. The red diamond in the ET vs. enduranceSpeed graph (top left graph) is the value of ET from the designer's brochure.

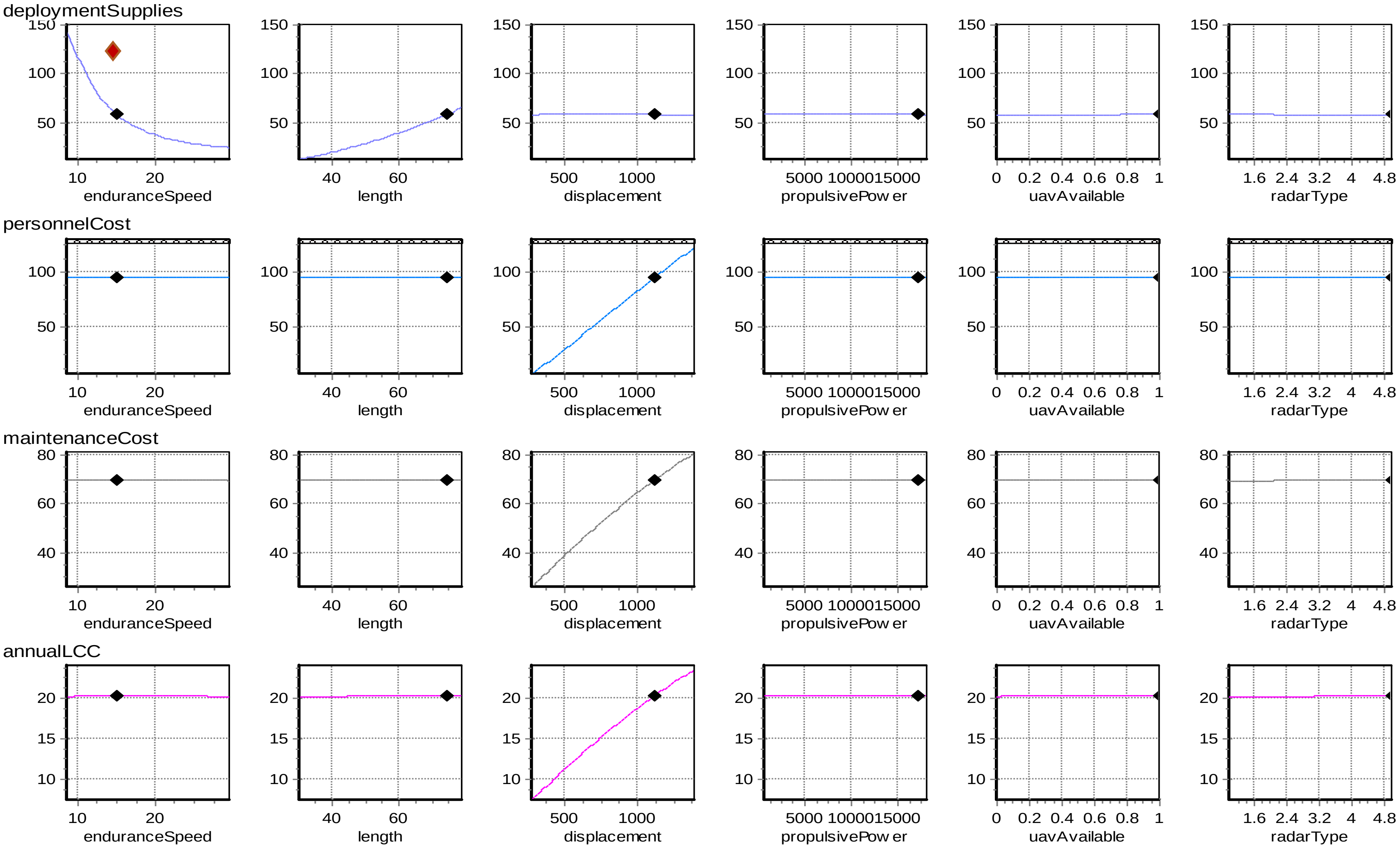


Figure 5: Remaining FIC design space with the infeasible regions indicated by the hatched regions. The indicative design is shown by the black diamonds. The red diamond in the deploymentSupplies vs. enduranceSpeed graph (bottom left graph) is the value of deploymentSupplies if the ET from the designer's brochure is used in the calculation.

In the top left graph of Figure 4, the indicative design's endurance speed and endurance time are indicated by the red diamond. This highlights a difference between historical ship design data, and the values claimed by the designer. The difference suggests that if the indicative design is to have an endurance time of 21 days, then perhaps the endurance speed will be closer to 8 knots, rather than the 15 knots claimed. Reiterating this point is the bottom left graph of Figure 5, where the red diamond generated using the design's data, sits well above the curve. This information could be used by stakeholders to seek clarifications, or further information on the methods used to calculate the endurance time from the designer.

Table 5: Particulars for an indicative patrol vessel design.

Main Characteristics (units)	Indicative Design
Length OA (m)	74.0
Beam (m)	10.9
Draft (m)	3.25
Sprint Speed (knots)	27
Endurance Speed (knots)	15
Range (nautical miles)	2000
Endurance Time (days)	21
Propulsion Power (kW)	17200
UAV Available	Yes
Radar Type	5 (high end S-band)
Crew	36

It is important to note that these aspects discussed here are only valid for the particular model developed in the test implementation. If the mission scenario activities are changed, or different relationships are used, then the inferences that can be made from the results are likely to change. However, some of the general trends (e.g. a larger monohull vessel will have a higher PTO than a smaller monohull vessel) will hold.

FUTURE RESEARCH

Linking Requirements to the Design Space

Morris [7] demonstrated how the first iteration of the C&RE methodology for an OTS procurement environment can integrate system and performance models within an MBSE environment using an appropriate metamodel. This integration facilitates the linkage of the conceptual design space and system requirements model. Work is currently being undertaken to integrate the research covered in this paper into an MBSE model, with the aim of alleviating issues that arose during the first implementation of the C&RE methodology.

Incorporate Uncertainty into the ROM Design Space

This suggestion for further research is related to the uncertainty introduced to the ROM design space through the use of parametric and surrogate models. As discussed previously, the surrogate relationship between PTO in sea-state five and displacement did not accurately reflect the simulation results at the upper end of the design space.

This could perhaps be addressed in part through the use of design lanes, or margins of error within the design space. In the interim, stakeholders experienced in naval vessel design could assist in interpreting the ROM design space with respect to uncertainty.

Further Investigate C&RE Methodology Utility

While the information provided by the ROM design space generated using the C&RE methodology presented in this paper appears to be useful, the authors suggest that the utility of the work would be better assessed using real OTS procurement projects. This could be done by applying the C&RE methodology to a current procurement project in its conceptual design phase and surveying stakeholders on their views at a later stage of the CSLC. Otherwise, the C&RE methodology could be applied to a previous OTS procurement, to investigate whether it was capable of identifying any procurement issues that have arisen with hindsight.

CONCLUSIONS

This paper presented a refined C&RE methodology for an OTS procurement environment that built upon previous research. The refinements covered in the paper focused on incorporating the non-major system FIC into the analysis domain of the C&RE methodology and methods of presenting a view of the ROM design space. Testing of the refined C&RE methodology was performed by implementing it for an indicative patrol vessel capability.

Testing indicated the C&RE methodology appears to be useful as a means of providing OTS procurement stakeholders with a ROM a design space that links mission performance to design parameters. This ROM design space can be used by stakeholders to identify risks associated with the OTS constraint and inform requirement trade-off decisions, such as the requirement for seakeeping ability against procurement and through-life costs. The ROM design space also provides stakeholders with a means of comparing design data for potential OTS capability options, with trends generated from historical design data. In the test implementation, vessel characteristics from an OTS design were overlaid on the design space, with a point of interest identified regarding the endurance time given by the designer.

Although limitations are introduced to the C&RE methodology through parametric and surrogate modelling, the methodology does meet its goal of providing stakeholders with information to identify risks and inform requirements development, early in the CSLC, using a minimal set of operational needs. Research is underway to further refine the methodology by developing methods of linking requirements to the ROM design space.

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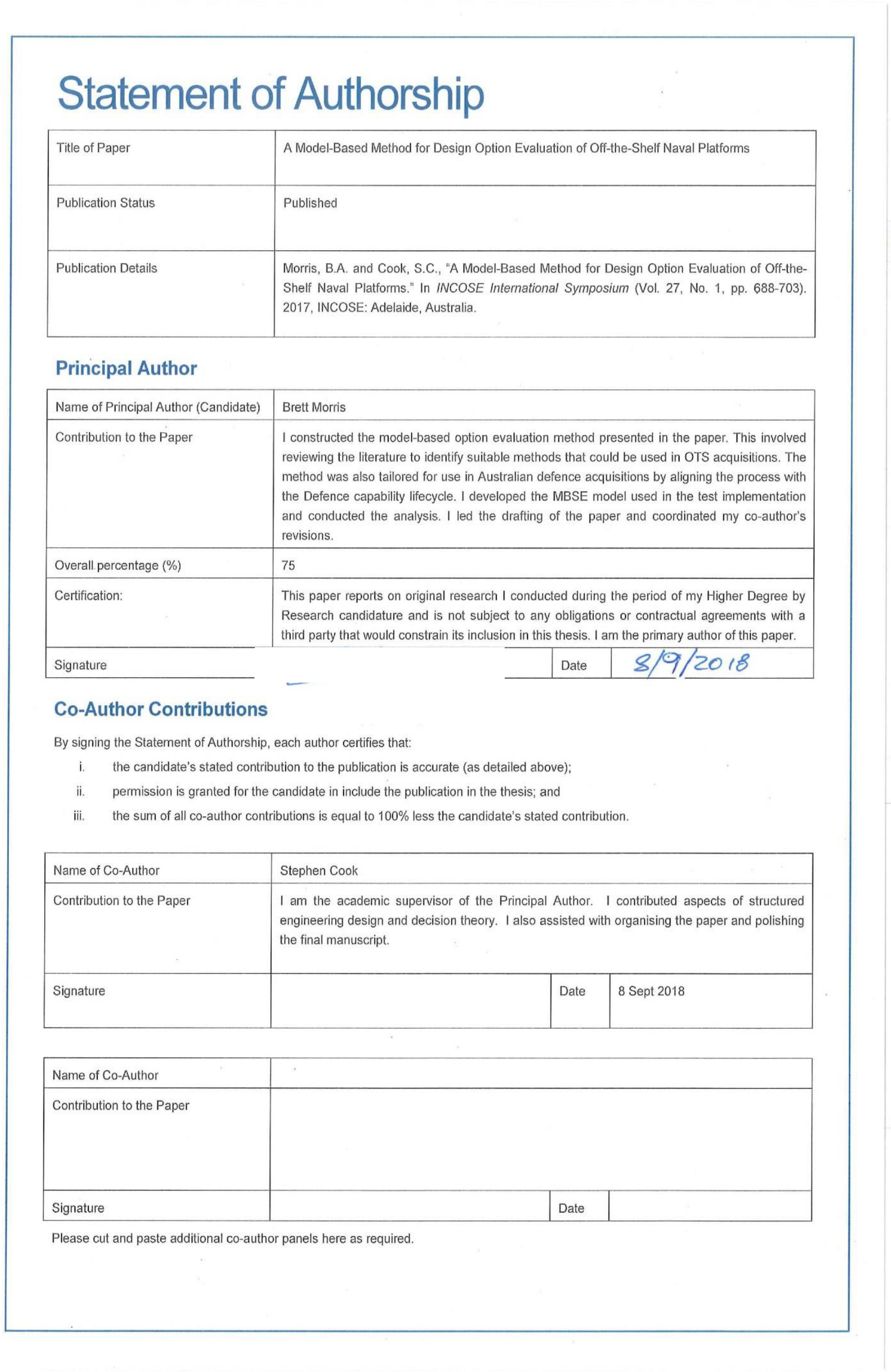
Appendix D: A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms



Statement of Authorship

Title of Paper	A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms
Publication Status	Published
Publication Details	Morris, B.A. and Cook, S.C., "A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms." In *INCOSE International Symposium* (Vol. 27, No. 1, pp. 688-703). 2017, INCOSE: Adelaide, Australia.

Principal Author

Name of Principal Author (Candidate)	Brett Morris		
Contribution to the Paper	I constructed the model-based option evaluation method presented in the paper. This involved reviewing the literature to identify suitable methods that could be used in OTS acquisitions. The method was also tailored for use in Australian defence acquisitions by aligning the process with the Defence capability lifecycle. I developed the MBSE model used in the test implementation and conducted the analysis. I led the drafting of the paper and coordinated my co-author's revisions.		
Overall percentage (%)	75		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	8/9/2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Stephen Cook		
Contribution to the Paper	I am the academic supervisor of the Principal Author. I contributed aspects of structured engineering design and decision theory. I also assisted with organising the paper and polishing the final manuscript.		
Signature		Date	8 Sept 2018

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

Please cut and paste additional co-author panels here as required.

A Model-Based Method for Design Option Evaluation of Off-the-Shelf Naval Platforms

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Abstract. Off-the-Shelf (OTS) strategies have become prevalent in the acquisition of naval platforms because the strategy is perceived as a means of reducing the acquisition cost and schedule risk. This paper covers a method to conduct an evaluation of shortlisted OTS naval platform design options that utilises Model-Based Systems Engineering (MBSE). MBSE is used as a means of developing and managing the traceability of evaluation criteria, managing the evaluation itself and facilitating reuse of the design patterns present both in naval platforms and acquisition processes. The paper concludes with a description of a pilot test of the method for an Offshore Patrol Vessel, which found it to be useful to manage the evaluation criteria traceability, maintain design data and identify weak spots in OTS design options.

Introduction

The adoption of Off-the-Shelf (OTS) strategies for the acquisition of complex defence systems is now prevalent in countries like Australia, where the design and engineering workforce, as well as the financial resources available within the Department of Defence are constrained. Naval platforms are a prime example of complex defence systems where OTS acquisition strategies are routinely implemented. For naval platform acquisitions, the OTS strategy is perceived as a means of reducing the acquisition cost and schedule risk (Saunders, 2013). The trade-off of 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).

Saunders (2013), in proposing a framework for Systems Engineering (SE) in OTS acquisitions, noted the need to tailor Systems Engineering processes to this task. This view of OTS procurement is shared by Lebron et al. (2000: p. 7-1) with the statement: "Above all, the typical systems engineering thought process must be adjusted to incorporate the potential risks of COTS technology". A key part of this process in OTS acquisitions is the evaluation of design options during tender evaluation. The evaluation must select the most suitable design to address the capability need that initiated the acquisition process. Authors such as Kontio et al. (1995) and Constantine and Solak (2010) have also identified the unique nature of OTS procurement and have proposed methods of conducting OTS option selection, or option evaluation during OTS acquisitions.

This paper describes part of a larger research program that seeks to construct a Model-Based Systems Engineering (MBSE) methodology to support stakeholders in the early stages of OTS naval platform acquisitions. Cook et al. (2014) previously investigated a method to perform design option evaluation using a MBSE model linked to an analytical model. The research in this paper builds upon the work of Cook *et al.* by formalising the method and implementing the option evaluation in a different MBSE standard. The present research also uses MBSE as a means of developing and managing the traceability of evaluation criteria, managing the evaluation process itself and facilitating reuse of the design patterns present in naval operations, platforms and acquisition processes. The paper opens with background on the research and existing approaches for conducting option evaluation. This is followed by a description of the model-based approach for OTS naval platform design option evaluation method. The final section of the paper covers a pilot study of the method undertaken for an Offshore Patrol Vessel class naval platform.

BACKGROUND

The overall methodology to support the early stages of OTS naval platform acquisitions, assumes a naval platform has been identified as the solution to a capability need and takes a preliminary concept of operations, or capability description as its key input. The overall methodology, its parts and its alignment with some systems lifecycles is shown in Figure 1.

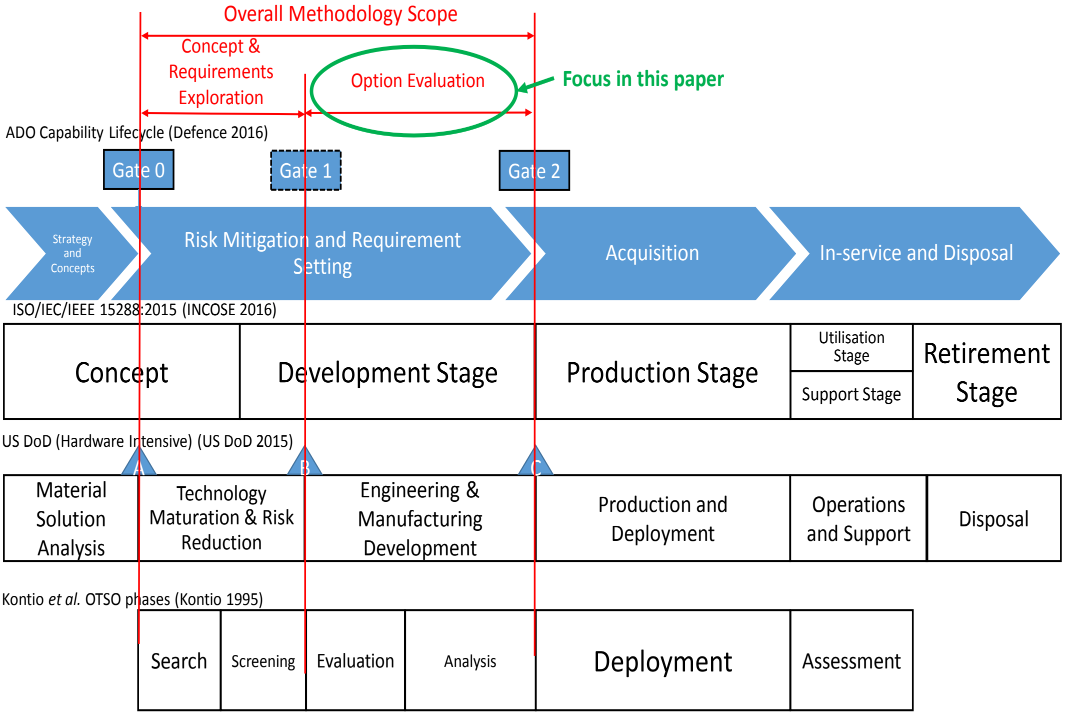


Figure 1: System lifecycles and the stages of interest for the research, along with the focus of this paper

The first part of the methodology is a model-based approach to Design Space Exploration, or Concept and Requirements Exploration (C&RE) as shown in Figure 1, which was described by Morris and Thethy (2015). The focus during the C&RE is informing requirements development by giving stakeholders a view of the design space that is linked to measures of performance (MOPs). Stakeholders can use this view to trim the design space to the region of designs likely to best meet the capability needs and to set requirements accordingly so that only suitable OTS design options are taken forward in the acquisition process. The second part of the methodology, which is the focus of this paper as shown in Figure 1, is a model-based method for option evaluation. This part of the methodology supports the selection of a preferred design from those designs shortlisted during C&RE and can also use the MBSE model developed during C&RE.

The stages of interest in the Australian Defence Organisation (ADO) system lifecycle span the risk mitigation and requirements setting stage. In the United States Department of Defense (US DoD) lifecycle, described in DoDI 5000.02 (DoD, 2015), the technology maturation and risk reduction stage appears to overlap with the first part of the ADO risk mitigation and requirements setting stage. This overlap is due to the common focus of reducing the various risks associated with the acquisition, along with the development and trade-off of designs and requirements. The overlap with the System Lifecycle Processes standard, ISO/IEC/IEEE 15288:2015 (ISO/IEC/IEEE, 2015) lifecycle shown in Figure 1 is also due to the activities undertaken to "…verify the feasibility of concepts, to aid the understanding of stakeholder needs, to explore architectural trade-offs, and to explore risks and opportunities" (Walden et al., 2015: p. 30). The stages of the Off-the-Shelf Option (OTSO) method proposed by Kontio et al. (1995), although initially intended for OTS software development projects, is included in Figure 1 as the selection of OTS options is "…an important activity in the project, with a high potential impact on the product and project objectives" (Kontio et al., 1995: p. 2). The alignment of the OTSO stages with the first part of the ADO Risk Mitigation and Requirements Setting stage is due to the 'Search and Screening' activities of the OTSO method being used to inform changes to requirements (Kontio et al., 1995).

The focus of the research covered in this paper is the second part of the ADO Risk Mitigation and Requirements Setting stage as shown in Figure 1. The final step in this pre-acquisition stage of OTS naval platforms, is to select a design option that best meets the capability need. Selection of this option requires an evaluation to be performed. In this stage of the ADO lifecycle, option evaluation is specifically referenced with "each option is assessed to confirm feasibility, acceptability and suitability" (Defence, 2016: p. 31). Option evaluation is classified as a 'Decision Management Process' in the INCOSE Systems Engineering Handbook (SEH) (Walden et al., 2015) and ISO/IEC/IEEE 15288:2015. The stages in the OTSO method provide a useful reference for such an OTS system lifecycle, with the evaluation of the shortlisted alternatives and analysis of the evaluation aligning with the second part of the ADO risk mitigation and requirements setting stage. The alignment arises as the evaluation stage "produces data on how well each alternative (option) meets the criteria defined" (Kontio et al., 1995: p. 8).

Approaches to Option Evaluation

Buede (2000) describes a generic approach to option evaluation comprising the following steps:

1. Define the objectives (evaluation criteria).
2. Define a value scale (i.e. threshold and objective values) and value function (i.e. increasing or decreasing linear, logarithmic, exponential and S-curve functions) for the evaluation criteria.
3. Assign value weights.
4. Aggregate the weighted evaluation criteria values into an overall score for each option.

Other authors generally follow similar approaches for option evaluation (see for example (Kontio et al., 1995) and (Julian et al., 2011)), where the development of evaluation criteria, their weights and values, is accompanied by a search and screening of OTS components and a subsequent analysis of the evaluation results. A useful approach to ensuring traceability in the development of option evaluation criteria (step one of the Buede (2000), approach above) is provided by Edwards et al. (2015) who propose the following steps:

1. Requirements Analysis
2. Define functional objectives
3. Map requirements to functional objectives
4. Establish product structure
5. Map functional objectives to product structure
6. Define metrics
7. Craft value functions
8. Determine (MOP) priority weightings
9. Optimise product configuration.

The option evaluation approaches of Buede (2000), and Edwards et al. (2015) appear suitable for developmental systems acquisitions, along with systems including a high proportion of OTS components. Typically, there is a need to initially trade-off OTS naval platform design options at the whole-of-platform level rather than develop design variants from OTS components, which suggests a tailored method is required. Furthermore, where scope for design changes exists, which technically violates the OTS acquisition strategy, yet often occurs, the method should also allow for the identification of 'weak spots' to highlight potentially high-value subsystem trades.

RESOURCES FOR SUPPORTING OFF-THE-SHELF NAVAL PLATFORM OPTION EVALUATION

In constructing a method for the evaluation of OTS naval platforms, three guiding principles have been borne in mind in an effort to enhance its utility:

1. Maintain traceability of evaluation criteria – ideally, these will be linked to the original, strategic intent of the platform being acquired in order to ensure a defensible, rigorous evaluation.

2. Assist the stakeholders to make defensible decisions, in a structured manner, that account for competing goals and objectives.
3. Maximise the capacity to reuse elements – thereby reducing subsequent acquisition efforts to implement the method and the resources required to manage these projects.

From the open literature, three key resources that adhere to these principles have been identified to facilitate the construction of a model-based naval platform option evaluation method: MBSE, Multi-Criteria Decision Making (MCDM) and Pattern-Based Systems Engineering (PBSE).

Model-Based Systems Engineering

MBSE is an emerging discipline that uses a central computer model rather than, or alongside, a set of documents, as a means of describing a system of interest (Robinson et al., 2010). It is debatable whether models will go on to replace specification documents in the foreseeable future, particularly in the acquirer/tenderer environment of Defence acquisitions. Campbell and Solomon (2011) note “In terms of clarity of representation, the diagram based model approach of MBSE….has shown itself to be of immense benefit, particularly in the early stages of system design”. Recent surveys of the issues and successes of implementing Model-Based Conceptual Design (MBCD) (the application of MBSE to the concept stage of a systems lifecycle), highlight the key benefits of MBSE in the early stages of system design as clarifying the problem space and informing requirements development (Morris et al., 2016). The surveys also highlight issues with MBSE due to modelling without purpose and a lack of information on best practice and the return on investment of implementing MBSE (Morris et al., 2016).

MBSE is implemented through the use of a methodology, which is a collection of related processes, methods and tools (Estefan, 2008). According to Estefan (2008), a process defines *what* is to be done, a method defines *how* it will be done and a tool will facilitate the *what* and *how*. The underlying structure of the methodology is provided by a metamodel. A metamodel defines the classes of elements and the permissible relationships between these classes in a system model (Logan et al., 2013). Several architecture frameworks are suitable, with some modifications and extensions, for use as MBSE metamodels in Defence systems development (Logan et al., 2013). These metamodels include the Department of Defense Architecture Framework (DoDAF), the Ministry of Defence Architecture Framework (MODAF). In the ADO context however, the DoDAF compliant Whole-of-System Analytical Framework (WSAF) (Robinson, 2011) has been endorsed for MBSE practice within the Capability Development Group (CDG) (Plenty, 2012).

Morris (2014) demonstrated a means of linking executable models to MBSE models though the introduction of an *analysis domain* into the WSAF metamodel. The analysis domain can be extended further to include the elements needed to conduct a model-based option evaluation as shown in Figure 2. The analysis domain can be integrated with the other metamodel domains through the use of model integration software that can either execute Systems Modelling Language (SysML) parametric diagrams, or wrap executable models. This provides a means of embedding traceability into the analysis, as it will be linked to the capability needs captured in an MBSE model. As such, MBSE adheres to guiding principle one as described above. Although the research described in this paper has been implemented in a SysML based MBSE tool, the modelling principles and techniques could be implemented in tools based on other standards that allow the underlying metamodel, or schema, to be tailored.

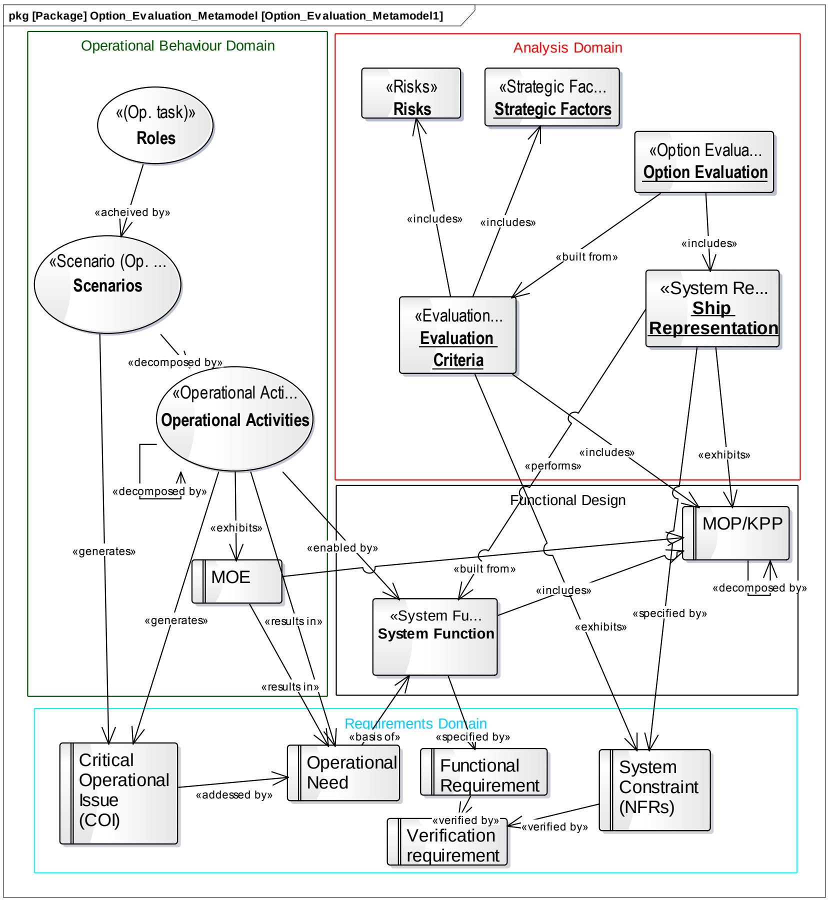


Figure 2: Part of the MBSE metamodel based on the WSAF reference model for the option evaluation. Note that "risk" elements can be caused by any of the other elements, but connectors are hidden for clarity.

Multi-Criteria Decision Making

The evaluation of naval platform design options is an example of a decision problem where consideration needs to be given simultaneously to a number of competing objectives (e.g. performance and cost), as well as a range of stakeholders with differing viewpoints. 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 with the purpose "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 therefore aligns with guiding principle two above and is suitable for inclusion in the option evaluation method constructed.

Several approaches to MCDM have been developed, which broadly fall into methods to address categories of multiple-objective or multiple-attribute problems (Mollaghasemi and Pet-Edwards, 1997: p. 4). Multiple-objective problems typically have a large number of feasible solution alternatives, whereas multiple-attribute problems generally have relatively fewer solution alternatives (Mollaghasemi and Pet-Edwards, 1997: p. 4). Naval platform tender evaluations, where the number of alternatives is typically 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). For naval platform option evaluation, the MAV method appears to be the most suitable. This suitability lies in the use of value functions for the attributes, which aren't included in simple scoring methods, along with the lack of a need to incorporate the additional complexity of uncertainty included in MAUT. Value functions 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). The need to make pairwise comparisons of attributes in the AHP, make it infeasible due the large number of attributes that typically need to be considered for naval platforms.

Buede provides an argument for using the Rank Order Centroid (ROC) technique to elicit value weights by citing research that demonstrated ROC weights typically provide more accurate results compared to other weight elicitation techniques (Buede, 2000: p. 368). ROC weights, *w*, for *k* alternatives with ranks, *r*, can be calculated using Equation 1.

$$w_i = \left(\frac{1}{k}\right)\sum_{j=i}^{k}\left(\frac{1}{r_j}\right) \qquad (1)$$

Pattern-Based Systems Engineering

In developing and testing the method, it became evident that naval platform conceptual design contains several generic structures that can conceivably be part of a design pattern. Structures are apparent in naval platform physical and functional architectures, as well as missions and performance measures. Pfister *et al.* describe the use of a design pattern as "…a way practitioners can represent invariant knowledge and experience in design" (Pfister et al., 2012: p. 323). They go on to state the objectives of design patterns are (Pfister et al., 2012: p. 323):

- "To improve performance (comprehensiveness, relevance), reliability (proven solutions, justified and context based)
- To gain economic value (time saving)
- To facilitate collaborative work by sharing design pattern repositories."

All of these uses and objectives align with the guiding principle three for the construction of the naval platform model-based option evaluation method given above. Design patterns that could be included in the method are given in Table 1.

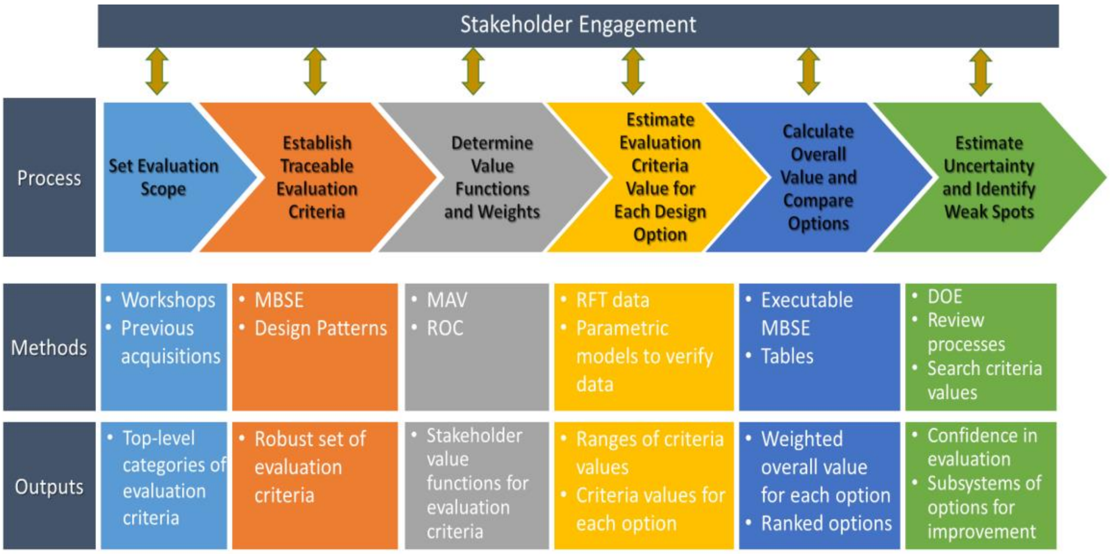
Table 1: Design patterns that could be used in the naval platform option evaluation method

Design Pattern	**Pattern Describes**	**Uses**
Universal Naval Task List (UNTL) (CNO, 2007)	Hierarchy of naval operational activities and measures	Building mission scenarios, Critical Operational Issues and performance evaluation criteria (KPPs)
Design Building Blocks (DBB) (Andrews and Pawling, 2003)	Naval platform functional architecture	Generic breakdown of naval platform functions into categories of fight, move, float and infrastructure
Extended Ship Work Breakdown Structure (ESWBS) (SAWE, 2007)	Naval platform physical architecture	Generic breakdown of physical naval platform components, including loads and margins

It is worth noting that the use of an appropriate MBSE metamodel (as discussed in the preceding section) would enable the aggregation of several of the design patterns in Table 1 into a larger, linked design pattern. Such a metamodel could facilitate the reuse of not only the individual patterns and their knowledge, but also inform acquisition stakeholders of previous sources of risks and opportunities within design patterns.

A PROPOSAL FOR A MODEL-BASED NAVAL PLATFORM OPTION EVALUATION METHOD

A method which leverages the resources from the previous section, comprising the following process, methods and outputs has been constructed for the option evaluation of naval platforms and is shown in Figure 3.



Stakeholder Engagement

Process	Set Evaluation Scope	Establish Traceable Evaluation Criteria	Determine Value Functions and Weights	Estimate Evaluation Criteria Value for Each Design Option	Calculate Overall Value and Compare Options	Estimate Uncertainty and Identify Weak Spots
Methods	• Workshops • Previous acquisitions	• MBSE • Design Patterns	• MAV • ROC	• RFT data • Parametric models to verify data	• Executable MBSE • Tables	• DOE • Review processes • Search criteria values
Outputs	• Top-level categories of evaluation criteria	• Robust set of evaluation criteria	• Stakeholder value functions for evaluation criteria	• Ranges of criteria values • Criteria values for each option	• Weighted overall value for each option • Ranked options	• Confidence in evaluation • Subsystems of options for improvement

Figure 3: Proposed model-based naval platform option evaluation method.

Scope the Evaluation

In scoping the option evaluation, the competing objectives need to be considered and included or deemed out of scope as appropriate. Pahl and Beitz note the evaluation objectives "…must cover the decision relevant requirements and constraints as completely as possible (Pahl and Beitz, 2007: 110). Naval platform acquisitions will generally have competing objectives of performance, costs, schedule and growth potential. There may be various strategic factors that have the potential to influence the evaluation as well. The top-level scope of naval platform option evaluations are likely to include factors related to:

- Mission Performance
- Economics
- Schedule and Technical risk
- Non-Functional Requirements
- Strategic factors

Using the model-based approach, the "evaluation criteria" type elements can be linked to the categories of evaluation criteria deemed within scope using the "include" relationship, as shown in Figure 2. The evaluation scope can be elicited from stakeholders within workshops, or reused from previous naval platform acquisitions.

Establish Traceable Evaluation Criteria

Evaluation criteria will fall into several categories dependent on the scope set in the first step of the proposed method. A discussion on possible methods to establish traceable evaluation criteria for the categories in the previous section is provided below. Whichever method is used, the evaluation criteria will need to be established with stakeholder input, or reused from previous acquisitions. Having stakeholder input may assist with generating 'buy-in' with the overall evaluation. There is also a need to ensure evaluation criteria are as independent as possible, to reduce the likelihood of criteria being given additional or insufficient weight in the overall evaluation.

Mission Performance Evaluation Criteria

A top-down approach to requirements development should yield a set of requirements, Measures of Effectiveness (MOEs) and MOPs that are linked to the originating capability need. In an MBSE approach, the traceability of the top-down Systems Engineering can be established by tracing the high level missions identified in a concept of operations or capability need statement, through scenarios of operational activities and the related critical operational issues, to operational needs to system functions and their Key Performance Parameters (KPPs). 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 used as mission performance evaluation criteria. These criteria will include aspects related to compliance with legislative and statutory requirements, since a design option's ability to perform the high level missions will be effected if it cannot operate within the overarching legislative environment. The traceability of the performance evaluation criteria is shown in the metamodel in Figure 2. The "MOP/KPP" element in the MBSE metamodel shown in Figure 2 captures the mission performance evaluation criteria and is related to the “evaluation criteria” element by a “includes” relationship. Figure 4 shows this traceability in more detail.

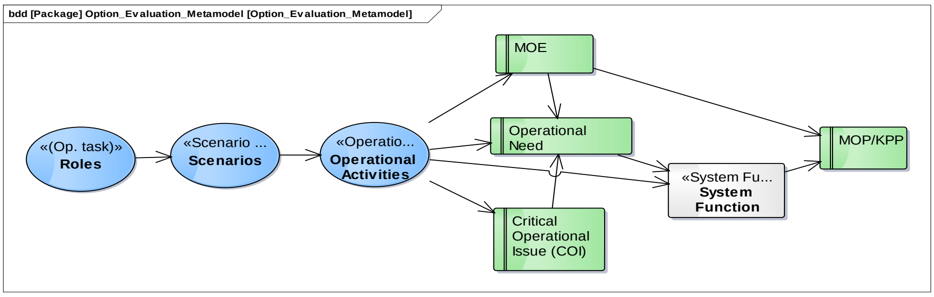


Figure 4: Trace from the naval platform operational concept to the performance evaluation criteria (KPPs). Note this path is maintained in the MBSE metamodel (shown in Figure 2).

Economic Evaluation Criteria

These criteria will include the acquisition and through life cost of each OTS design option. Consideration should also be given to other costs associated with the integration of each option with extant or planned Defence Systems-of-Systems (SoS) the naval platform will be part of, infrastructure, and personnel training systems. The aforementioned constrained resources typically available within countries conducting OTS naval platform acquisitions, indicates a likely level of importance of these criteria. In the MBSE metamodel shown in Figure 2, these criteria will be captured in the “system constraint” element type and is related to the “evaluation criteria” element by a “includes” relationship.

Schedule and Technical Risk

The schedule and technical risks for OTS naval platform acquisitions are likely to have been identified in the lifecycle stages leading up to the stage when the option evaluation will be performed. It is therefore imperative that the level of these risks associated with each of the design options is considered as part of the evaluation. In the MBSE metamodel shown in Figure 2 for the option evaluation method, these criteria will be captured in the “risk” element type and is related to the “evaluation criteria” element by a “includes” relationship.

Non-Functional Requirements Evaluation Criteria

Another aspect to include in the evaluation criteria are the *non-functional requirements* (NFRs). These requirements have also been termed *quality attributes, constraints, goals, extra functional requirements* (Chung et al., 2000). NFRs have also been termed *ilities* (Mirakhorli and Cleland-Huang, 2013). Eliciting then tracing NFRs to system components has proved problematic as “…they often exhibit cross-cutting and broad-reaching impacts across the system and are realised through components and behaviours …” (Mirakhorli and Cleland-Huang, 2013: 299).

Pattern based methods appear to be suitable for naval platform NFRs as they provide a means of replicating existing naval platform NFR knowledge. NFR Patterns also provide “...a better solution for managing the complexity of the NFR elicitation process” (Ullah et al., 2011). Further suitability of pattern based methods of NFR elicitation and traceability, such as using a pattern of predetermined NFRs, is suggested by Gabb and Henderson with (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."

In the model-based approach proposed here, the list of NFRs could be developed as a design pattern in a SysML profile that can be reused in subsequent acquisition projects. In the MBSE metamodel shown in Figure 2, these criteria will be captured in the "system constraint" element type and is related to the "evaluation criteria" element by a "includes" relationship.

Strategic Factors Evaluation Criteria

This set of evaluation criteria is included to capture the non-technical criteria that often accompany naval platform acquisitions. These criteria may include the preferences related to strategies associated with national interests. For example, the strategic need to strengthen ties with other countries could be a factor in the acquisition of a naval platform if a designer of an option under consideration was from a strategically important country. These factors could also include commercial aspects such as those associated with the capacity of the option designer to deliver the design. Tracing strategic factors criteria is not likely to be straight forward, given they can be related to a range of aspects beyond the control of the acquisition project. A specific element for these criteria has been included in the MBSE metamodel shown in Figure 2, where the "evaluation criteria" element "includes" the "strategic factors" elements.

Determine Value Functions and Weights

As discussed above, the Multi-Attribute Value Analysis method appears to be well suited to naval platform option evaluation due in part to the inclusion of utility functions in the evaluation. Utility functions 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 utility function curves (normalised between threshold and objective values) are shown in Figure 5. The curves in the top row are used for evaluation criteria that increase in utility between the threshold and objective values (i.e. zero and one on the x-axis). The curves on the bottom row are used for evaluation criteria that decrease in utility between the threshold and objective values (Buede, 2000). Stakeholders will typically be engaged to select the utility function for each evaluation criteria.

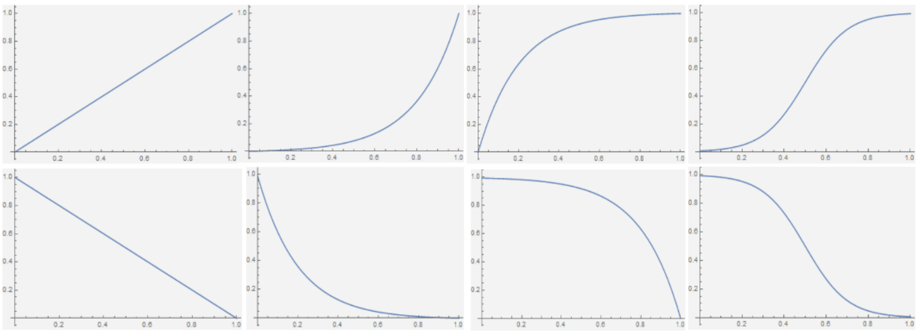


Figure 5: Common value function ($v_i(x_i)$) curves, normalised between threshold and objective values, for increasing utility (top) and decreasing utility (bottom) (Buede, 2000).

ROC is the preferred method of determining evaluation criteria weights in the proposed method due to its accuracy compared to other methods, as highlighted above. This method was also found to be reasonably straight forward to apply during testing. Where a suitably mature Concept of Operations (CONOPS) exists for the naval platform to be acquired, the threshold and objective values for the evaluation criteria, as well as mission performance evaluation criteria weights may be determined through analysis of the mission scenarios.

Estimate Evaluation Criteria Values

In this step, the values of the evaluation criteria for each of the design options under consideration are estimated. These values will ordinarily be estimated using data provided by designers responding to a Request for Tender (RFT) during an OTS naval platform acquisition project. This will mean that if the initial steps of the naval platform option evaluation method proposed in this paper are performed as early as possible in the acquisition program, data to estimate the traceable evaluation criteria can be requested in the RFT. The designer data provided in a RFT could be verified through parametric equations where appropriate, such as those given in Table 4 of Morris and Thethy (2015).

Calculate Overall Value and Compare Options

In evaluating technical products, summation of the evaluation criteria is the usual method of calculating the overall value (Pahl and Beitz, 2007). This approach should only be considered to be accurate if the evaluation criteria are independent. In practice, even when this condition is only approximately satisfied, the assumption of the overall value being an addition of the sub values seems to be justified (Pahl and Beitz, 2007). The overall weighted value (OWV) of a design option can be determined for *n* criteria with weights from equation 1 and normalised value functions $v_i(x_i)$ using equation 2.

$$OWV = \sum_{i=1}^{n} w_i v_i(x_i) \qquad (2)$$

To compare design options the summation rule from equation 2 can be used to assess variants in two key ways (Pahl and Beitz, 2007):

1. **Determine maximum overall value** – where the variant with the largest overall weighted value (OWV) is judged to be the best

2. **Determine the rating** – where the rating of a variant compared to an imaginary ideal (i.e. the maximum possible overall value) is used to rate variants.

Estimate Uncertainty and Identify Weak Spots

Errors or uncertainties in the evaluation could fall into two main categories (Pahl and Beitz, 2007):

1. **Subjective errors** – due to bias and partiality, which can be mitigated using the views of several people from different departments/backgrounds, and using unidentifiable names for design options (e.g. A, B, etc.).
2. **Procedure inherent shortcomings** – which result from the "prognostic uncertainty" inherent in estimating the evaluation criteria values. These uncertainties can also be due to uncertainties in requirements formulation and design descriptions.

Weak spots are where a design option's values for individual evaluation criteria are in the lower end of the threshold to objective range relative to the other design options. These are particularly important for promising design options with good overall weighted values. Although not strictly in line with an OTS strategy, it may be possible to eliminate these weak spots against individual criteria during further development if design changes are allowable in the acquisition project (Pahl and Beitz, 2007). Allowances for changes to OTS designs may need to be considered for factors impacting interoperability (e.g. communications systems) and suitability (e.g. statutory compliance).

AN OFFSHORE PATROL VESSEL PILOT STUDY

To test the utility and robustness of the proposed model-based option evaluation method, a pilot study was conducted using an unclassified United States Coast Guard (USCG) CONOPS for a Medium Security Cutter (WMSM) (USCG, 2008). This CONOPS is representative of a typical Offshore Patrol Vessel naval platform CONOPS and was used as the basis of the C&RE test implementation covered in Morris and Thethy (2015). The C&RE case study for the Medium Security Cutter CONOPS narrowed the suitable design space down to designs that were at or near the length constraint of 80 metres. The pilot study covered in this section, uses estimated criteria values for two indicative OTS designs within the suitable design space found on the internet. In a full implementation of the option evaluation method for a tender evaluation, designer data provided for a Request For Tender (RFT) would usually be used for the evaluation criteria.

Step 1 – Set Evaluation Scope: For the pilot study, the scope was assumed to be all of the factors descibed in the "Scope the Evaluation" section above, as shown in Figure 6. These top-level factors were weighted during workshop testing, where participants were asked to rank the evaluation categories from their individual perspectives and the overall rank determined from the aggregated scores.

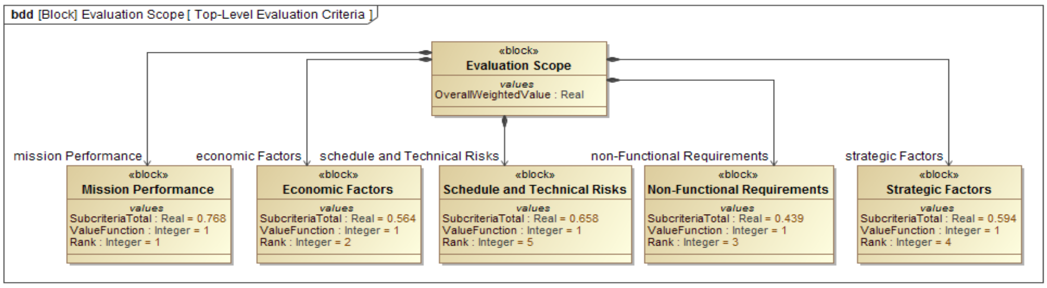


Figure 6:Top-level evaluation criteria in the scope for the option evaluation

Step 2 – Establish Traceable Evaluation Criteria: The pilot study focused on a subset of the mission performance evaluation criteria due to the need for brevity in the paper format. Nonetheless, this focus provides an example of how the proposed model-based option evaluation method can be applied and MBSE used to make their traceability explicit. To establish these mission performance evaluation criteria, the top-level tasks were decomposed into scenarios comprising elements from the Universal Naval Task List (UNTL) (CNO, 2007) design pattern. Figure 7 shows the traceability from the operational tasks (law enforcement and other mandated tasks), through the USCG scenarios, to the UNTL operational activities (e.g. NTA.1.4.8.1 - conduct alien migrant interdiction operations).

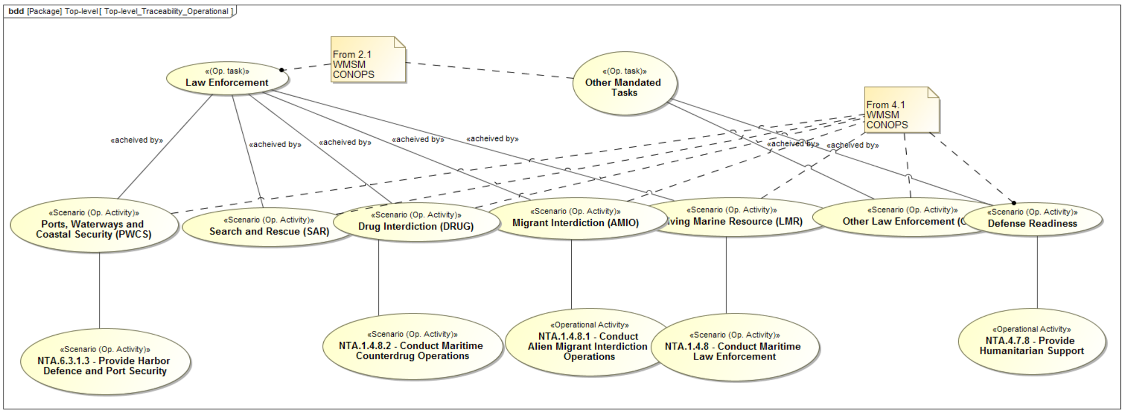


Figure 7: Traceability from the Medium Security Cutter Operational Tasks, through USCG Scenarios to UNTL Operational Activities.

Each of the top-level UNTL operational activities shown in Figure 7 was decomposed further (not shown) into the UNTL operational activities that would be performed when undertaking the scenarios. The Critical Operational Issues (COIs) for each scenario were also identified. The operational activities were able to be identified from the scenario descriptions provided in the Medium Security Cutter CONOPS. The UNTL operational activity that occurred most often in the scenarios was the Universal Naval Task List operational activity, NTA.1.1.2.3.7 – conduct small boat operations. The traceability from this operational activity and its related Critical Operational Issue, through the resulting operational needs and the functions that the needs are the “basis of” (which come from a ship functional architecture design pattern), to the related MOPs, is shown in Figure 8. Three of these MOPs were identified as KPPs (evaluation criteria) related to the COI (top left of diagram) during consultations with Subject Matter Experts.

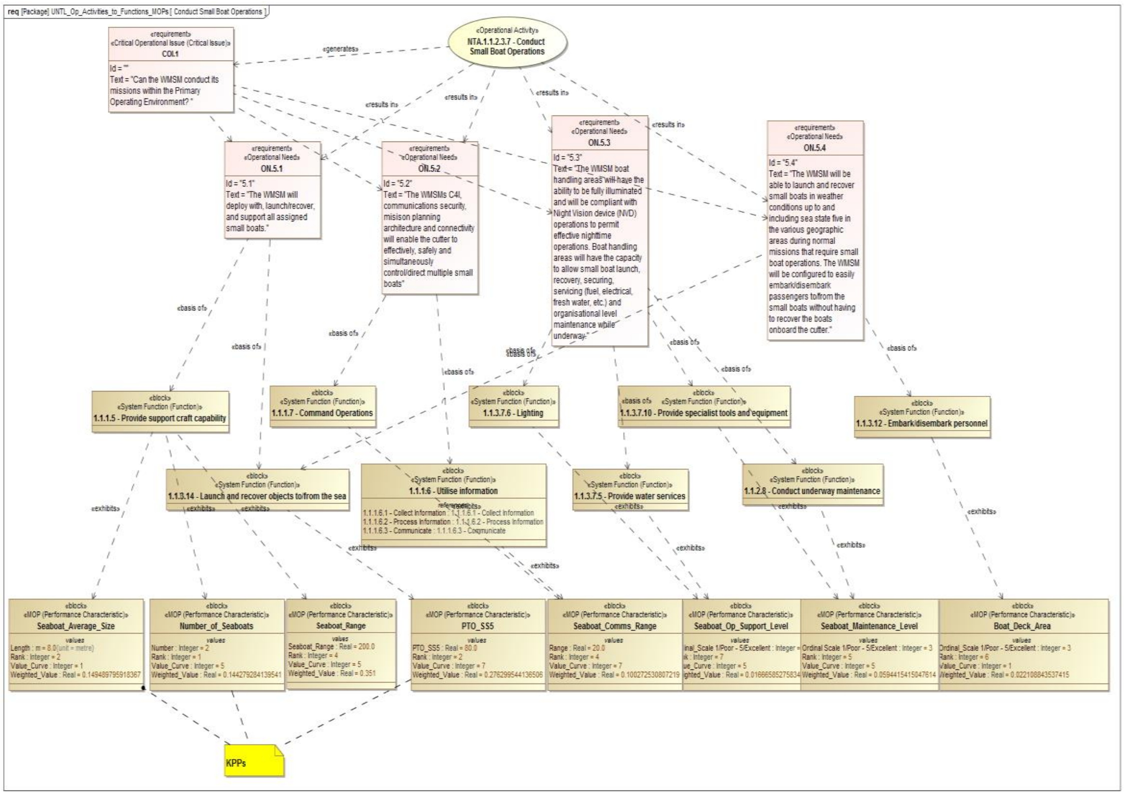


Figure 8: Traceability from the Conduct Small Boat Operations, through the Operational Needs and System Functions to MOPs. Three of these MOPs were identified as KPPs during consultations with SMEs.

Step 5 – Calculate Overall Weighted Value and Compare Options: In this pilot study, the Overall Weighted Value for the subset of mission performance evaluation criteria related to seaboat operations was calculated from Equation 2 using a spreadsheet. The spreadsheet was wrapped into a SysML based MBSE model via model integration software. This allowed the evaluation criteria values (KPPs), ranks and value curve identifiers to be held as value properties in the KPPs, which were modelled as SysML blocks in the MBSE model, as shown in the bottom level of Figure 8. When executing the analysis, these KPP value properties were read from the MBSE model, sent to the spreadsheet where the KPP weighted values and OWV were calculated, then the OWV was written back to a block in the MBSE model. Each of the value properties of the design options were held as block instances in the MBSE model for updating and further analysis. The evaluation inputs and outputs are shown in Table 2.

Table 2: Sample Option Evaluation for the criteria related to small boat operations. The yellow cells highlight the largest difference between designs for these criteria and indicate a weak spot of Option B (Note PTO_SS5 is “Percent Time Operable in Sea-State Five).

KPP	**Rank**					**Option A**		**Option B**	
Name	**Number**	**ROC Weight**	**Threshold**	**Objective**	**Value Curve**	**KPP**	***w*KPP(v)***	**KPP**	***w*KPP(v)***
Seaboat_Average_Size	2	0.1944	5	11	1	8	0.09722	6	0.03241
Number_of_Seaboats	1	0.6111	1	3	5	2	0.56475	3	0.61111
PTO_SS5	2	0.1944	50	90	7	80	0.17969	80	0.17969
					TOTALS		**0.84167**		**0.82321**

From Table 2, it can be seen in the green highlighted cells, Design Option A had a higher OWV than Design Option B for the subset of performance evaluation criteria (KPPs) related to small boat operations.

Step 6 – Estimate Uncertainty and Identify Weak Spots: The level of confidence in the evaluation criteria values used in the pilot study was low since they were estimated from the internet. However, they were deemed sufficient for a test implementation of the option evaluation method as it was the method, rather than the designs that were under evaluation. A Design of Experiments (DOE) study was conducted to investigate the sensitivity of the results to changes in the criteria rankings, which found the results were impacted in less than 25% of the experiments. This gives confidence in the criteria rankings and hence weights used in the evaluation. The yellow cells in Table 2 indicate where the largest difference was between the two designs for the evaluation criteria considered. This implies the seaboat average size of design B is a weak spot of the design option. If there was scope to change design B to accommodate larger seaboats, this could be a change worth pursuing.

CONCLUSIONS

This paper has proposed a model-based method for conducting OTS naval platform option evaluations. The option evaluation is the second part of a MBSE methodology that has been constructed to support stakeholders in the early stages of OTS naval platform acquisitions. The proposed method makes use of MBSE, MCDM and design patterns to enhance the traceability, rigour and reusability in these evaluations.

The proposed method has been pilot tested and was found to be useful as a means of managing the evaluation criteria traceability, maintaining design data and identifying weak spots in OTS design options. Implementing the evaluation within an MBSE environment incurs an overhead in terms of effort relative to commercial spreadsheet software. Nonetheless, this overhead should be offset by the value provided in the explicit traceability of evaluation criteria provided by MBSE. The overhead will also be offset if there are changes in requirements, which frequently occurs during acquisition projects, as the MBSE will be able to be rapidly updated and the evaluation revisited. Furthermore, the ability to reuse MBSE models and design patterns in subsequent OTS naval platform acquisition projects should mean that the effort required to implement the method will be reduced.

Although the pilot test only covered a subset of the performance evaluation criteria, in other implementations of the method, it has been found that KPPs will often be repeated across a number of operational activities. For example, Percent Time Operable (PTO) can be a KPP for several operational activities including small boat operations, aircraft operations, and replenishment operations. While the method was constructed with OTS naval platform acquisitions in mind, the method could conceivably be applied to the evaluation of concept design alternatives in a developmental acquisition program.

Additional implementations of the method should be undertaken to further refine it and stakeholder feedback sought on its utility to quantify any benefit over standalone option evaluation approaches.

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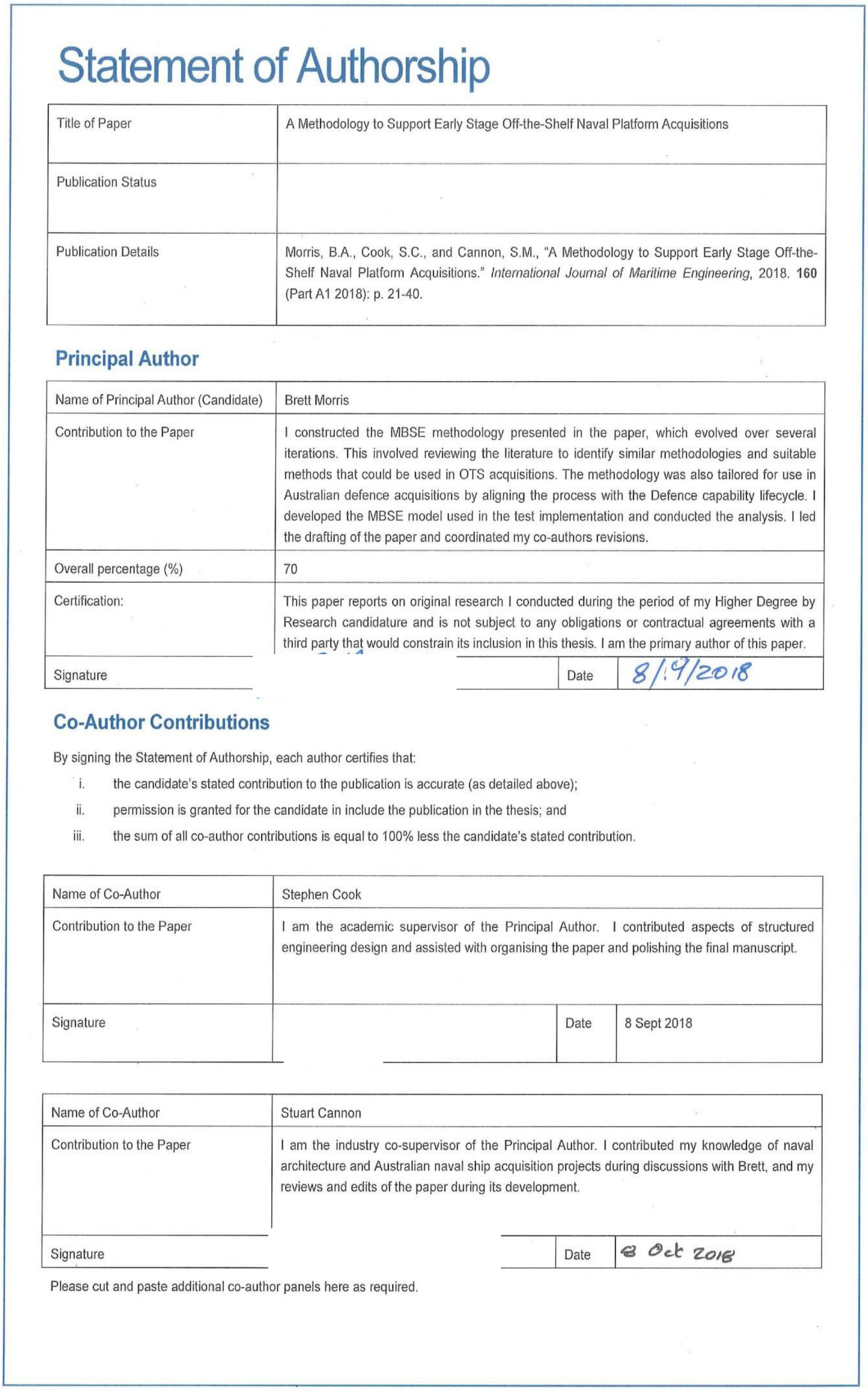
Biographies

Brett Morris is a Naval Architect/Systems Engineer who joined the Defence Science and Technology Group in 2007. He has previously worked for the RAN in the Directorate of Navy Platform Systems and has conducted research in the fields of Naval ship concept design, modelling and simulation of ship performance, along with MBSE. Brett has a Grad. Dip. in Systems Engineering, a BE (Nav. Arch.) and is currently undertaking part-time research towards a PhD.

Stephen Cook is a part-time professor at the University of Adelaide where he works in the Entrepreneurship, Commercialisation and Innovation Centre undertaking research in system of systems engineering and complex project management theory and practice. Until June 2014 he was the Professor of Systems Engineering at the University of South Australia where he led a number of research concentrations in the field. Preceding this he accumulated twenty years of industrial R&D and SE experience spanning aerospace and defence communications systems in both DSTO and industry. His research interests focus on the development of MBSE practices, the SE of large-scale defence capabilities, and relating complexity theory to SE practice and organisational improvement. He also works with Shoal Engineering Pty Ltd applying his knowledge to a range of systems engineering management and research challenges. Prof Cook is a past President of the Systems Engineering Society of Australia, an

INCOSE Fellow, a Fellow of Engineers Australia, a Fellow of the Institution of Engineering and Technology (UK), and a Member of the Omega Alpha Association.

Appendix E: A Methodology to Support Early Stage Off-the-Shelf Naval Vessel Acquisitions



Statement of Authorship

Title of Paper	A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions
Publication Status	
Publication Details	Morris, B.A., Cook, S.C., and Cannon, S.M., "A Methodology to Support Early Stage Off-the-Shelf Naval Platform Acquisitions." *International Journal of Maritime Engineering*, 2018. **160** (Part A1 2018): p. 21-40.

Principal Author

Name of Principal Author (Candidate)	Brett Morris		
Contribution to the Paper	I constructed the MBSE methodology presented in the paper, which evolved over several iterations. This involved reviewing the literature to identify similar methodologies and suitable methods that could be used in OTS acquisitions. The methodology was also tailored for use in Australian defence acquisitions by aligning the process with the Defence capability lifecycle. I developed the MBSE model used in the test implementation and conducted the analysis. I led the drafting of the paper and coordinated my co-authors revisions.		
Overall percentage (%)	70		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	8/9/2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Stephen Cook		
Contribution to the Paper	I am the academic supervisor of the Principal Author. I contributed aspects of structured engineering design and assisted with organising the paper and polishing the final manuscript.		
Signature		Date	8 Sept 2018

Name of Co-Author	Stuart Cannon		
Contribution to the Paper	I am the industry co-supervisor of the Principal Author. I contributed my knowledge of naval architecture and Australian naval ship acquisition projects during discussions with Brett, and my reviews and edits of the paper during its development.		
Signature		Date	8 Oct 2018

Please cut and paste additional co-author panels here as required.

THE TRANSACTIONS OF THE ROYAL INSTITUTION OF NAVAL ARCHITECTS

Part A – International Journal of Maritime Engineering

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

B A Morris, Defence Science and Technology Group and The University of Adelaide, Australia, **S C Cook,** The University of Adelaide, Australia and **S M Cannon**, Defence Science and Technology Group, Australia.

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:

4. Maintaining traceability to the original, strategic intent of the vessel being acquired in order to ensure a defensible outcome.
5. Assisting the stakeholders to make defensible decisions that account for competing goals and objectives.
6. 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.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by the Australian Defence Science and Technology Group for the research covered in the paper. The authors would also like to acknowledge the contributions of those who have provided SME input and feedback during testing of the methodology.

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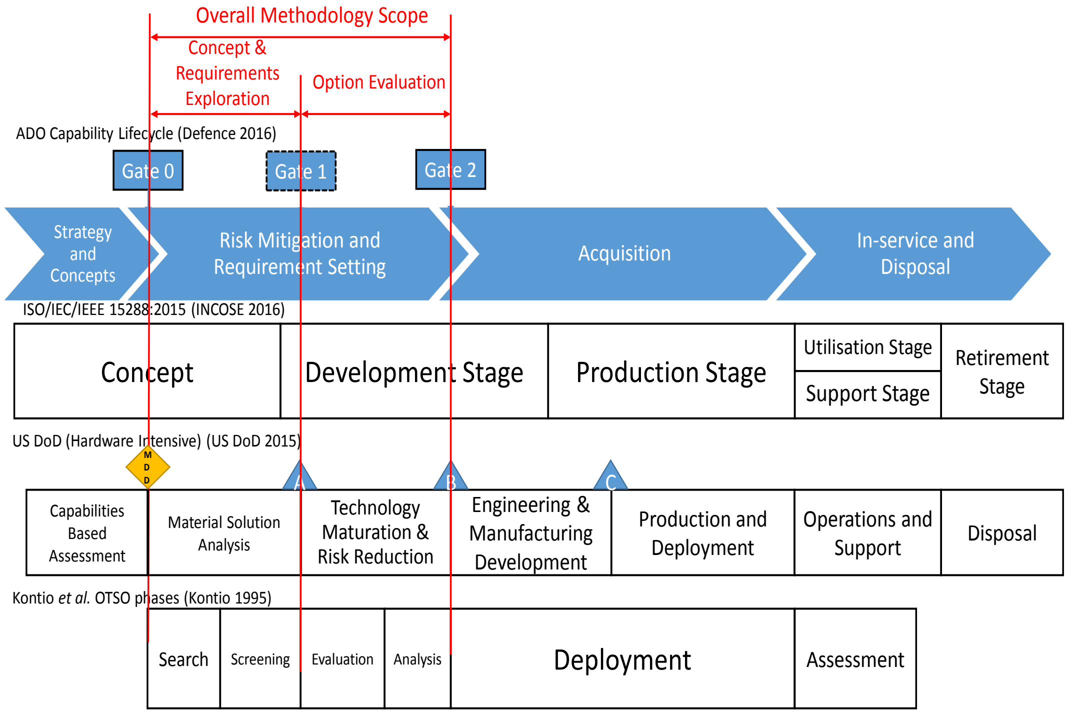


Figure 1: Various system lifecycles and the stages of interest for the research covered in the paper. The methodology constructed as part of the research covers the ADO risk mitigation and requirements setting stage as shown.

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.

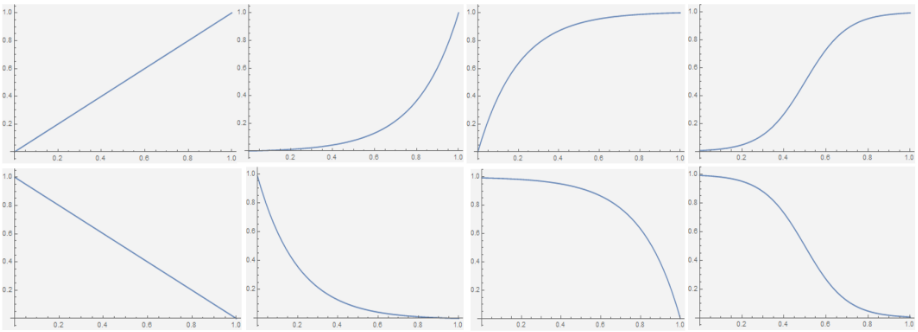


Figure 2: Common value function ($v_i(x_i)$) curves, normalised between threshold and objective values, for increasing utility (top) and decreasing utility (bottom) (Buede, 2000).

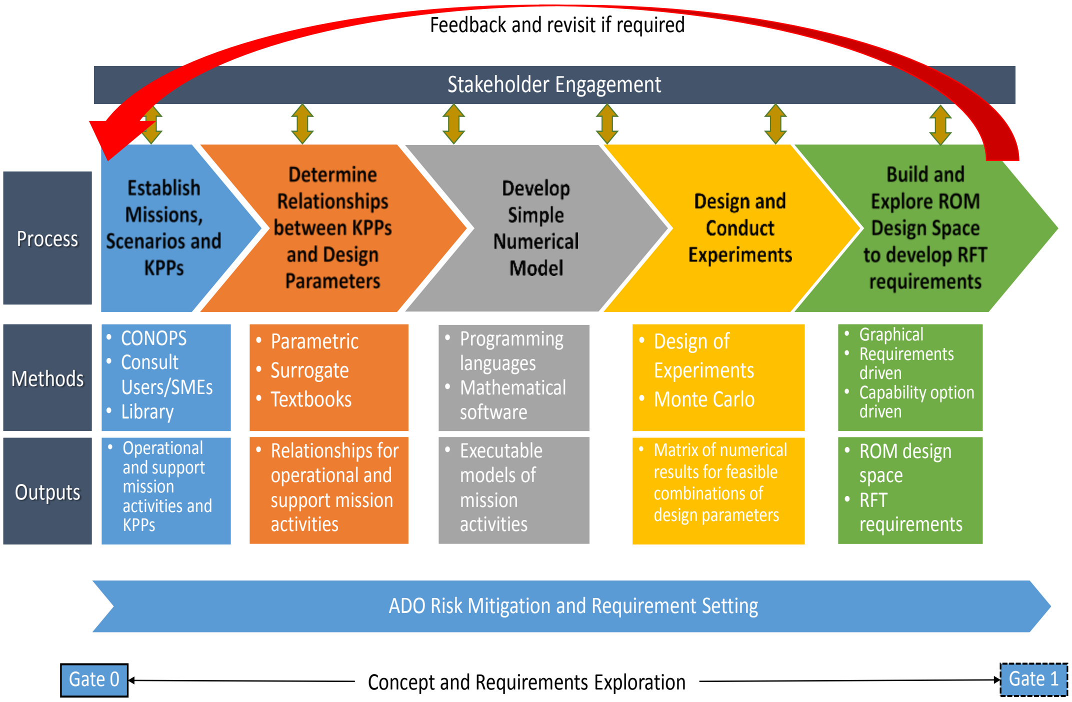


Figure 3: Concept and Requirements Exploration Stage of the methodology supports activities between decision points at Gate 0 and Gate 1 of the ADO capability lifecycle.

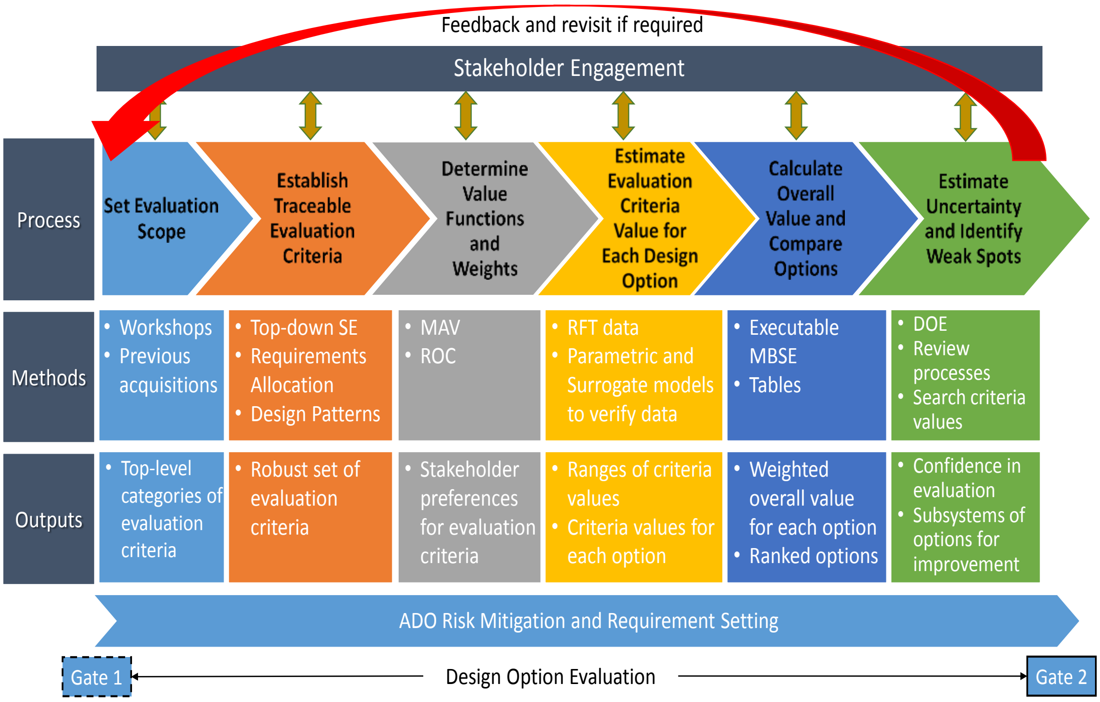


Figure 4: Design Option Evaluation stage of the methodology supports activities between decision points at Gate 1 and Gate 2 in the ADO capability lifecycle.

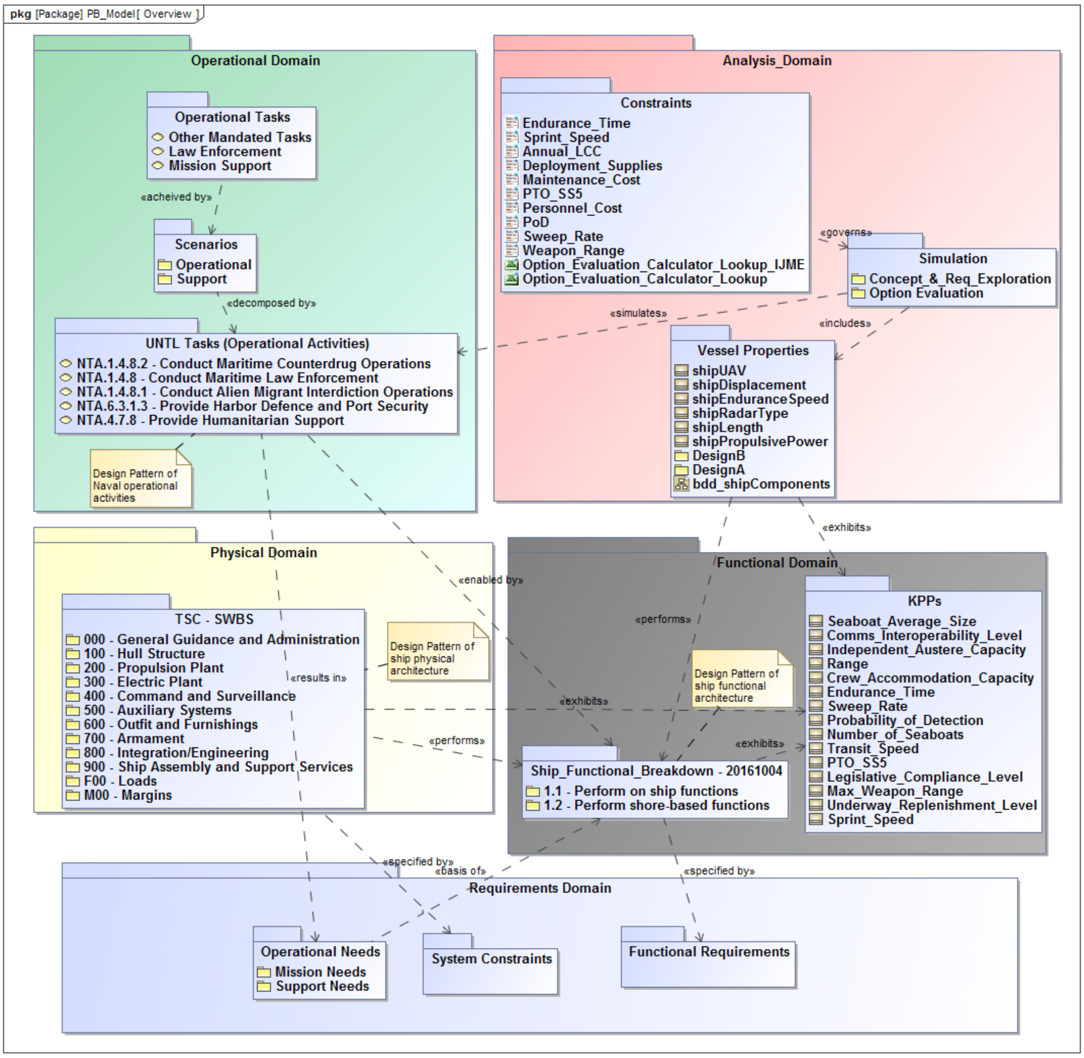
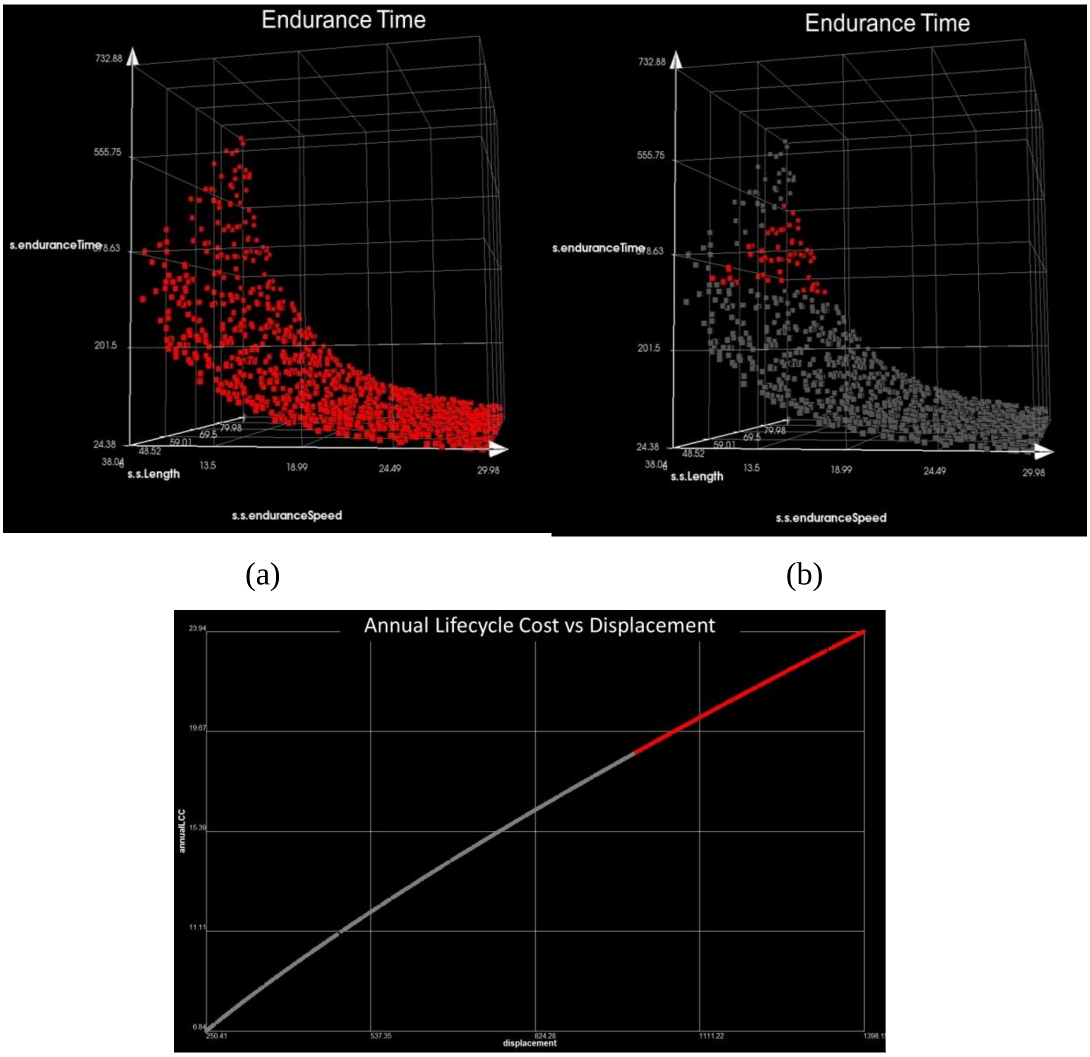


Figure 5: Overview of the MBSE model developed for the USCG MSC implementation. The figure shows the different domains in the extended WSAF metamodel and the relationships between the elements within each of these domains.



(a) (b)

(c)

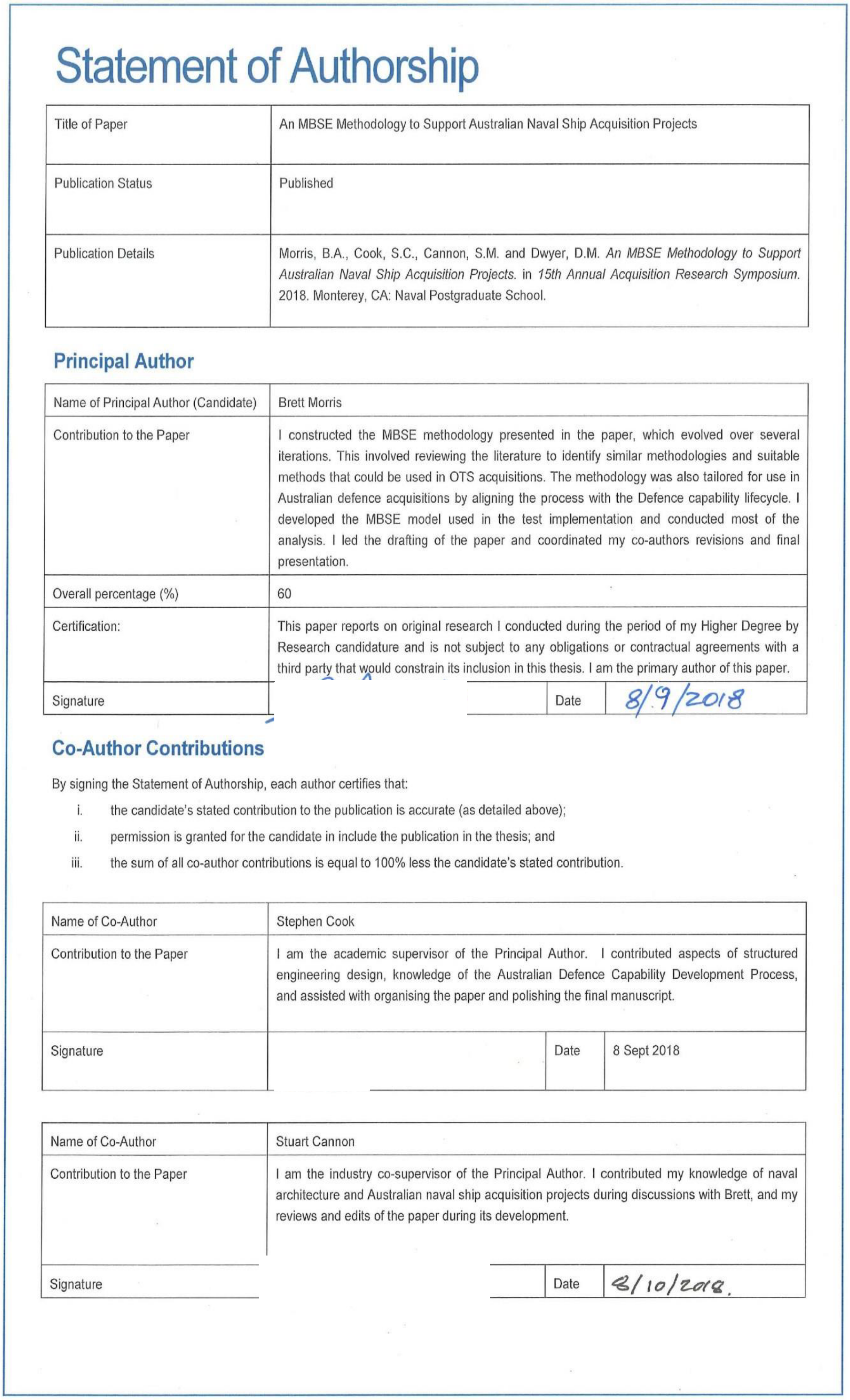
Figure 6: (a) Design space for the Endurance time KPP before constraining the design space to threshold values, and (b) after constraining the design space to threshold values of endurance time and range, and (c) the constrained design space for the competing annual lifecycle cost KPP. The red design 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 weight ranking, value curve identifier and KPPs for each option are read from the MBSE model. The yellow cells highlight the largest differences between the two designs and indicate the weak spots of option A relative for option B are for Endurance Time, Range and Seaboat Average Size. The weak spot of option B relative to option A is the Crew Accommodation Capacity.

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_Interoperability_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_Accommodation_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.

Appendix F: An MBSE Methodology to Support Australian Naval Vessel Acquisition Projects



Statement of Authorship

Title of Paper	An MBSE Methodology to Support Australian Naval Ship Acquisition Projects
Publication Status	Published
Publication Details	Morris, B.A., Cook, S.C., Cannon, S.M. and Dwyer, D.M. *An MBSE Methodology to Support Australian Naval Ship Acquisition Projects.* in *15th Annual Acquisition Research Symposium.* 2018. Monterey, CA: Naval Postgraduate School.

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Contribution to the Paper	I constructed the MBSE methodology presented in the paper, which evolved over several iterations. This involved reviewing the literature to identify similar methodologies and suitable methods that could be used in OTS acquisitions. The methodology was also tailored for use in Australian defence acquisitions by aligning the process with the Defence capability lifecycle. I developed the MBSE model used in the test implementation and conducted most of the analysis. I led the drafting of the paper and coordinated my co-authors revisions and final presentation.		
Overall percentage (%)	60		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	8/9/2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	I am the academic supervisor of the Principal Author. I contributed aspects of structured engineering design, knowledge of the Australian Defence Capability Development Process, and assisted with organising the paper and polishing the final manuscript.		
Signature		Date	8 Sept 2018

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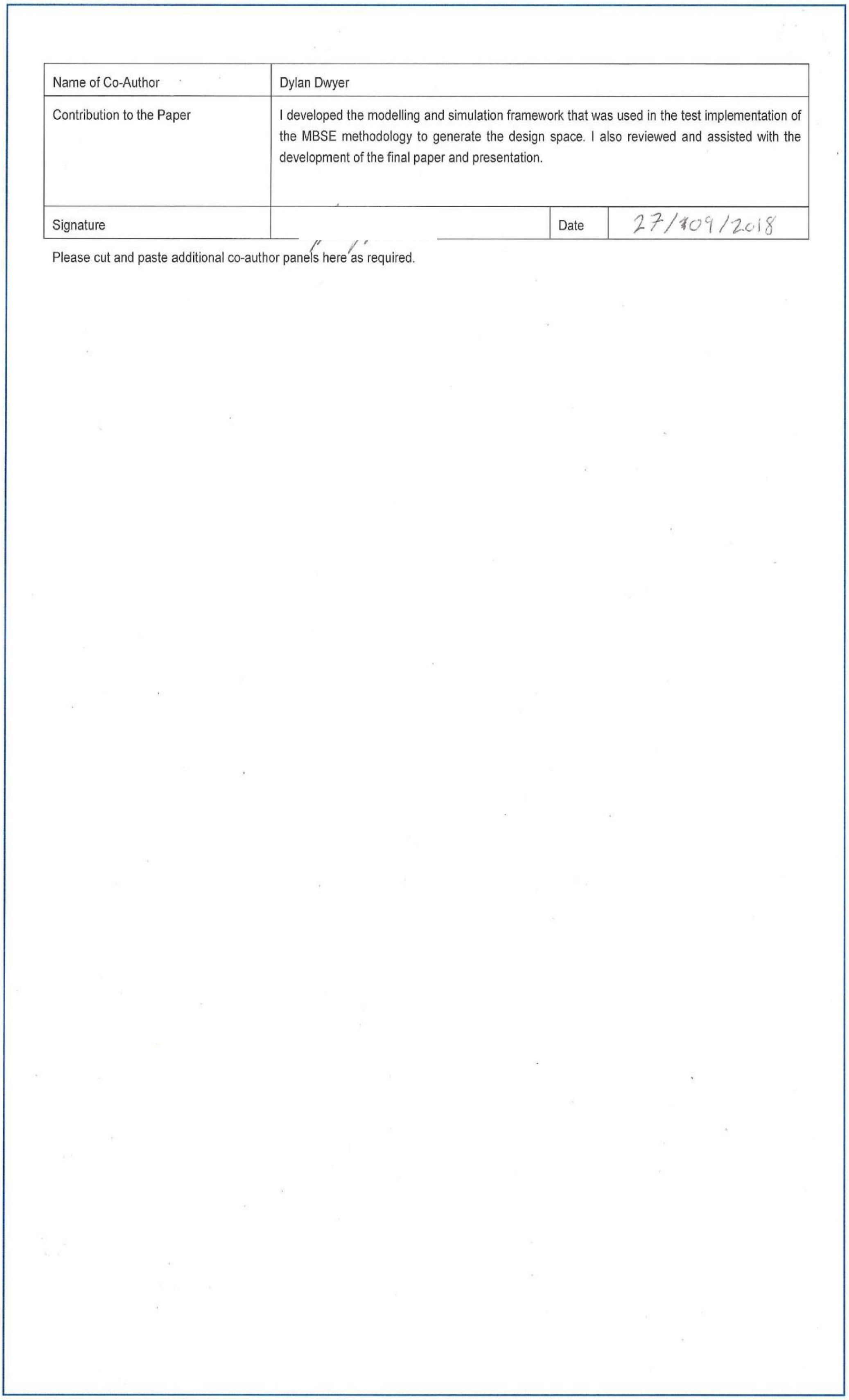
Contribution to the Paper	I am the industry co-supervisor of the Principal Author. I contributed my knowledge of naval architecture and Australian naval ship acquisition projects during discussions with Brett, and my reviews and edits of the paper during its development.		
Signature		Date	8/10/2018.



Name of Co-Author	Dylan Dwyer		
Contribution to the Paper	I developed the modelling and simulation framework that was used in the test implementation of the MBSE methodology to generate the design space. I also reviewed and assisted with the development of the final paper and presentation.		
Signature		Date	27/~~1~~09/2018

Please cut and paste additional co-author panels here as required.

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 (Peever, 2015: p. 13):

> '…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…'

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 US 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 US 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.

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 (Defence, 2017b: p. 105):

- ‘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.’

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:

> 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, Roedler, Forsberg, Hamelin, & Shortell, 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.

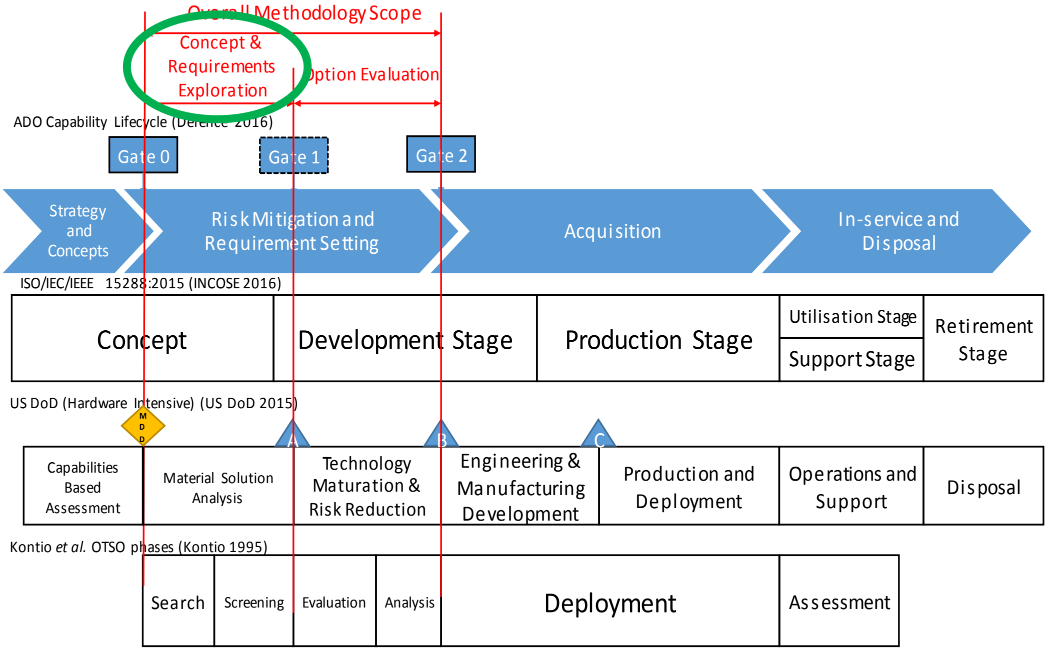


Figure 1: Various system lifecycles and the stages of interest for the research. The Concept and Requirements Exploration part of the MBSE methodology in the green oval is the focus of this paper.

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 and Cook (2017) and 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. Then the paper 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. A focus 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, Harvey, Robinson, and Cook (2016) also reports 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 US Government Accountability Office (GAO) made a strong case for the use of MBSE in Defence acquisition projects with: '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:

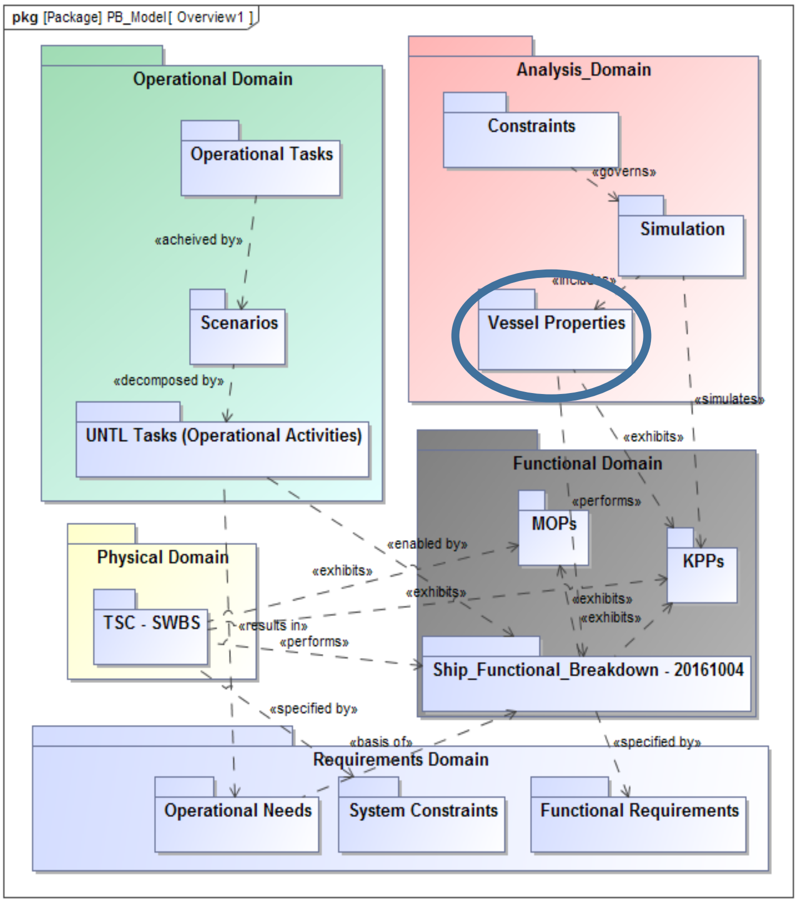
1. Maintain traceability to the original, strategic intent of the vessel being acquired in order to ensure a defensible outcome.
2. Assist the stakeholders to make defensible decisions that account for competing goals and objectives.
3. Maximise the capacity to reuse elements – thereby reducing subsequent 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, Morris, Harvey, and Gordon (2013: p. 3) state:

> 'The principal reason for using metamodels in MBSE is to create structure and consistency in the model and associated products.'

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, Do, Robinson, Lay, & Niedbala, 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.



Acronyms:
UNTL = Universal Naval Task List.
TSC = Technical Subject Code.
SWBS = Ship Work Breakdown Structure.
MOP = Measure of Performance.
KPP = Key Performance Parameter.

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**	**MDA**	**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, Rodgers, Wharington, & Demediuk, 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.

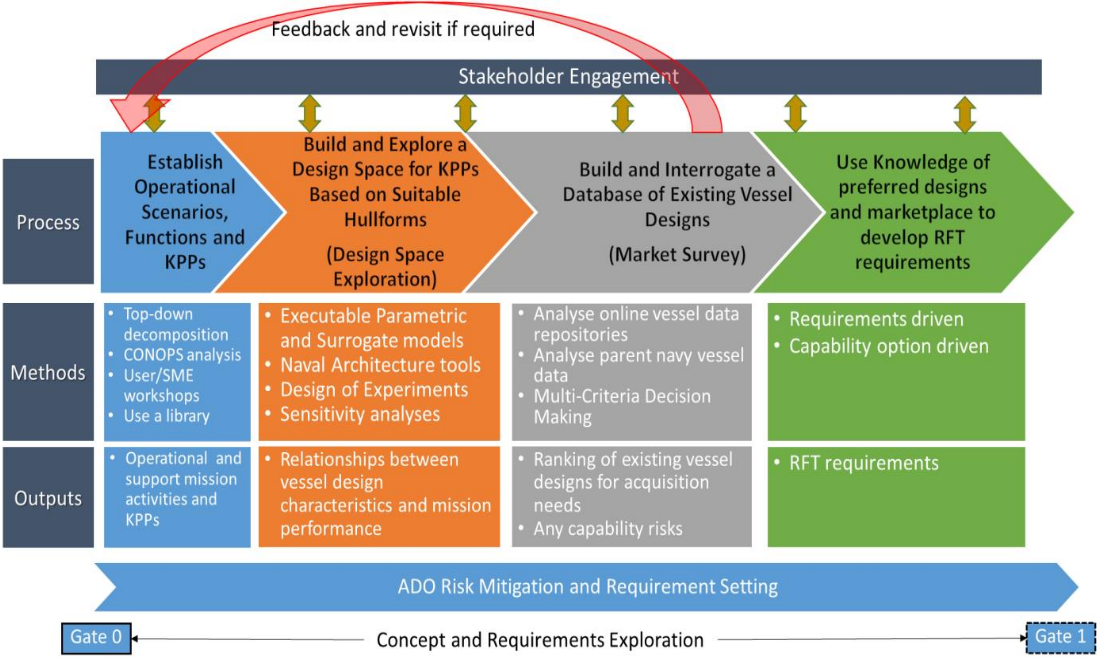


Figure 3: Overview of the Off-the-Shelf Concept and Requirements Exploration methodology

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.

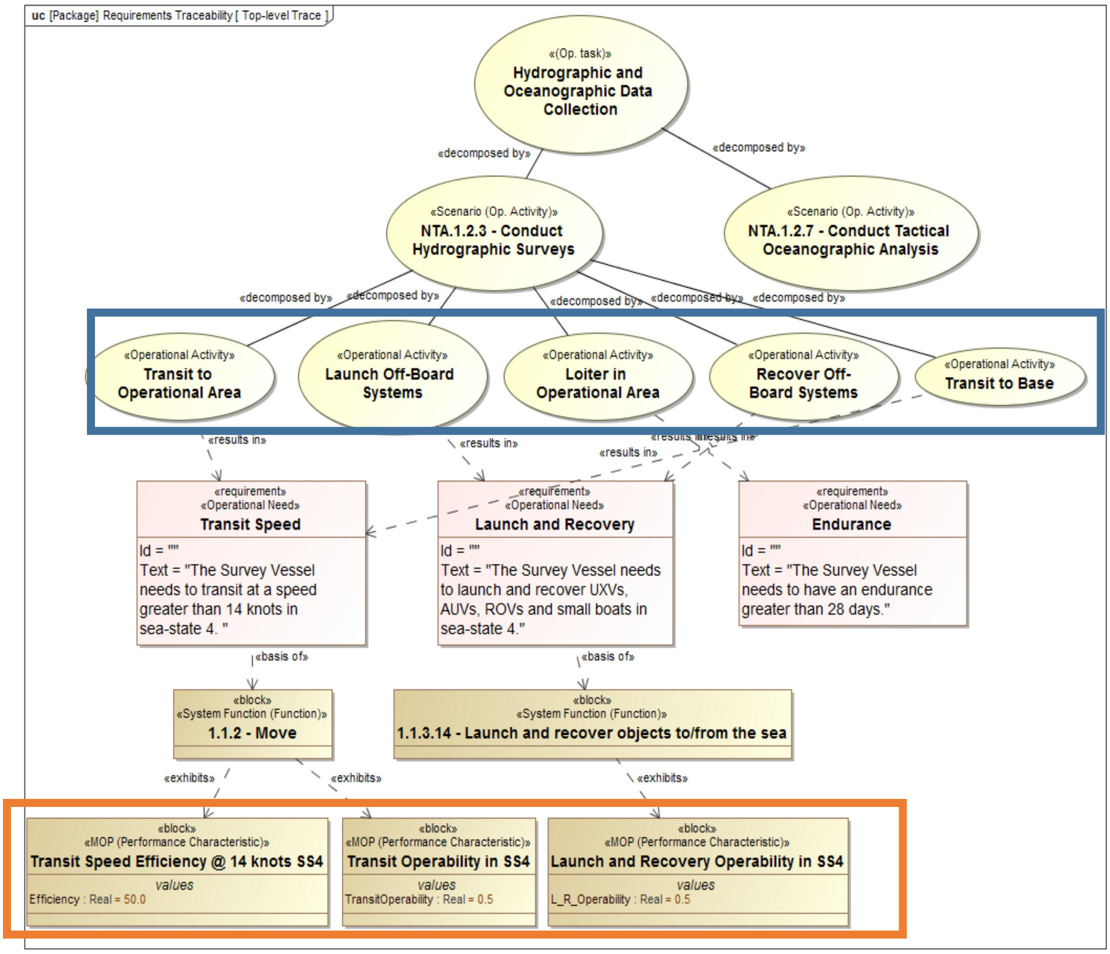


Figure 4: Decomposition from high-level guidance through to the KPPs related to the transit speed and Launch and Recovery Operational Needs.

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.

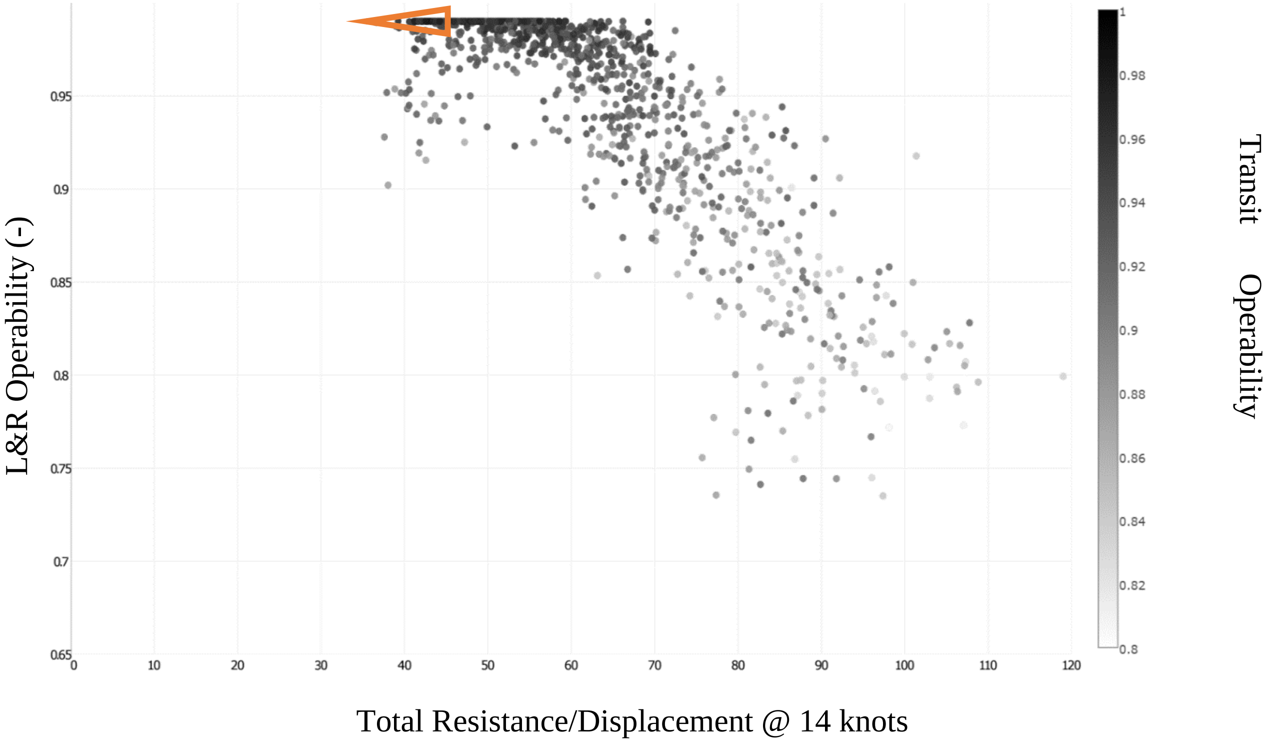


Figure 5: Scatterplot of the 1000 run DOE for the hydrographic survey vessel hullform in sea state 4.

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 four 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.

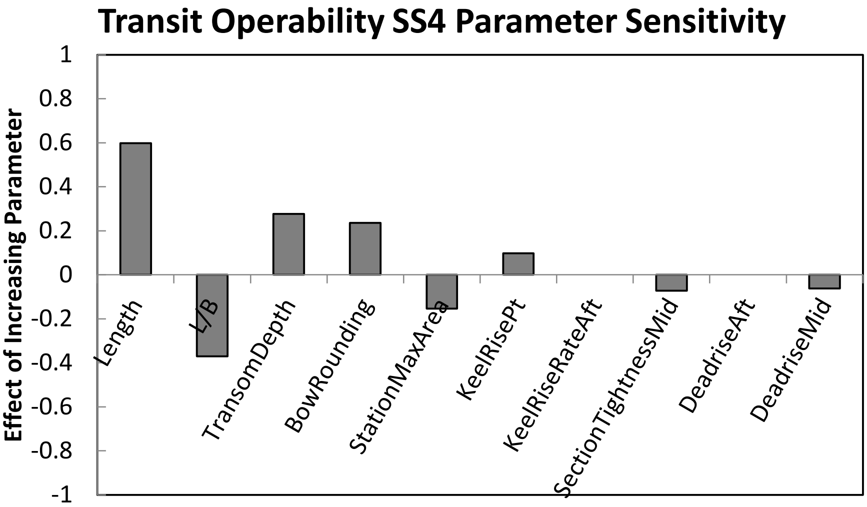


Figure 6: Vessel design parameter sensitivity for the Transit Operability in sea state four KPP.

Figure 7 shows the vessel design parameter sensitivities for the launch and recovery operability in sea state four 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.

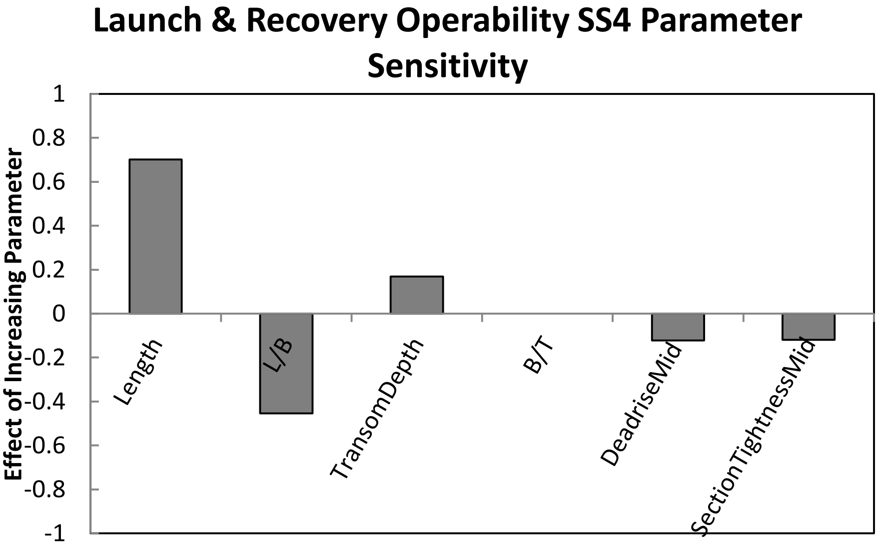


Figure 7: Vessel design parameter sensitivity for the launch and recovery operability in sea state four KPP.

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.

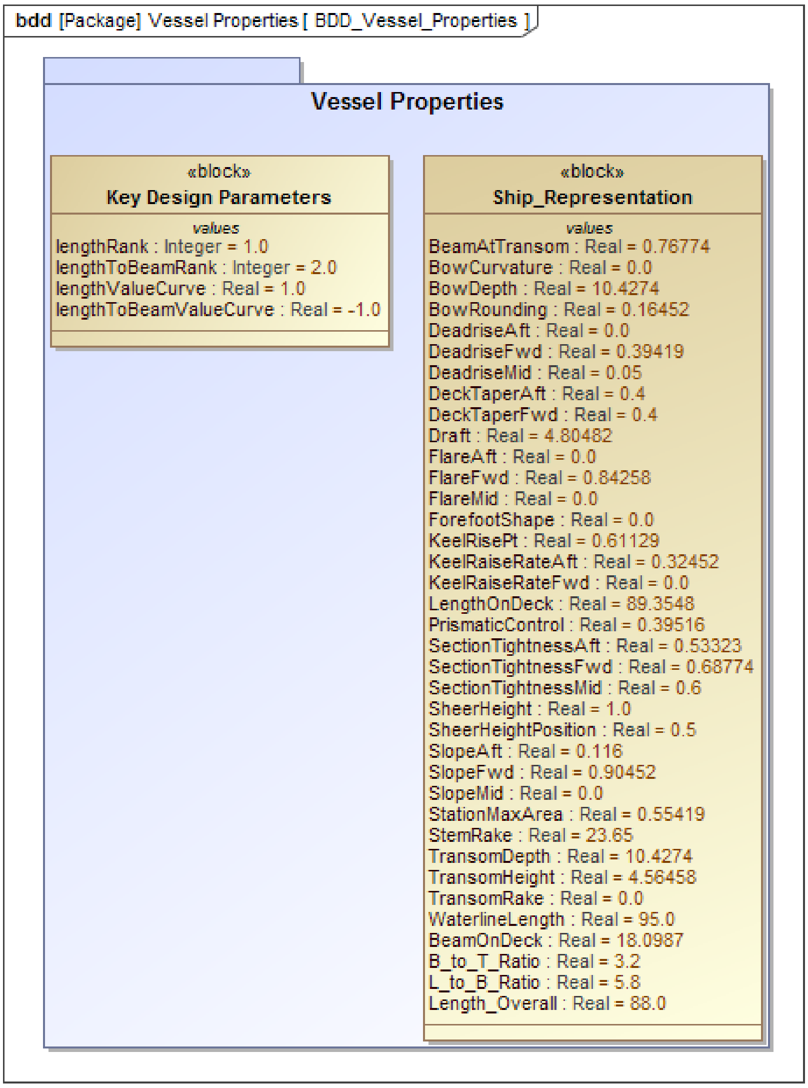
This step uses the knowledge gained from the previous step to build, then rank a database of existing vessel designs based on the preferred combinations of design parameters. For the hydrographic survey vessel example implementation, a database of existing designs was built from relevant existing vessel 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 ten vessels in the database with lengths between 65 and 95 metres is shown in Table 3.

Table 3: Top ten 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.



bdd [Package] Vessel Properties [BDD_Vessel_Properties]

Vessel Properties

«block»
Key Design Parameters

values
lengthRank : Integer = 1.0
lengthToBeamRank : Integer = 2.0
lengthValueCurve : Real = 1.0
lengthToBeamValueCurve : Real = -1.0

«block»
Ship_Representation

values
BeamAtTransom : Real = 0.76774
BowCurvature : Real = 0.0
BowDepth : Real = 10.4274
BowRounding : Real = 0.16452
DeadriseAft : Real = 0.0
DeadriseFwd : Real = 0.39419
DeadriseMid : Real = 0.05
DeckTaperAft : Real = 0.4
DeckTaperFwd : Real = 0.4
Draft : Real = 4.80482
FlareAft : Real = 0.0
FlareFwd : Real = 0.84258
FlareMid : Real = 0.0
ForefootShape : Real = 0.0
KeelRisePt : Real = 0.61129
KeelRaiseRateAft : Real = 0.32452
KeelRaiseRateFwd : Real = 0.0
LengthOnDeck : Real = 89.3548
PrismaticControl : Real = 0.39516
SectionTightnessAft : Real = 0.53323
SectionTightnessFwd : Real = 0.68774
SectionTightnessMid : Real = 0.6
SheerHeight : Real = 1.0
SheerHeightPosition : Real = 0.5
SlopeAft : Real = 0.116
SlopeFwd : Real = 0.90452
SlopeMid : Real = 0.0
StationMaxArea : Real = 0.55419
StemRake : Real = 23.65
TransomDepth : Real = 10.4274
TransomHeight : Real = 4.56458
TransomRake : Real = 0.0
WaterlineLength : Real = 95.0
BeamOnDeck : Real = 18.0987
B_to_T_Ratio : Real = 3.2
L_to_B_Ratio : Real = 5.8
Length_Overall : Real = 88.0

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.

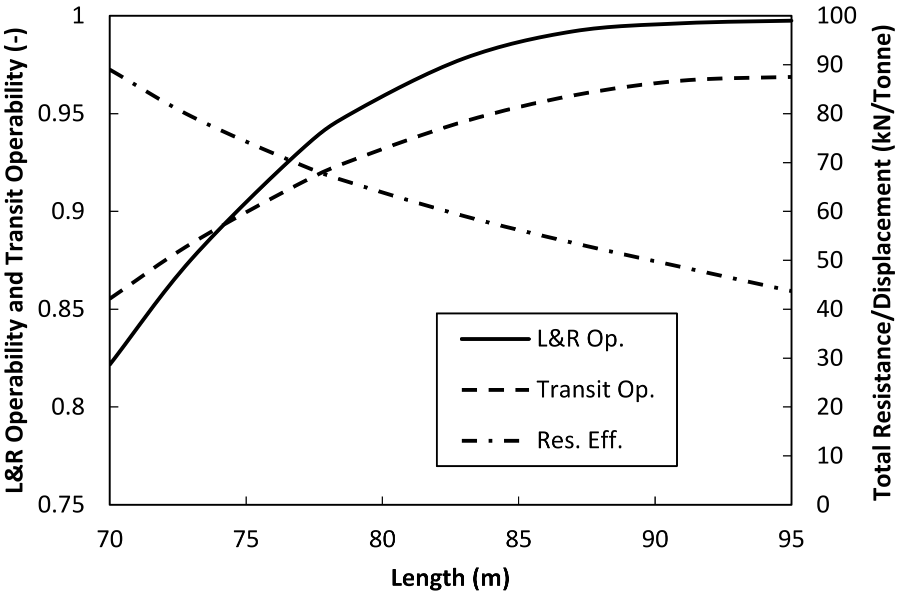
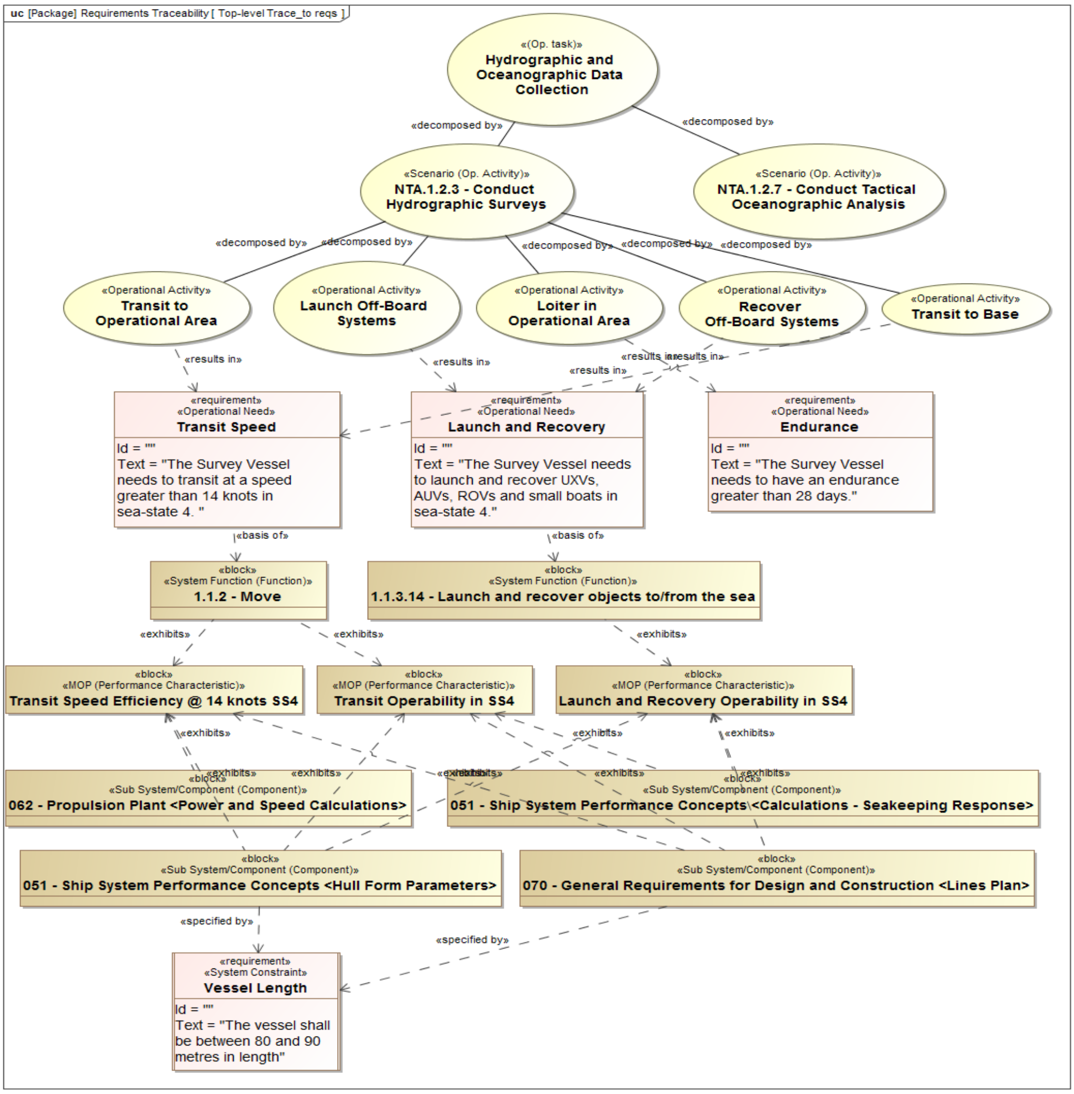


Figure 9: Relationships between vessel length and the operabilities (L&R Op. and Transit Op.) in sea state4 KPPs and transit speed efficiency (Res. Eff.) in sea state 4 KPP for the hydrographic survey hullform.

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) has 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.



Transit Speed
Id = ""
Text = "The Survey Vessel needs to transit at a speed greater than 14 knots in sea-state 4. "

Launch and Recovery
Id = ""
Text = "The Survey Vessel needs to launch and recover UXVs, AUVs, ROVs and small boats in sea-state 4."

Endurance
Id = ""
Text = "The Survey Vessel needs to have an endurance greater than 28 days."

Vessel Length
Id = ""
Text = "The vessel shall be between 80 and 90 metres in length"

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. Note that only a partial mapping is shown for clarity.

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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Stephen Cook is the Professor of Defence Systems at the University of Adelaide where he works in the Entrepreneurship, Commercialisation and Innovation Centre undertaking research and teaching in system of systems engineering and complex project management. He is also a Systems Engineering Advisor with Shoal Engineering Pty Ltd where he applies his knowledge to a range of systems engineering management and research challenges. Until June 2014 he was the Professor of Systems Engineering at the University of South Australia where he led a number of research concentrations for over 15 years. Preceding this he accumulated 20 years of industrial R&D and SE experience spanning aerospace and defence communications systems. Prof Cook, PhD, is an INCOSE Fellow, a Fellow of Engineers Australia, and a Member of the Omega Alpha Association.

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Dylan Dwyer graduated from the Australian Maritime College with a Bachelor of Engineering (Naval Architecture) with Honours. He joined DST Group in 2016 as a graduate Naval Architect working under the discipline of Platform Systems Analysis. In his time at DST Group Dylan has developed, and is continuing to expand his knowledge of Systems Engineering practices. Dylan is currently undertaking studies towards a Masters in Systems Engineering.