AN INVESTIGATION INTO THE APPLICATION OF FORMAL DECISION MAKING TECHNIQUES TO DESIGN ALTERATIONS AND ADDITIONS (As&As) FOR VESSELS OF THE ROYAL FLEET AUXILIARY (RFA)

DAVID FRANKS

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

May 2018

Dedication

Submission of this thesis represents the attainment of a personal and professional goal, profoundly felt since its journey has been long and difficult amidst life and career challenges. Completion of the thesis is dedicated to my children, Matthew and Rebecca, in the expectation that it will encourage them to strive for achievement throughout the journeys of their own lives, especially when faced with their most challenging circumstances.

Abstract

The Royal Fleet Auxiliary (RFA) is a flotilla of ships, owned by the United Kingdom (UK) Ministry of Defence (MoD), which serves to resupply naval vessels during worldwide operations. Design Alterations and Additions (As&As) are implemented throughout their service lives in order to 'Upgrade' and 'Update' their capability. This research offers an original contribution to knowledge by applying formal decision making techniques to A&A reasoning in a way that, to the best knowledge of the researcher, has not previously been implemented as an integral part of the in-service design control process for RFA ships. In delivering this contribution, Multi Attribute Decision Making (MADM) techniques are investigated and applied.

Three MADM techniques are applied: SAW (Simple Additive Weighting), AHP (Analytic Hierarchy Processes) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution). Application of these techniques defines the scope boundary and so rules out exhaustive investigation into the wider decision making approaches that could form the focus of future research.

Literature reviews indicate that formal decision techniques have been extensively studied and applied – seemingly to the point of saturation. For this reason, the research does not claim to have developed new techniques. Rather, the contribution to knowledge lies in the systematic application of the techniques. In this respect, a niche topic is identified involving the implementation of As&As during Fleet Time (FT). Investigation results in the systematic identification and categorisation of the Risk Factors (RFs) constraining FT implementation.

Two different techniques (SAW and AHP) are applied to FT As&As. The outcomes demonstrate a consistent trend and so offer mutual assurance. In addition, comparison of the techniques indicates that, whilst SAW offers a convenient and intuitive approach, the AHP imposes a higher cognitive burden. This is regarded as significant by the researcher since As&As are subject to schedule and cost constraints, whereby pragmatic and proportional approaches are more likely to find programme acceptance.

Based upon an actual decision involving the selection of materials for a ship sea water system, TOPSIS is used to evaluate the options against key criteria. A sensitivity analysis indicates that selection will be influenced in the direction of

the criteria weighting. Since ‘procurement cost’ is an important criterion for As&As, the thesis demonstrates a methodology for the delivery of robust cost estimates. This involves the treatment of cost uncertainty using risk analysis software based upon the Monte Carlo technique.

The researcher consolidates studies into systematic decision methodologies for As&As. Credibility is claimed since methodologies are based upon established techniques and tested against A&A examples. Credibility is also claimed from the theme, running throughout the thesis, that the studies build upon the professional experience of the researcher and involve engagement with Suitably Qualified and Experienced Personnel (SQEP).

Acknowledgements

The researcher wishes to offer special thanks to his academic supervisor, Prof. Jin Wang. This thesis would not have been completed without Prof. Wang's support, guidance and patience. The researcher also wishes to offer thanks for the academic supervision offered by Prof. Zaili Yang and Dr. Alan Wall, and for the external academic advice offered by Prof. David Andrews.

With regard to specific content, the researcher acknowledges the contributions and support offered in the form of the following:

- David Rush offered guidance throughout the professional experience of the researcher in support of the RFA between 2008 and 2012. In addition, David provided contributions to support descriptions of the RFA and As&As within Chapter 2 and Chapter 3. At the time of writing, David was the Capability, Safety and Design Authority Group Leader, Commercially Supported Shipping, MoD.
- Gareth Nicklin, (Lt Cdr, RN), offered discussion and advice towards the material selection issues considered within Chapter 7. The chapter draws upon a paper presented by Gareth at INEC 2008 that is directed towards the impacts of Microbiologically Induced Corrosion. At the time of writing, Gareth was a colleague of the researcher working within the field of design assurance for marine systems.
- Paul Shipley conducted a review of Chapter 7 and offered advice towards the arguments presented. At the time of writing, Paul was a Programme Chief Engineer within the MoD.
- Ian Baker provided the 'riskHive Analyser' software used to conduct the cost uncertainty analysis within Chapter 8. Ian previously provided cost risk training undertaken by the researcher. At the time of writing, Ian was a director for 'riskHive Solutions Ltd'.
- Tim Duke offered discussion of the 'riskHive' software and demonstrated use of the 'Arrisca Analyser'. At the time of writing Tim was a Cost Engineer within the MoD and a former colleague of the researcher.

- Tom Jones offered assistance towards compiling the cost data associated with the A&A work package discussed within Chapter 8. At the time of writing Tom was a Cost Engineer within the MoD and a former colleague of the researcher.

- Catherine Franks and Deirdre Williams offered discussion and advice towards the presentation of thesis content. Catherine offered the benefit of academic librarian experience. Deirdre offered the benefit of civil service administrative experience.

More widely, the researcher acknowledges the Subject Matter Expertise that has informed this thesis, as offered by the range of stakeholders encountered by the researcher throughout his professional experience. These have included RFA and RN sea-going engineers, MoD design engineers, MoD cost engineers and engineers with responsibility for design and production within commercial shipyards - notably Cammell Laird shipyard. Their expertise has been offered with competence, passion and the desire to ‘get it right’.

Finally, the researcher gratefully acknowledges the support offered by the MoD throughout these studies in the interests of furthering his professional development.

Table of Contents

List of Tables

List of Figures

Abbreviations

A(s)&A(s)	Alteration(s) and Addition(s)
A/C	Air Conditioning
ACP	Annual Certification Period
AFSH	Auxiliary Fleet Support Helicopter (Fort Rosalie Class)
AfSup	Afloat Support
AHP	Analytic Hierarchy Process
ALARP	As Low As Reasonably Practicable
AMP	Assisted Maintenance Period
AO	Auxiliary Oiler (WAVE Class)
AOL	Auxiliary Oiler Light (Rover Class)
AOR	Auxiliary Oiler Replenishment (Fort Victoria Class)
AOT	Auxiliary Oiler tanker (Leaf Class)
AAR	Appropriate, Attributable and Reasonable
ASCG	Automated Small Calibre Gun
AVI	Aviation (Functional Capability Group)
BoE	Basis of Estimate
BR(d)	Book of Reference (digitally stored and presented)
C3	Command Control and Communicate (Functional Capability Group)
CAAS	Cost Assurance and Analysis Service
CAS	Condition Assessment Scheme
Cat	Category (of urgency)
CCTV	Closed Circuit Television
Cdr	Commander
CDA	Copper Development Association
CDF	Cumulative Distribution Function (also Cumulative Density Function)
CEBOK	Cost Engineering Body of Knowledge
CEDD	Cost Engineering Directed Development
CER	Cost Estimating Relationship

Chap.	Chapter
CIWS	Close-In Weapon System
CL	Cammell Laird
CO	Commanding Officer
CO2	Carbon Dioxide (firefighting system)
COTS	Commercial Off The Shelf
CSA	Certification of Safety for Aviation
CSE	Certification of Safety for Explosives
CSP	Contractor Support Period
CSS	Commercially Supported Shipping
CuNi	Copper-Nickel
DCB	Design Control Board
DE&S	Defence Equipment & Support
DES Ships	Defence Equipment & Support - Ships
DEC	Directorate Equipment Capability
dk	Deck
DP	Docking Period
DRA	Defence Reform Act
DSA	Disposal Services Authority
DSA-DMR	Defence Safety Authority – Defence Maritime Regulator
DSPCR	Defence and Security Public Contracts Regulations
DSTL	Defence Science and Technology
ELECTRE	ELimination Et Choix Traduisant la REalité (ELimination and Choice Translating REality)
ENV	Environmental (Functional Capability Group)
EU	European Union
FCG	Functional Capability Group
FISS	Future In-Service Support
Flt	Flight
FOI	Freedom Of Information

FRS	Forward Repair Ship
FSS	Fleet Solid Support
FT	Fleet Time
FT_DP	Fleet Time Decision Point
FTS	Fleet Time Support
GDP	Gross Domestic Product
HAB	Habitability (Functional Capability Group)
HAB_RF	Habitability Risk Factor
HCO	Helicopter Control Officer
HFO	Heavy Fuel Oil
HRAS	Heavy Replenishment At Sea
ICE	Independent Cost Estimate
ICEAA	International Cost Estimating and Analysis Association
ILS	Integrated Logistic Support
IMO	International Maritime Organization
INV	Invasiveness
INV_RF	Invasiveness Risk Factor
IPMS	Integrated Platform Management System
IS	Ideal Solution
ITT	Invitation To Tender
LCU	Landing Craft Utility
LFE	Learning From Experience
LR	Lloyd’s Register
LSDA	Landing Support Dock Auxiliary (Bay Class)
Lt	Lieutenant
MADM	Multi Attribute Decision Making
MARPOL	Marine Pollution (convention)
MARS	Military Afloat Reach and Sustainability
MAS	Machinery And Systems (Functional Capability Group)

Max	Maximum
MCA	Maritime and Coastguard Agency
MCDM	Multi Criteria Decision Making
MCR	Machinery Control Room
MCTA	Marine Commissioning Trialling and Acceptance
MIC	Microbiologically Influenced Corrosion
Min	Minimum
ML	Most Likely
MMMF	Man Made Mineral Fibres
MMS	Main Machinery Space
MoD	Ministry of Defence
MODM	Multi Objective Decision Making
MS	Microsoft
NAB	Nickel Aluminium Bronze
NATO	North Atlantic Treaty Organization
NCHQ	Naval Command Headquarters
NDP	Naval Design Partnering
NIS	Negative Ideal Solution
OCIMF	Oil Companies International Marine Forum
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OOW	Officer Of the Watch
PDF	Probability Distribution Function (also Probability Density Function)
PESA	Public Expenditure Statistical Analyses
PMBOK	Project Management Body of Knowledge
QDC	Qualifying Defence Contract
QEC	Queen Elizabeth Class
RAS	Replenishment At Sea
RASCO	RAS Control

REPL	Replenishment (Functional Capability Group)
RF	Risk Factor
RFCO	Risk Factor Control Option
ROM	Rough Order of Magnitude
Ro-Ro	Roll on – Roll off
RF	Risk Factor
RFA	Royal Fleet Auxiliary
RN	Royal Navy
RP	Refit Period
RO	Reverse Osmosis (fresh water production)
RR	Rank Reciproca
S	Separation
SAF	Safety (Functional Capability Group)
SAW	Simple Additive Weighting
SDD	Sodium Dimethyl Dithiocarbonate
SDI	Structure Damage and Integrity (Functional Capability Group)
SDSR	Strategic Defence and Security Review
SME	Subject Matter Experts
SOLAS	Safety of Life At Sea (convention)
SQEP	Suitably Qualified and Experienced Personnel
SSCR	Single Source Contract Regulations
STCW	(International Convention on) Standards of Training, Certification and Watchkeeping for Seafarers
STUFT	Ships Taken Up From Trade
SURV	Survivability
SURV_RF	Survivability Risk Factor
SWL	Safe Working Load
SYS	(Ship) Systems
SYS_RF	(Ship) Systems Risk Factor
TLC	Through Life Cost

TLS	Through Life Support
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UK	United Kingdom
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UPC	Unit Procurement Cost
US	United States (of America)
USN	United States Navy
VERTREP	Vertical Replenishment
WBS	Work Breakdown Structure
WMTC	World Maritime Technology Conference
WPM	Weighted Product Method
wrt	with respect to

Chapter 1: Introduction

1.1 Background

This thesis is directed towards the decision making for design changes to ships of the Royal Fleet Auxiliary (RFA) throughout their service life.

The RFA is a flotilla of surface ships, owned by the UK MoD, which serves to resupply naval vessels during worldwide operations of the Royal Navy (RN), NATO[1] and the UN[2]. RFA ships are primarily civilian-manned, although RN personnel may form part of ships' crews as operators and maintainers where military equipment forms part of RFA ship systems.

In-service support is directed towards RFA vessels throughout their lifecycle in terms of Upgrade (adding ship capability), Update (maintaining ship capability) and Upkeep (assuring continuous ship availability in compliance with statutory and classification requirements)[3].

As part of that in-service support, design Alterations and Additions (As&As) are applied to RFA vessels in order to Upgrade and Update their capability. The term 'A&A' relates to a formal engineering design change, including the associated management process, which alters the structure, systems or layout of the vessel (DE&S, 2015).

The consideration of an A&A proposal, and its subsequent implementation if supported, is brought about by informed reasoning and expert judgement by Suitably Qualified and Experienced Personnel (SQEP) throughout a design control process. This involves collective decision making during Design Control Boards (DCBs), as explained further within Sections 3.5 and 4.1.

This thesis is largely concerned with the DCB practices and business processes conducted by the researcher during his work supporting the RFA between 2008 and 2012. More widely, the thesis draws upon the professional experience gained

[1] NATO – North Atlantic Treaty Organization, a political and military alliance founded in 1949 and consisting of 29 member countries in 2017, from North America and Europe.
[2] UN – United Nations, an international organization founded in 1945 and consisting of 193 member states in 2017. The work of the UN is directed towards international security, development, human rights and humanitarian assistance.
[3] The terms 'Upgrade', 'Update' and 'Upkeep' are capitalised here because they are formally defined terms used within the context of RFA As&As, as explained within Chapter 2 and further explained within Chapter 3.

by the researcher within a number of MoD posts between 2007 and 2017, inclusive, as a marine engineer conducting design assurance and cost engineering.

1.2 Contribution to Knowledge - Research Hypothesis and Objectives

This research seeks to offer an original contribution to knowledge by applying formal decision making techniques to A&A reasoning in a way that has not previously been implemented as an integral part of the in-service design control process for RFA ships. Therefore, this research examines the hypothesis[4] that formal decision making techniques can be applied to As&As for RFA ships.

In order to investigate this hypothesis, this thesis has the following supporting objectives:

- Investigate and explain the nature of the RFA within its context as a flotilla of ships to which a regulatory framework applies that imposes requirements for ship safety, the management of systems obsolescence and the delivery of continuous operational effectiveness.
- Investigate and explain the concept of As&As as the means of implementing in-service design change in order to Upgrade and Update RFA ships. Demonstrate the DCB management process that is applied to the delivery of Upgrade and Update with respect to the decision making directed towards the acceptance, development and implementation of As&As.
- Investigate and explain the concept of Multi Attribute Decision Making (MADM)[5] as the means of evaluating a range of decision alternatives against a range of key criteria (attributes) judged important within the decision context.
- Investigate and demonstrate the application of MADM within the context of the decision making directed towards the acceptance, development and implementation of As&As within the design control process for RFA ships in service.

[4] The term ‘hypothesis’ is being used qualitatively to establish a supposition as a starting point for further investigation. It is not used in the sense of statistical analysis.
[5] In this context, the terms ‘Multi’ and ‘Multiple’ are used interchangeably.

- Investigate and demonstrate the significance of financial cost as a key criterion against which design options are evaluated. Provide a pragmatic understanding of the cost engineering principles applicable to As&As, including the analysis of cost uncertainty.

Building upon the professional experience of the researcher, this thesis seeks to offer a pragmatic and proportional approach that could be applied to A&A decision scenarios that will be subject to practical time and cost constraints.

1.3 Scope of Study and Delimitation

The objectives within Section 1.2 state the proposed contribution to knowledge and define the scope of work in terms of investigations into:

- The RFA.
- The As&As implemented to RFA ships.
- The MADM techniques that may be applied to As&As.
- The cost engineering associated with As&As.

The studies are, therefore, focussed upon the decision making applicable to As&As. However, the scope of work has the following delimitation:

- The thesis does not seek to offer an exhaustive critical review of decision making techniques. Nor does it seek to propose any new or hybrid decision techniques. Rather, a bounded range of established MADM techniques is defined, reviewed and applied, as explained within Chapter 4.
- Whilst the computation of decision making techniques is investigated and applied, the psychology of decision making is not the focus of this study. Only in Chapter 7 is discussion directed towards cognitive bias where the impact of bias towards cost is demonstrated by a sensitivity analysis.
- The thesis postulates the application of a bounded number of MADM techniques to a bounded number of A&A scenarios. The aim is to demonstrate how formal techniques could be applied in a way not previously implemented. It is the expectation of the researcher that this study will form the basis of future research to expand upon the findings. Hence, the thesis does not seek to formulate and present a comprehensive framework of decision support tools applicable to all decision making scenarios for As&As.

1.4 Structure of Thesis

The structure of the thesis is shown within Figure 1.4.1.

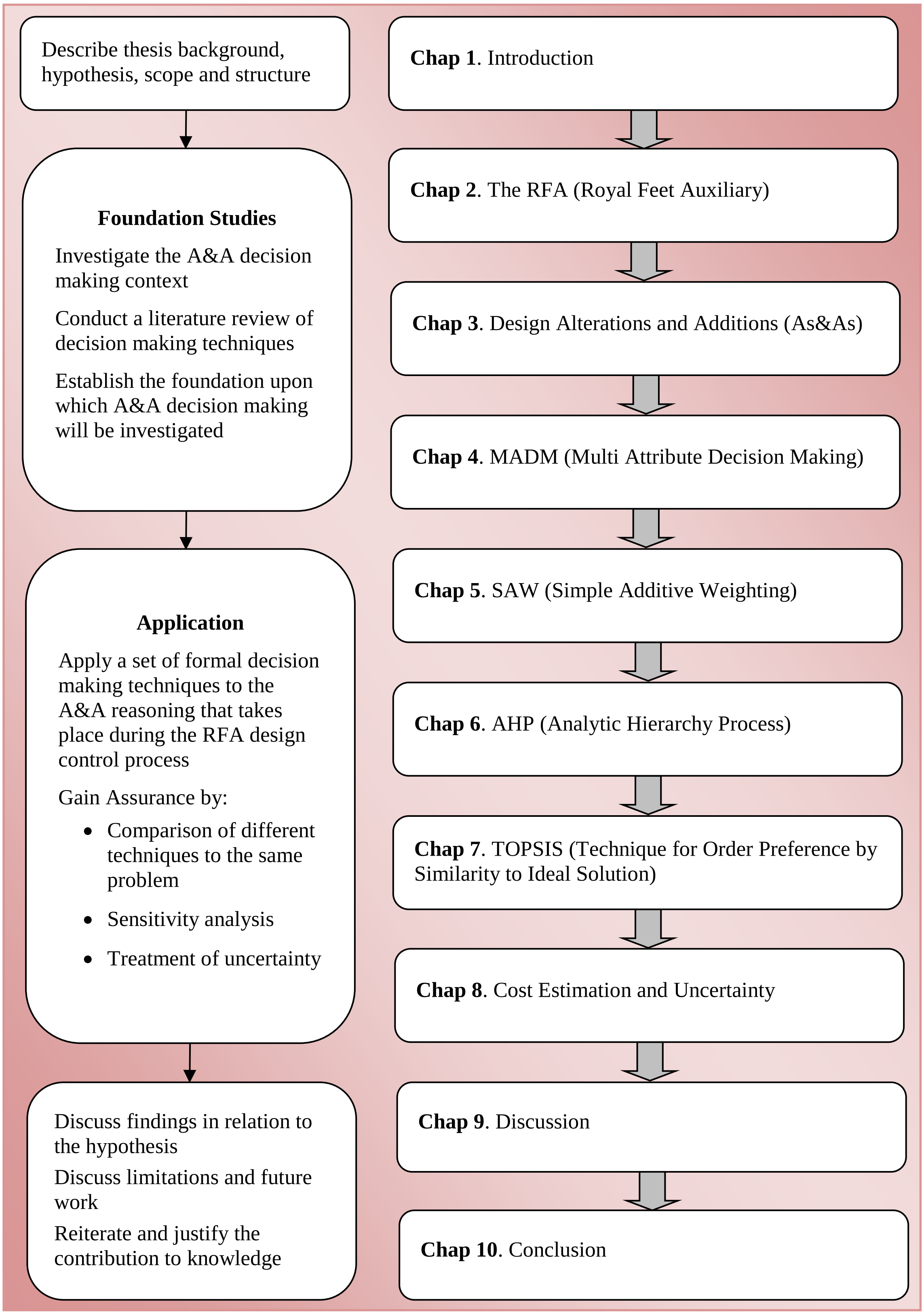


Figure 1.4.1. The Thesis Structure

Chapters 1 to 4 provide the foundation upon which subsequent chapters apply formal techniques to A&A decision making. No single chapter is devoted to a literature review. Instead, literature reviews are conducted throughout the thesis to establish understanding towards the body of knowledge for the subjects as each is encountered.

The research is introduced within Chapter 1. The research context is given, the hypothesis is stated and the scope of work is defined.

Chapter 2 offers a detailed introduction to the RFA in terms of its role and the types of vessels.

Chapter 3 defines As&As within the context of the in-service support given to vessels of the RFA. A description of the design control process related to As&As is given, together with A&A examples drawn from actual records across 6 ship classes, covering 9 of the 13 ships in RFA service between 2008 and 2012.

Chapter 4 introduces MADM and the underlying concepts for a number of MADM techniques.

Chapters 5 to 7 are concerned with the application of MADM techniques, appropriate to the A&A decision problem, with the aim of making decisions that have systematic and objective justification. Throughout application of the MADM techniques, judgements are made towards decision attributes and options. The basis upon which these judgements are justified is described within Appendix B.

Chapters 5 and 6 demonstrate the application of two decision techniques (SAW and AHP) to the same A&A problem, thereby providing the basis for comparison.

Chapter 7 applies a further technique (TOPSIS) to an actual selection exercise in a way that was not performed during the original exercise. Chapter 7 also demonstrates, by a sensitivity analysis, that a decision outcome can be biased towards ‘procurement cost’ by preferably weighting the cost attribute. This demonstrates the need for robust cost estimation when including cost as an attribute. For this reason, Cost Engineering, including the treatment of cost uncertainty, forms the focus of Chapter 8.

Chapters 9 and 10 discuss the research findings, suggest further work that could build upon the thesis and offer a response to the objectives stated at the outset of the thesis.

Chapter 2: The Royal Fleet Auxiliary (RFA)

Abstract

The RFA is a civilian-manned fleet, owned by the UK MoD, which serves to resupply naval vessels during worldwide operations of the RN, NATO and the UN. This chapter offers a detailed introduction to the RFA in terms of its role and the types of vessels employed to perform that role. The changing structure of the RFA flotilla between 2007 and 2017 is described and explained, then the planned future vessels are introduced.

2.1 The Concept of Global Fleet Support for Naval Vessels

Forward Support is that aspect of naval operational logistics by which military capability can be sustained when fleet elements operate away from home ports with global reach. Martin (2016a) asserts that 'sustained reach' is the most important attribute for naval forces since maritime security is a global concept. Furthermore, he argues that a navy with global commitments must have considerable afloat support logistics, since logistics will determine whether a naval ship or task force can sustain those commitments for extended periods (Martin, 2016b). Hence, without a network of overseas sovereign bases, and owing to the vast distances defined by 'global reach', there is a requirement to resupply naval vessels during deployments for military operations, exercises and other commitments which, in the contemporary world, include humanitarian relief, anti-piracy patrols and counter-narcotics operations. This requirement is satisfied by vessels generically referred to as 'auxiliaries', universally understood as vessels designed to provide combatant ships with support. This support is most typical as the Replenishment At Sea (RAS) of fuel, ammunition, food and supplies, as shown within Figure 2.1.1. Support may also include ships providing transport, forward repair, amphibious landing and survey services.

In all cases, support is provided by vessels having design characteristics and capabilities dedicated towards their particular role. As an example, the concept of forward repair was illustrated during the second World Maritime Technology Conference (WMTC) when Kimber (2006a) presented a paper describing the historical perspective, current capabilities and future requirements for repair and maintenance at sea. In addition, the naval architectural characteristics of a proposed Joint Support Ship were presented by Andrews & Pawling (2007) for a number of configurations developed using their SURFCON Design approach.

Figure 2.1.1. Replenishment At Sea (RAS) Between Vessels

2.2 The Royal Fleet Auxiliary (RFA)

The RFA was first established in 1905 and is a civilian-manned fleet, owned by the UK MoD, which supports worldwide operations of the RN, NATO and the UN (Royal Navy, 2017a). The RFA flotilla is capable of resupplying naval vessels with fuel, ammunition, food, fresh water, spare parts and a range of other supplies. In addition, it can provide support facilities for aviation, casualty evacuation, amphibious operations and forward repair.

2.3 Vessel Type and Role

A profile for the RFA is given within Appendix A. This shows the ships, their type and their role[6]. It covers the period 2007 to 2017 and so encompasses the engineering experience for RFA vessels gained by the researcher between 2008 and 2012. It is evident that a significant number of elderly vessels were taken out of service between 2007 and 2017. As discussed within Sections 2.5 and 2.6, these will be replaced as part of programmes for future ships. At the time of writing, the latest (Tide Class) tankers had not been commissioned into RFA service.

[6] Information has been extracted from various sources within the public domain including the websites for the Royal Navy, the UK Ministry of Defence, the RFA Historical Society and Wikipedia. Details were current in Aug 2017 before the Tide Class tankers were commissioned into RFA service.

2.4 Regulatory Framework and General Design Characteristics

Vessels of the RFA are not designed and built to be naval warships. Naval regulations for Royal Fleet Auxiliaries (Royal Navy, 2011) clarify that RFA vessels are registered as British merchant ships under the 'Merchant Shipping (Ministry of Defence Ships) Order-in-Council 1989 No. 1991'. The vessels are built and maintained in accordance with Lloyd's Register (LR) Classification Rules. Furthermore, the Secretary of State for Defence requires that, as far as reasonably practicable, the safety and environmental management of MoD shipping activities is at least as safe and effective as that required for UK commercial shipping activities (DSA-DMR, 2016)[7]. Consequently, Merchant Shipping Acts are applied to RFA vessels[8] and the Maritime and Coastguard Agency (MCA) acts as the UK Flag Authority. It therefore follows that each vessel is subject to ongoing statutory and class certification during periodic Upkeep[9] periods in accordance with a 5-year refit cycle, meaning that a routine of regular maintenance and inspection milestones is repeated every 5 years.

Since the RFA is owned and operated by the UK Government, and since the UK is a member state of the International Maritime Organization (IMO), all RFA vessels must comply with the IMO conventions, codes and regulations aimed at safety, environmental concerns, legal matters, technical co-operation, maritime security and the efficiency of shipping. Enforcement is enacted by national and regional maritime authorities from member countries.

Therefore, it follows that, except for those vessels having particular naval characteristics (notably RFA Fort Victoria, the Bay Class LSDAs and RFA Argus), the fundamental design for ships of the RFA flotilla closely resembles that for commercial tankers, cargo vessels and support ships. Indeed, the Leaf Class tankers, RFA Argus and RFA Diligence were originally built for commercial service before becoming 'Ships Taken Up from Trade' (STUFT) to support

[7] The UK Defence Safety Authority sets out rules and standards, for Defence Health, Safety and Environmental Protection, at three levels consistent with the Secretary of State's policy. These are: Level 1, Departmental Policy, Level 2, Defence Regulations and Level 3, Guidance on Compliance. Specific statements towards MoD shipping regulations are made at Level 2, as referenced.

[8] The Merchant Shipping (Ministry of Defence Ships) Order 1989 prescribes those sections of the Merchant Shipping Acts applicable to MoD (Government) ships on non-commercial service.

[9] The terms 'Upgrade', 'Update' and 'Upkeep' are given capital first letters because they have formal definition in the RFA context – as explained within this Chapter and further explained within Chapter 3.

military operations around the time of the Falklands conflict in 1982. These ships were subsequently acquired by the UK Government, renamed, and put through a major conversion programme for RFA service.

The AFSH replenishment ships (Fort Austin, Fort Rosalie), the Rover Class tankers[10] and the Leaf Class tankers[11] could be characterised as single hull construction with diesel engines powering single shaft-lines. The more recent Wave Class tankers were constructed with double hulls to comply with MARPOL 73/78[12] environmental legislation (IMO, 2017a) and were built with electric ship technology having computerised platform management systems and a diesel electric configuration for propulsion and hotel services. The RFA Diligence[13] also has electric propulsion. In this case, electric motors are geared into azimuthing thrusters. Having originally been designed as a support ship for North Sea oil platforms, RFA Diligence has a dynamic positioning system that could be employed in difficult sea conditions whilst servicing submarines and surface vessels. Whilst not operated as an ice patrol ship, the hull was built to ice-class specification permitting the potential for navigation in polar regions without the assistance of an icebreaker.

Whilst RFA vessels are registered as merchant vessels and are not designed or operated explicitly as warships, it is the case that the RFA flotilla has an integral role towards naval operations. Therefore, RFA ships differ from commercial designs according to their roles in support of military objectives. The departure from commercial design is conspicuous in terms of the capability to Replenish at Sea (RAS), the carriage of munitions in magazines, the aviation capabilities and the communication equipment permitting integration with RN command and control systems. Military communications and radar offer enhanced situational awareness which, together with self defence capability (e.g. CIWS armament), contributes towards increased levels of survivability. Furthermore, by utilizing the self defence armament of an RFA vessel or its helicopter assets, the RFA could potentially act as a ‘force multiplier’ in support of amphibious forces, anti-surface

[10] RFA’s Black Rover and Gold Rover taken out of service 2016 and 2017

[11] RFA’s Oakleaf, Brambleleaf, Bayleaf and Orangeleaf taken out of service between 2007 and 2015.

[12] MARPOL 73/78 is the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978.

[13] RFA Diligence was taken out of RFA service in 2016 and offered for sale by the MoD Disposal Services Authority.

and anti-submarine operations, as well as deterrence patrols and protection of vital sea areas and shipping. The anti-piracy operations ongoing since 2008 in the Gulf of Aden and off the Horn of Africa provide examples, with RFA Fort Victoria having operated in support of the NATO led ‘Operation Ocean Shield’ during 2012.

Falling outside of the regulatory framework for merchant shipping, hazards that are associated with the naval operation and design of RFA ships are subject to Naval Authority inspection and certification for each ship. Examples include the construction of magazines or helicopter hangar facilities. These would be subject to Certification of Safety for Explosives (CSE) and Certification of Safety for Aviation (CSA).

2.5 RFA Fleet Reductions Between 2007 and 2017

2.5.1 Elderly Tankers Taken Out of Service Between 2007 and 2017

Appendix A indicates that in 2007, the RFA ships capable of providing oiler capability included a high proportion of elderly tankers. The ‘Rover’ and ‘Leaf’ Class tankers, having been launched in the 1970’s, were considered to be at the end of their service life and therefore the focus of life extension or replacement programmes. This was illustrated when, in March 2017, RFA Gold Rover was given her official end of service ceremony after 43 years supporting RN global operations (Royal Navy, 2017b). At the time she left service, RFA Gold Rover was the oldest vessel in the RFA flotilla.

Other tankers demonstrated a similar trend. Hence, having undergone her last major docking period in 2009, RFA Bayleaf ceased operational service in June 2011. In 2012 the Disposal Services Authority (DSA), acting for the UK MoD, conducted an open competition for the disposal of ‘Ex-RFA Bayleaf’. The status of preferred-bidder was awarded to the Turkish company LEYAL Ship Recycling Ltd who submitted a proposal for recycling at their dedicated dismantling facility in Aliaga, Turkey. In a report compiled by the DSA and published by the MoD (MoD, 2012a), the claimed final outturn was that 98% of materials had been sold or recycled. The report also noted that a sister ship, Ex-RFA Brambleleaf, had been dismantled in 2009 by Van Heyghen Recycling (part of the international Galloo Recycling Group) and that 98% of the material (a total of 7,249 Tonnes) had been recovered and recycled. RFA Brambleleaf had been taken out of service during the first half of 2007 along with RFA Oakleaf. RFA Oakleaf was dismantled by LEYAL Ship Recycling Ltd in 2011 (MoD, 2011).

The final Leaf Class support tanker, RFA Orangeleaf, was taken out of service in September 2015. RFA Orangeleaf had been built in the UK at Cammell Laird shipyard, Birkenhead, and launched in 1975 before being commissioned for service with the RFA in 1984 (Royal Navy, 2015).

Furthermore, in January 2016, a written question had been submitted to the Secretary of State for Defence to ask which assets were identified for decommissioning over the forthcoming 12 months. A formal response (UK Parliament, 2016) was offered stating:

"the following major equipment platforms are planned to be taken out of service in 2016: RFA Black Rover - Royal Fleet Auxiliary Fleet Support Tanker".

2.5.2 The Impact of Maritime Regulation on RFA Tanker Reductions

From Appendix A and Section 2.5.1, it can be appreciated that, except for RFA Wave Knight, RFA Wave Ruler and RFA Fort Victoria, all of the tankers operated by the RFA in 2007 had progressively been decommissioned by 2017. Whilst this might be explained purely on the basis of the age of the decommissioned ships, the most significant causal factor was the requirement to comply with a 1992 amendment to MARPOL regulations for ship construction aimed at preventing maritime oil pollution (IMO, 2017a). This made it mandatory for tankers ordered after 6 July 1993 to be fitted with double hulls or demonstrate an alternative design approved by the IMO, if they were 5,000 dwt and greater. Furthermore, the double hull requirement must be applied to existing ships under regulation 20 in Annex I of MARPOL 73/78 (previously regulation 13G). Additional background and discussion of the legal impact is offered by Liu & Maes (2009).

Double hull regulation had been developed in response to accidents involving oil pollution with costly and highly damaging effects to marine life and coastlines. The following significant incidents (IMO, 2017b) have had a direct influence on regulation:

- The SS Torrey Canyon, a Suezmax[14] tanker, spilled 120,000 tons of crude oil when it ran aground entering the English Channel in Feb 1967. At that time, this was the largest vessel ever to be wrecked. The grounding led to an environmental disaster and was instrumental in a step forward in marine pollution thinking. Previously, the potential for marine pollution had been recognised by the adoption of OILPOL 54, i.e. the International Convention for the Prevention of Pollution of the Sea by Oil, 1954. The scale of the Torrey Canyon disaster led to the IMO reviewing existing regulations and convening an international conference in 1973. This incorporated much of OILPOL 1954 (and its amendments) whilst also addressing chemicals, harmful substances carried in packaged form, sewage and garbage. With this conference still not ratified, a further conference took place 1978 following a number of additional tanker accidents. This gave rise to MARPOL 1973/78 which entered into force in October 1983. Together with subsequent amendments, this has become the main international convention covering prevention of marine pollution by ships from either operational or accidental causes (IMO, 2017c).
- The Exxon Valdez oil spill occurred in Prince William Sound, Alaska in 1989, when the vessel struck a reef and spilled approximately 11 million US gallons of crude oil. The owner, Exxon Mobil, claims to have spent over $4.3 billion as a result of the accident (Exxon Mobil, 2017). This included compensatory payments, cleanup payments, settlements and fines. The company claim to have compensated more than 11,000 local people and businesses within a year of the spill. A year later, the U.S. Congress required oil tankers to have double hulls whereby the US Oil Pollution Act of 1990 (OPA-90) required ship owners to phase out their single-hull tankers.
- MV Erika broke in two and sank having encountered heavy seas off the coast of France in Dec 1999. A major environmental disaster was caused by the release of 31,000 tons of Heavy Fuel Oil (HFO). Although the double hull amendment to MARPOL regulations had been adopted in 1992, the

[14] Suezmax is the term for the largest ship capable of transiting the Suez Canal in a laden condition. The typical deadweight of a Suezmax ship is 160,000 tons.

Erika incident prompted acceleration to the phase-out of single hull tankers leading to the 2001 amendment to MARPOL. This came into force in September 2003.

- The MV Prestige was carrying 77,000 tons of HFO grades and broke in half in Nov 2002, having become increasingly damaged during several days of stormy conditions off the coasts of France, Spain and Portugal. The consequent spill polluted the French, Spanish and Portuguese coastlines, as well as causing harm to the local fishing industry. The Prestige incident prompted a proposal by the European Union (EU) for more ambitious implementation of previously agreed international schemes aimed at preventing environmental damage due to oil spills. Specifically, three amendments were proposed, i.e. to prevent the carriage of heavy grade oil by single hull tankers, to accelerate the phasing out of single hull tankers and to implement the Condition Assessment Scheme (CAS) for the structural inspection of single hull takers over 15 years old. The proposals were subsequently accepted as an EU regulation (Liu & Maes, 2009), (EUR-Lex. 2017).

The requirements relating to single and double hull construction for oil tankers have been accepted by IMO member states and are contained within MARPOL Annex I. In terms of the single hull RFA tankers in service between 2007 and 2017, all of the regulations have had a negative impact upon their continued operation. The link between the age of these tankers and the requirement to phase out their operation is made within the MARPOL regulations. For example, the CAS inspection regime is applicable to all single-hull tankers of 15 years or older. Their continued operation must not go beyond 2015 or the date on which the ship reaches 25 years of age, whichever is earlier.

The inability to meet international regulations governing tanker design had been referred to as an 'environmental gap' by Kimber & Vik (2006b) during the second WMTC when a paper was presented outlining the single-hull dilemma and describing the new AEGIR naval replenishment tankers, jointly developed by the commercial ship designers Skipskonsulent and naval designers BMT Defence Services. It is the case then, that regardless of any other driver for the removal from service of an RFA single hull tanker, MARPOL regulations would require ship decommissioning. Indeed, all of the single hull tankers in service in 2007 had been removed from service by 2017, pending the introduction of the new (double hull) Tide Class tankers.

The only exception is the combined oiler and replenishment vessel, RFA Fort Victoria. Further to a request for clarification by the researcher to the MoD Design Authority responsible for RFA ships[15], the following response was provided regarding the Fort Victoria (FTVC) Refit Period during 2017 (RP17):

"During FTVC RP17 starting soon we will be investing heavily in steelwork and creating an ‘equivalent’ double hull standard that will allow us to re class her as a double hull tanker."

At the time of writing RFA Fort Victoria had recently returned to the UK following deployment over 2 years and was due to undergo a period of maintenance, equipment Upgrades and modifications during RP17. This was to enable the ship to operate in support of the new HMS Queen Elizabeth aircraft carrier from 2017 onwards.

2.5.3 Impact of UK Defence and Spending Reviews on Fleet Reduction

The rationale for the decommissioning or replacement of RFA vessels that have been in service for many decades is clear, i.e. increased burden of Upgrade, Update and Upkeep, together with non-compliance with current maritime regulations. However, vessel age is not in itself the factor determining fleet profile. Together with all other UK military capability, the size, role and structure of the RFA flotilla is ultimately determined by UK Government defence policy. Strategic Defence and Security Reviews (SDSRs) are conducted by the UK Government to determine defence strategy and to balance that strategy with the means and resources needed to achieve defence objectives. Additional policy reviews are conducted to focus on specific aspects of defence capability whilst not conducting a fundamental reappraisal of overall strategy. Notable examples over recent decades that have significantly impacted the current size, role and structure of the RN and RFA fleet include the following:

- 1990 Options for Change;

[15] Email discussion, dated 21 Aug 2017, between David Franks (researcher) and David Rush (Capability, Safety and Design Authority Group Leader, Commercially Supported Shipping).

- 1998 Strategic Defence Review (SDR) and the 2002 SDR New Chapter;
- 2003 Defence White Paper: Delivering Security in a Changing World;
- Strategic Defence and Security Review 2010; and
- Strategic Defence and Security Review 2015.

It is evident from the outcome of these reviews that the underlying naval trend impacting the RFA has been one of reduced numbers of surface vessels, restructuring away from the bias for open-ocean operations, (as formally envisaged in the North Atlantic ‘Cold War’ scenarios) and the replacement of elderly vessels with fewer ship-types having more advanced capability. A greater emphasis has been placed upon near coast (littoral) operations, deployment within a coalition of nations, rapid reaction and the need for a flexible response to emerging threats.

This has taken place against a backdrop of global economic hardship such that, since 2010, there has been a trend of reductions in defence spending as a percentage of GDP[16] by the UK[17] and across NATO as a whole (NATO, 2017).

UK Spending Reviews were introduced by the Government in 1998 and are used by the chancellor to set out how much departments can spend over a forthcoming period of three or four years. Furthermore, the UK Government (HM Treasury) publishes details of spending in the form of annual Public Expenditure Statistical Analyses (PESA).

A 2015 Spending Review confirmed the commitment to meet a NATO investment pledge to spend no less than 2% of GDP on Defence for the rest of the decade. Public expenditure analysis indicated that, whilst this pledge held true, there was a trend of falling defence expenditure from 2010 to 2017 (UK Government, 2017a).

The SDSR that took place in 2010 was a radical reappraisal of UK defence commitments and resources that took place 12 years after the previous major Defence Review. A key aim of SDSR 2010 was to ensure the emergence of a

[16] Gross domestic product (GDP) is a means of indicating the performance of a country’s economy. It is a monetary measure of all goods and services produced in a given period (quarterly or yearly). The GDP offers the basis for international economic comparisons.
[17] NATO statistics indicate a trend of reductions in UK defence expenditure as a percentage of GDP from 2.48% in 2010 to 2.14% (estimated) in 2017.

coherent defence capability in 2020 whilst recognizing that sustainable defence could only be maintained on an affordable footing.

The Secretary of State for Defence at that time made the assertion that:

“Tough decisions are required to reconfigure our Armed Forces to confront future threats whilst we also tackle the £38bn deficit that has accumulated in the 12 years since the last Defence Review”.

It can therefore be appreciated that SDSR 2010 set the tone for a forthcoming decade of reassessment of defence commitments, re-structuring of defence forces and a determined drive for cost effective defence spending.

In terms of the direct impact upon the RFA, SDSR 2010 made explicit reference to the decommissioning of a Bay-Class amphibious support ship. Accordingly, RFA Largs Bay was promptly removed from service and offered for sale, (in 2011, she was commissioned into the Royal Australian Navy as HMAS Choules). Furthermore, SDSR 2010 made implicit reference to further reductions in RFA vessels by the statement that naval capabilities would include ‘a fleet of resupply and refuelling vessels scaled to meet the Royal Navy’s requirements’. This was closely followed by the removal from service of RFA Bayleaf in 2011. Similarly, in 2013 RFA Fort George was dismantled and recycled having been removed from service in 2011. The dismantling of Ex-RFA Fort George is noteworthy insomuch as the vessel was of contemporary design, high capability and had undergone an extensive refit in 2008. SDSR 2010 was directly cited as the underlying justification for disposal within a report compiled by the DSA and published by the MoD (MoD, 2013). The report contains the following statement:

“Under the Strategic Defence and Security Review in 2010, the former Royal Fleet Auxiliary Fort George was identified for disposal and ceased operational service on the 1st June 2011”.

Following SDSR 2010, the major Defence Review made in 2015 outlined the concept of ‘Joint Force 2025’ as the structure of UK defence forces over the next decade (Mod 2015a). Within Joint Force 2025, naval forces include a Maritime Task Group centred around one of the two new Queen Elizabeth Class (QEC) aircraft carriers. The retention of the RFA services is confirmed and its future structure described, including the integration of new tankers and solid support ships (see Section 2.6.2). However, at its time of publication, Joint Force 2025 did not explicitly include two of the vessels currently offering key support roles, i.e. RFA Diligence providing forward repair and RFA Argus providing casualty reception and aviation facilities.

Following a Freedom of Information (FOI) request made to the MoD in November 2015, a formal response was offered stating that forecast out of service dates were 2020 for RFA Diligence and 2024 for RFA Argus (MoD 2015b). Despite this, by March 2017, RFA Diligence had been taken out of service and berthed at Portsmouth Harbour. At the time of writing, the DSA was undertaking the sale of the vessel (MoD, 2016). The FOI response included the following statement:

"The consideration of options to deliver the capabilities that these platforms enable, beyond these [out of service] dates, remains ongoing."

2.6 Future Ships from 2017

2.6.1 Drivers for Ship Replacement

Vessels with a long service life have machinery that has delivered high running hours and so is liable to reliability issues. Furthermore, aged equipment is prone to obsolescence in terms of the spare parts and consumables needed during maintenance and operation. Similarly, ship structures that have undergone exposure to harsh environmental conditions over decades of service become increasingly prone to corrosion and stress-related failure. Therefore, with age, ship systems and structure increasingly need an extensive regime of inspection, repair and replacement to satisfy statutory and class requirements, together with naval certification. These factors correlate to high Upkeep demands for elderly vessels, without which vessel availability would be diminished. However, the requirement for Upkeep is not the only consideration since elderly vessels with outdated technology will require upgrading and updating to offer continued capability assurances. All of these factors lead to increasing in-service costs. It can be appreciated that as the cost of ownership for these vessels becomes excessive, and as the capability of these vessels becomes diminished, the business case for vessel replacement becomes more apparent.

As discussed throughout Section 2.5.2, in the case of the Rover and Leaf Class tankers, the imperative to procure replacement vessels was heightened due to their single hull construction and consequent non-compliance with MARPOL (Annex I) legislation (IMO 2017a, IMO 2017b and IMO 2017c).

Furthermore, as discussed throughout Section 2.5.3, the requirement to retire elderly ships can be related to reviews in defence spending and capability. Conversely, as demonstrated by the Joint Force 2025 concept, Strategic Defence Reviews can also highlight the need for ship procurement to enhance future military capability.

It follows from the above that drivers for the procurement of replacement ships may be summarised as follows:

- Increased maintenance requirements for elderly ship systems;
- Increased maintenance requirement for elderly ship structure;
- Consequent high levels of Upkeep cost;
- Reduced operational availability due to reliability and obsolescence issues;
- Reduced operational capability due to outdated vessel technology;
- Consequent high levels of Upgrade and Update costs;
- Pressure to comply with the contemporary maritime regulatory framework;
- The need to provide cost effective capability towards current and future UK military strategy, as defined within Defence Reviews and Spending Reviews;
- Requirements to support new fleet operations that greatly exceed current capability; and
- Requirements to support new or projected fleet vessels in response to changes in fleet size or role.

2.6.2 RFA Vessels for Maritime Sustainment

As discussed within Section 2.5.3, SDSR 2015 (Mod, 2015a) makes explicit reference to the future procurement of three Fleet Solid Support (FSS) ships and confirms their integration within Joint Force 2025, along with the four new Tide Class Tankers due to enter RFA service from 2017. Upon delivery, this will represent the successful introduction of new RFA vessels under the Military Afloat

Reach and Sustainability (MARS) programme. The MARS Tanker and future FSS ship are represented within Figure 2.6.2.1 and Figure 2.6.2.2 respectively.

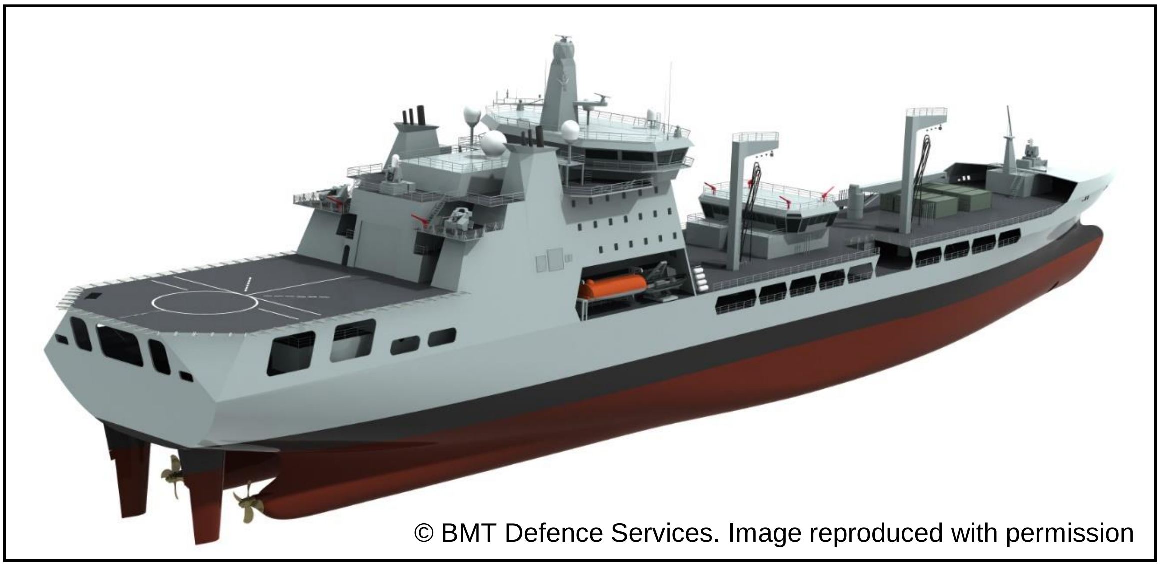


Figure 2.6.2.1. Representation of the MARS Tide Class Tanker

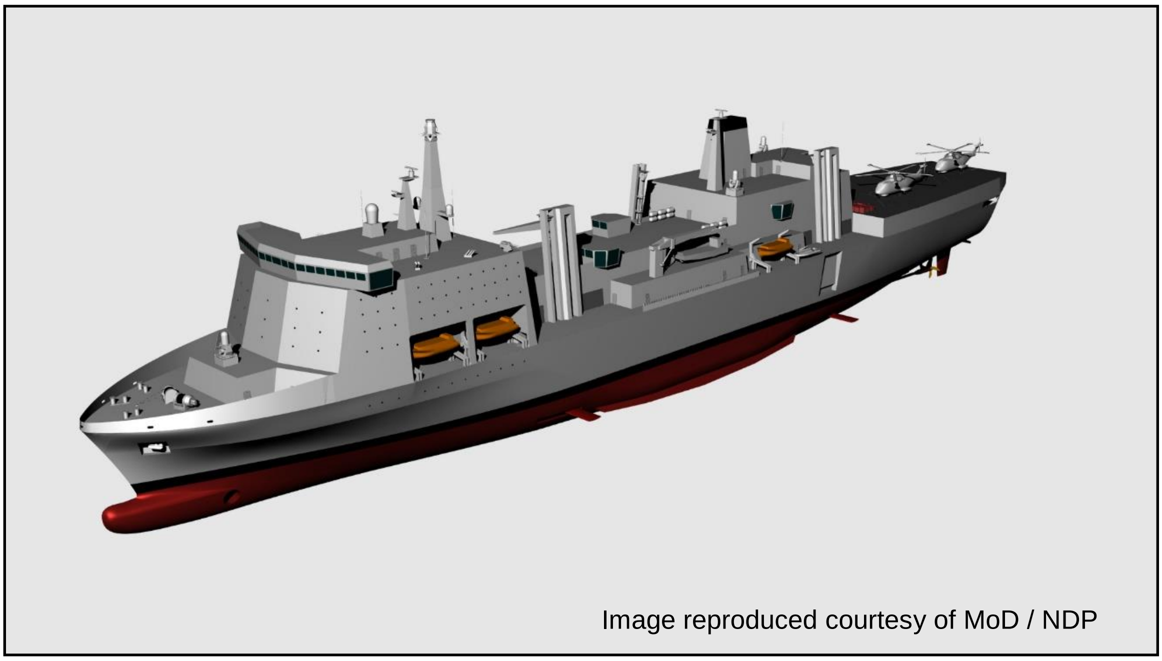


Figure 2.6.2.2. Representation of the Future Fleet Solid Support Ship

Following previous options studies into future fleet requirements, delivery of the MARS programme commenced in 2012 with a contract worth around £452m (MoD, 2012b). This was awarded to the South Korean manufacturer, Daewoo Shipbuilding and Marine Engineering (DSME), to build the four UK designed MARS tankers. Associated UK contracts were awarded for the provision of equipment, systems, design and support services. BMT Defence Services provided the design, safety assessment and through-life support assessment (BMT Group, 2017). The design is fundamentally based upon the BMT Aegir concept adopted by several of the world's navies (BMT Defence Services, 2017).

At the time of writing, the First-of-Class had been accepted from the shipbuilder and was due to undergo outfitting and capability trials at A&P Group in Falmouth, UK. The ship would then be commissioned into service as RFA Tidespring, first of the Tide Class tankers comprising her sister ships: Tiderace, Tidesurge and Tideforce. A Tide Class tanker performing resupply operations within the modern RN is represented within Figure 2.6.2.3.

Figure 2.6.2.3. Representation of a Tide Class Tanker Performing RAS

In support of the Joint Force 2025 Maritime Task Group (see Section 2.5.3), FSS vessels will provide ammunition, dry stores and food. Based upon the 2007 to 2017 trend across the RFA flotilla, it is highly likely that the future ships will replace the current RFAs Fort Rosalie, Fort Austin and Fort Victoria, with elderly ships undergoing life extension programmes to address capability gaps pending commissioning of new ships. At the time of writing, construction of the future FSS ships was not underway. Even so, due to novel aspects of the replenishment required for the new QEC aircraft carrier, the MoD commenced a de-risking design development programme with Rolls Royce in 2013 in the form of the

Heavy Replenishment At Sea (HRAS) demonstrator. This is a shore-based installation used to simulate transfers of bulk stores and munitions to the QEC Carrier from an RFA ship whilst underway (Royal Navy, 2013).

2.7 Conclusion

This chapter has offered the reader a detailed description of the RFA in terms of its role and the types of vessels employed to perform that role. The description sets the scene for future chapters that will examine the requirement for, and the implementation of, Alterations and Additions (As&As) to the existing design of ships. From the information offered within this chapter, the implementation of As&As can be understood in terms of the need to Upgrade and Update elderly vessels to maintain and enhance ship capability.

The chapter has described the radical change in shape of the RFA flotilla that occurred between 2007 and 2017. During this period, elderly vessels were kept in service by extensive and expensive work packages after decades of operations. Ultimately ship numbers were reduced dramatically, particularly in terms of the tankers that were non-compliant with MARPOL double hull regulations. The Defence and Spending Reviews that took place during the same period (especially SDSR 2010 and SDSR 2015) led to further reductions in ship numbers, but also confirmed the introduction of new vessels (Tide Class tankers and FSS ships) to support the future military capability set out in Joint Force 2025.

It is the view of the researcher that the period between 2007 and 2017, inclusive, will prove to be a pivotal decade in the history of the modern RFA due to the radical change in fleet structure - and the As&As implemented to maintain ship availability and capability whilst that change occurred. It is within this period (i.e. 2008 to 2012) that the researcher gained experience of the As&As implemented across the flotilla. This work provides the basis of the forthcoming chapters.

Chapter 3: Alterations and Additions (As&As)

Abstract

This chapter defines Alterations and Additions (As&As) within the context of the in-service support given to vessels of the Royal Fleet Auxiliary (RFA). The term 'A&A' is quite simply the name given to a formal engineering change including the associated management process. Descriptions of processes related to As&As are given together with A&A examples. The content is adapted from actual A&A records across 6 ship classes, covering 9 of the 13 ships in RFA service between 2008 and 2012. Hence, the examples offer a representative sample of proposals for As&As to RFA platforms. The chapter is largely concerned with the practices and business processes that were followed by the researcher during his work with the RFA between 2008 and 2012. However, to protect sensitive information, full details of As&As have not been disclosed nor have details relating to specific vessels. Furthermore, fully detailed business processes have not been reproduced.

3.1 A&A Definition – Change to Fit, Form or Function

When applied to vessels of the RN and RFA, the term ‘Alteration and Addition’ (A&A) is formally defined as being 'a change to an in-service vessel which alters the structure, systems and / or layout of the vessel' (DE&S, 2015). Less formally, As&As are associated with changes in fit, form or function. These are the design changes applied to vessels during their service life to Upgrade or Update capability in order to maintain their availability and operational effectiveness. Upgrade (or Type 'A') As&As are those that add capability to a vessel, for example a new weapon or communications system or a major piece of new legislation requiring a significant vessel change. Update (or Type 'B') As&As are those implemented to consistently maintain the endorsed capability of the vessel. They would include As&As to manage obsolescence, improve engineering usability, manage safety issues and respond to minor legislation changes.

3.2 Scope of Alterations and Additions

As&As range from minor design changes that may have been proposed by ship staff seeking to make operation more efficient, through to major modifications aimed at satisfying incoming legislation, increasing platform capability or the multiple changes required when extending the service life of a vessel. Examples range from the provision of additional storage facilities to the major structural, mechanical and electrical alterations involved in the updating of ships' generators, the retro-fitting of waste management systems or the installation of ballast water treatment plants. It should be appreciated that particular significance (and therefore priority) is given to As&As directed towards the assurance of ship safety and to the management of equipment obsolescence. Table 3.2.1 offers adapted examples of proposals for As&As to different ships across the RFA, received between 2008 and 2012. These relate to the broad spectrum of ship functions for RFA vessels. A priority has been assigned to each proposal along with a statement of its justification. Prioritisation is further explained within section 3.3.

Table 3.2.1. Examples of A&A Proposals for a Range of RFA Ships

Proposal Description	Ship Function	Urgency	Investigation
To fit an additional CCTV monitor adjacent to the radar sited on the bridge.	Aviation	To achieve a SIGNIFICANT improvement in safety & effectiveness.	When the "Darken ship shutters" are closed on the bridge, the Helicopter Control Officer cannot easily see the flight deck CCTV display in order to react in a safe and timely manner to any incident.
To replace obsolete IPMS Servers with equipment that will be fully supportable for 10 years.	Machinery and Systems	To overcome a CRITICAL deficiency in availability, reliability and maintainability.	During discussions with the OEM relating to a recent IPMS Server fault, it became clear that the servers are obsolete and spares are extremely limited.
Convert the Ship's Casualty Sorting Area into an Accommodation Stores Room.	Structure	To provide a DESIRABLE improvement in habitability.	This area is no longer used as a Casualty Sorting Area (agreed by the NCHQ Operating Authority) and is to be used as a storage area.
Address ladder steepness within the Main Machinery Space.	Safety	To overcome a SIGNIFICANT hazard to safety.	The proposal follows an accident on the ladder between changing room and Machinery Control Room (MCR).
Installation of Ballast Water Treatment equipment.	Environment	To comply with MANDATORY Merchant Shipping legislation	IMO Ballast Water Convention

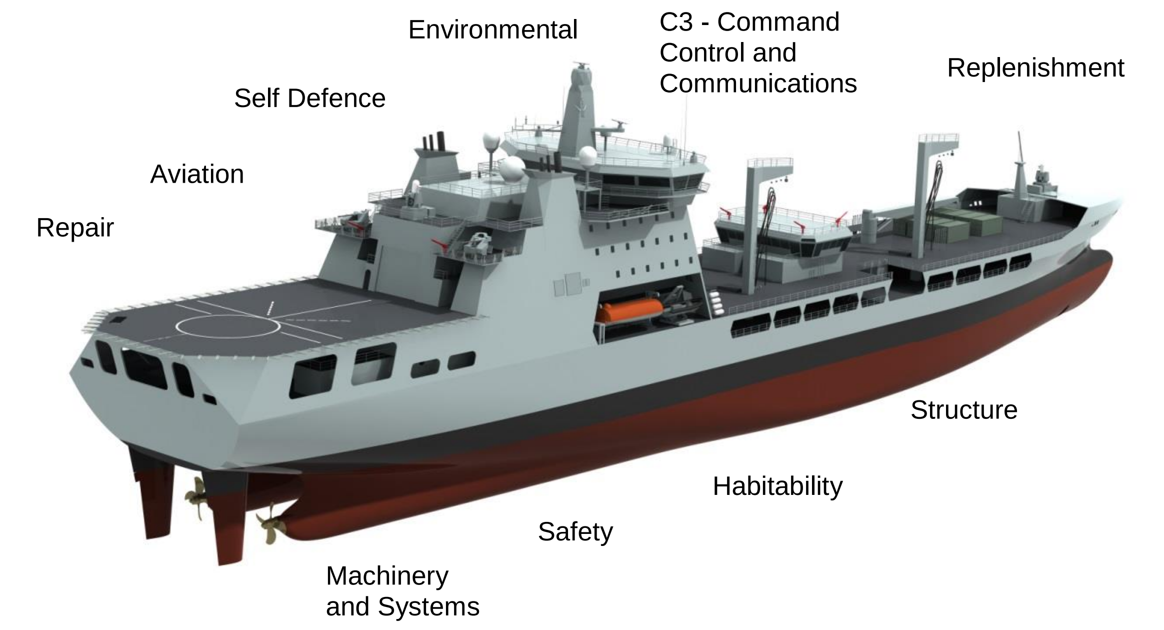
Consolidate Bridge equipment into ergonomic, supportable and documented consoles.	C3: Command Control Communications	To achieve a DESIRABLE improvement in effectiveness.	The Bridge comprises many equipment additions over time. During refit period there is an opportunity to re-design the bridge to deliver an ergonomic layout.
Harbour Generator - Manufacture and fit a resilient bulkhead transition piece for the generator exhaust	Habitability	To overcome a SIGNIFICANT deficiency in habitability.	Noise and vibration levels in the cabins above the generator are uncomfortable for cabin occupants and borderline for acceptable noise limits for crew accommodation.
Replace existing Close-in Fenders for vessels with an improved system as used by NATO.	Repair	To achieve an ESSENTIAL improvement in effectiveness.	Some current fenders have limited cushioning effect. The bolts that hold the rubber to the metal frame gradually pull out. The original fenders develop negative buoyancy – one has been lost at sea.
To provide an emergency stop for the Diesel cargo pumps in the vicinity of the Stern Refuelling Manifold	Replenishment	To overcome a SIGNIFICANT hazard to safety.	Stern refuelling introduces hazards at the manifold remote from RASCO. Valuable time would be lost communicating with RASCO during an emergency

3.3 Prioritisation of A&A Proposals Based Upon Ship Function

For any vessel, certain functionality is associated with its structure, systems and layout. For example, lifeboats have a 'safety' function whereas main engines form part of the 'machinery' function. Similarly, heating, lighting and air conditioning are all part of so-called ship hotel systems and hence provide a function towards crew 'habitability'. As&As are implemented during the service life of a vessel in order to continuously Upgrade or Update the various functions that combine to provide the vessel with the capability needed for its particular role. Identifying the function to which an A&A relates provides the basis for its prioritisation. For this reason, As&As are distinguished by assigning each to a particular functional group. Within the context of this discussion, the vessel shown within Figure 3.3.1 can be regarded as a generic RFA vessel that indicates the various functional groups. These are expanded within Table 3.3.1[18]. It should be noted that whilst the functional distinction for some As&As may be obvious (lifeboats are clearly related to the 'safety' function) other more ambiguous As&As must become the focus of discussion and interpretation between subject experts.

[18] The functional groups are based upon those defined for RN and RFA vessels but could equally be subject to alternative expert judgement for other vessel types.

Depending upon the role of a vessel, certain ship functionality will be considered more important than others. For example, the ability of a tanker to conduct 'replenishment' is essential whilst a Forward Repair Ship must prioritise 'repair' facilities over 'replenishment'. It may therefore be appreciated that, when considering the priority of an A&A proposal, the ship functionality to which the A&A is related must be considered along with the vessel role.



Source of vessel image: © BMT Services, reproduced with permission

Figure 3.3.1. Functional Capability for a Generic RFA Vessel

An additional consideration when determining the priority of an A&A is the urgency assigned to its implementation. Hence it may be MANDATORY[19] that an A&A is implemented if, for example, the A&A relates to changes in maritime regulations that would impact upon some aspect of ship certification. Similarly, it may be CRITICAL that an A&A is implemented to introduce new safety measures to safeguard against accident or hazard. Other As&As might lead to a SIGNIFICANT improvement in system efficiency and cost effectiveness. At the lower end of the scale, a DESIRABLE A&A might be associated with some MINOR improvement in effectiveness.

It should be recognised that there are military and non-military ship functions. Within Figure 3.3.1 and Table 3.3.1, the military functions are Aviation, C3, Self

[19] These capitalised urgency terms are based upon those applied to RN and RFA vessels but could equally be subject to alternative expert judgement of other decision makers.

Defence, Repair and Replenishment. The remaining functions are non-military, but not necessarily less important as they largely influence the safety and comfort of the seafarers. Consideration of this functional split is important when considering capability at the higher levels and can influence the level of justification required for securing funding for engineering change projects.

Table 3.3.1. Illustration of Ship Functions Applicable to RFA Vessels

Ship Function	Illustration of Scope
Aviation	Any A&A associated with Aviation facilities including flight deck, hangar, aircraft fuelling, helicopter starting.
C3 - Command, Control and Communications	Includes ship internal and external communication systems, radar and navigation systems not otherwise assigned to ship safety.
Self Defence	Relates to ship self defence systems.
Environmental	Associated with MARPOL and so related to the release of pollutants including the spillage of cargo, the overboard discharge of waste and machinery products or the release of engine emissions.
Habitability	Related to ship layout and systems that determine living conditions for ship staff and embarked personnel. Includes hotel services, cabin standards and messing facilities.
Machinery and Systems	Related to the wide-ranging machinery keeping the ship moving and operating including prime movers, generators, auxiliary systems and deck equipment.
Repair	Associated with the capability to provide services to other vessels as part of the forward logistics role. Includes repair workshops and facilities to offer services to vessels alongside.
Replenishment	Associated with the specific replenishment role including Replenishment At Sea (RAS), storage of replenishment provisions and handling of replenishment provisions.
Safety	Encompasses all systems directed towards safety of crew, embarked personnel and the ship itself.
Structure	Related to ship structure and physical measures to maintain integrity and reduce damage.

3.4 Priority Scoring for As&As

From Section 3.3 it may be appreciated that the priority of an A&A can be expressed in terms of its importance towards the functional capability of the ship (with some functions being more important than others), together with a category of urgency (e.g. mandatory, significant or desirable), (Royal Navy, 2003). Further to this, numerical values must be assigned in order to quantitatively evaluate priority relative to other As&As for the same vessel and other vessels within the flotilla. The assignment of values permits numerical computation within algorithms designed to prioritise lists of A&A candidate items[20]. This forms an essential part of the process to determine work packages for a particular vessel whereby all As&As are numerically ranked. This is important, not least because a finite financial budget will be available for any maintenance opportunity and greatest value for money will be sought by deciding upon a scope of work that offers the most favourable cost-benefit evaluation.

3.5 The Decision Making Response to A&A Proposals

As can be appreciated from Table 3.2.1, proposals for As&As can be generated in response to changes in maritime legislation, the need to Upgrade vessel capability, the need to overcome equipment obsolescence, the need to redress performance deficiencies or the need to offer duty-of-care by reducing safety risks to levels considered ALARP[21].

Upon receipt of an A&A proposal, the response of the RFA Design Authority is to conduct investigations that form the basis of informed, collective discussion and decision making by a panel of Suitably Qualified and Experienced Personnel (SQEP). This takes place during formal Design Control Boards (DCBs). The effectiveness of a DCB is determined by the SQEP in attendance. Therefore, the concept involves assembling the naval customer (represented by NCHQ), the RFA Design Authority, the MoD waterfront project managers (i.e. those detached to the shipyard), the shipyard engineers (i.e. the suppliers) and other required Subject Matter Experts (SME). In practice, if DCB members have conflicting opinions, consensus must be reached by measures that include conducting investigation to gain further information, benchmarking against best practice applied to other vessels and prioritising according to authoritative references (regulations and guidance) applicable to RN / RFA vessels. Ultimately, the naval customer dictates the operational priorities that will guide and influence decisions.

A business process has been developed by the RFA Design Authority that supports the evaluation of A&A proposals during DCBs. Figure 3.5.1 is an adaptation of that process, offered by the researcher based upon its practical

[20] The RFA Design Authority has developed its own pragmatic algorithm based upon a simple assignment of numerical scores to A&A proposals.

[21] ALARP – As Low As Reasonably Practicable. A recognised risk management term for a concept that involves balancing a risk against the trouble, time and money needed to control it. The goal is to reduce risk by adopting all measures, except where they are ruled out because they necessitate grossly disproportionate sacrifices (HSE, 2017).

implementation between 2008 and 2012. Figure 3.5.1 shows the following key DCB stages and intentions:

- **Stage 1**. An A&A is proposed to address some requirement, as discussed within Section 3.1 and Section 3.2.
- **Stage 2.** The underlying nature and type of engineering for the A&A proposal is identified and an appropriate technology lead is assigned.
- **Stage 3.** The A&A proposal is investigated using SME as appropriate. This could include ship staff, other MoD project teams, external consultants, subcontractors or specialist service providers. Feasibility studies or ship visits may be required to uncover detail for the proposal and its design intent.
- **Stage 4.** The investigation outcomes facilitate informed decision making at DCBs by a SQEP panel. Expert judgement is applied to support or reject the proposal.
- **Stage 5.** If supported, the SQEP panel considers and decides upon the attributes and implications of the A&A including the functional capability associated with the A&A. This determines its priority as discussed within Section 3.3. Furthermore, since the same functional capability may be common to several vessels, consideration of the A&A serves to identify potential reductions in capability or availability across the entire flotilla. The complexity and scale of the A&A (i.e. Major or Minor) is evaluated. This has implications towards ship certification and the appraisal of design proposals by the classification society. An A&A 'owner' is assigned to be responsible for the project management of the A&A through to its ultimate implementation.
- **Stage 6.** A tasking instruction is delivered to the technical authority (shipyard or other design service provider) to develop the design guidance for the A&A implementation. This must consider the wide range of design implications towards the vessel.

It is evident that the DCB process provides a systematic framework for either accepting and developing an A&A proposal or rejecting that proposal. Furthermore, the formal records of DCBs offer audit of decisions that can provide the basis for trend analysis and Learning From Experience (LFE). This serves to inform subsequent investigations of As&As for other RFA vessels.

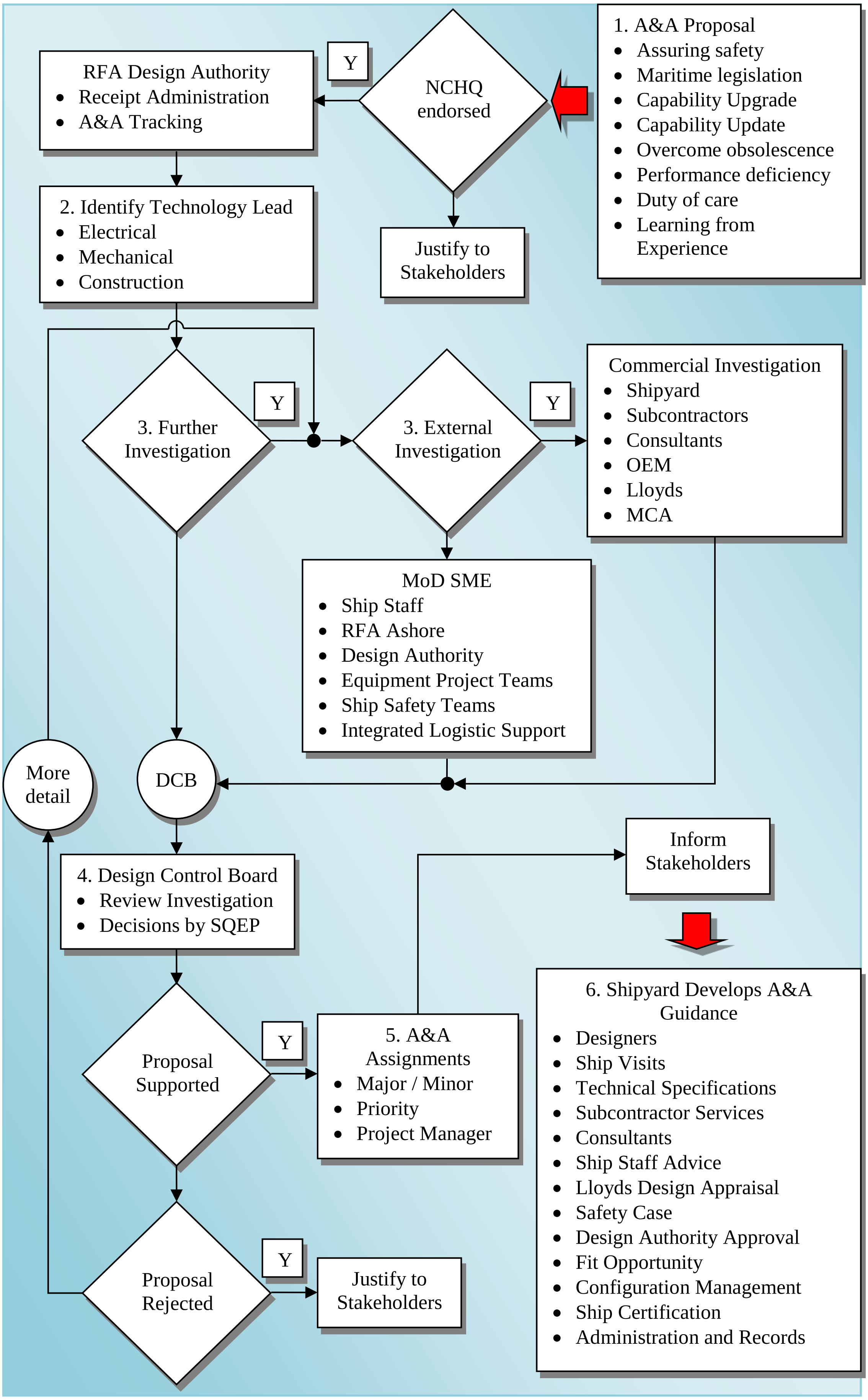


Figure 3.5.1. The DCB Response to A&A Proposals

3.6 Conclusion

This chapter defined As&As within the context of the in-service Upgrades and Updates that are routinely proposed for RFA vessels. Representative examples of A&A proposals were presented, having been adapted from actual records. It has been demonstrated that the decision making approach taken towards A&A proposals, whilst following well documented processes, is performed largely on the basis of expert judgement, i.e. informed collective reasoning by SQEP. This thesis seeks to explore additional and / or alternative techniques that can assist the consideration of As&As by SQEP. Accordingly, the following chapters consider the application of established decision techniques to the reasoning that takes place in response to A&A proposals.

Chapter 4: Techniques for Making Decisions with Multiple Criteria in the Context of Alterations and Additions (As&As)

Abstract

In preceding chapters, the RFA has been described, the concept of As&As explained and the decisions associated with As&As introduced. This chapter introduces a number of decision support techniques, thereby completing the foundation upon which formal techniques will be applied to A&A decision making. When faced with the need to choose between alternative outcomes, decision making is the evaluation of possible options against the criteria judged important within the decision context. A literature review of decision making techniques reveals that a plethora of formal approaches has been developed over many decades. Similarly, the scope of decision problems to which formal approaches have been (and continue to be) applied is seemingly unlimited. For this reason, it is the view of the researcher that an exhaustive investigation into the field of 'decision making' is both impractical and unnecessary in the context of this thesis. Rather, this chapter reviews a bounded number of approaches that have been categorised as techniques for Multi Attribute Decision Making (MADM). The chapter introduces the concept of MADM and explains the basis upon which certain MADM techniques have been selected for application within this thesis.

4.1 The Nature of DCB Reasoning and Decisions for As&As

Within the context of the Upgrade and Update applied to RFA vessels, Chapter 3 defined an A&A as "a change to an in-service vessel which alters the structure, systems and / or layout of the vessel" (DE&S, 2015). In addition, Chapter 3 offered a description of the decision making that takes place in response to proposals for As&As. It was explained that informed reasoning and expert judgement is applied by Suitably Qualified and Experienced Personnel (SQEP) throughout the Design Control Board (DCB) process[22]. Figure 4.1.1 gives an adaptation of this process.

[22] The DCB Process is introduced within Chapter 3 and discussed further within Chapter 4.

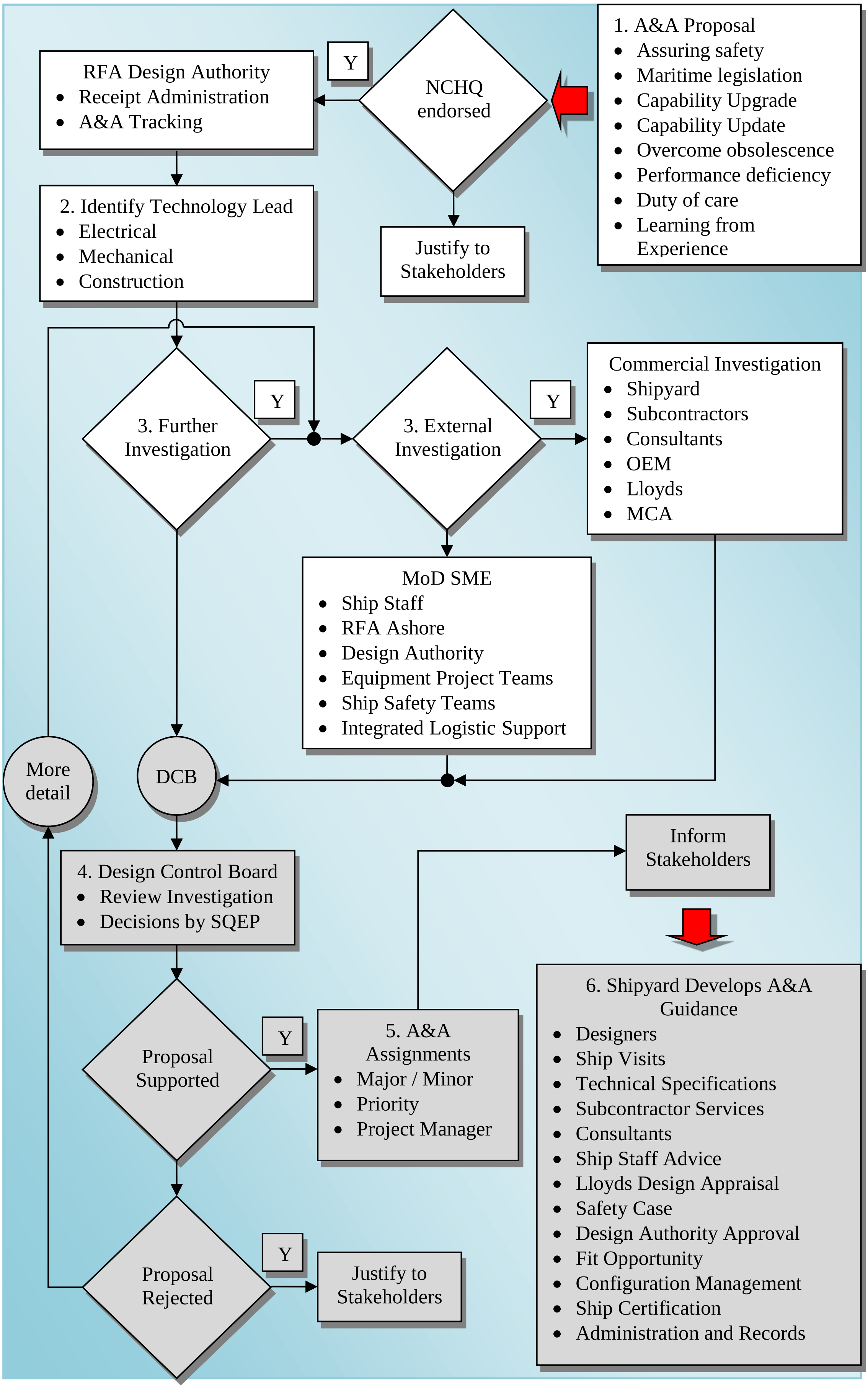


Figure 4.1.1. Key Decision-Points for As&As within the DCB Process

The shaded regions indicate the stages within the overall process where the substantial informed decisions are taken towards A&A proposals by a SQEP panel. The shaded areas relate to the following A&A decision making:

- **Support or Reject**. At Stage 4, a decision is made to either support or reject an A&A proposal. Within the RFA Design Authority, the decision is routinely made on the basis of expert judgement, perhaps involving qualitative deliberations. Benefit may be derived from the application of some numerical scoring process, whereby each A&A proposal would be evaluated against acceptance / rejection criteria and scored accordingly.
- **Major or Minor.** At Stage 5, a decision is made concerning the scale and complexity of an A&A proposal, i.e. it is either a major or minor A&A. Again, this decision is routinely made by expert judgement with consideration given to criteria that include: technological complexity, requirement for specialist services, time taken to implement, financial cost and impact upon ship certification. If a numerical scoring system were to be applied, these would be the criteria against which A&A proposals could be quantitatively evaluated. It should be noted that some criteria could be considered more important than others. For example, the impact of design change upon ship certification may be considered more important than the time it takes to implement. For this reason, an approach involving criteria weighting would be needed.
- **Priority Assignment.** Also at Stage 5, a decision is made to assign a priority for the implementation of the A&A. When considering the priority, the ship functionality to which the A&A is related must be considered along with the vessel role and the category of urgency (e.g. mandatory, significant or desirable). It may be appreciated, therefore, that comparison between As&As takes place in order to evaluate their relative importance within a list of As&As. It may also be appreciated that, when considering the ship functionality to which the A&A is related, some functions will be more important than others. These concepts are described more fully within Chapter 3, but it is clear from this discussion that priority could be made on the basis of A&A comparison and evaluation against weighted ship functionality.

- **Development of Design Options.** Within Stage 6, the design detail of a supported A&A is developed. This includes considering the design change implications towards the ship, and towards management of the ship by the RFA. Ultimately, the aim is to produce the guidance that will be used to implement the A&A whilst offering assurances towards the vessel including ship class, certification, configuration management and safety case. When faced with a number of possible solutions for any A&A, the design options need to be evaluated against the criteria judged important in the context of that A&A. As the design develops, increasingly detailed information will facilitate quantitative analysis with reduced uncertainties. Once the A&A has been fully developed, a suitable opportunity (the 'fit opportunity') will be decided upon for its implementation.

Having considered the type of reasoning that is applied to A&A proposals, it is the assertion of this thesis that an A&A can be thought of as a decision making problem that, depending upon the context and information available, either already has the following generic characteristics or could be suitably adapted to fit the following generic characteristics:

- Informed expert judgement applied by SQEP.
- Selection of candidate items based upon scoring.
- Evaluation of candidate items against weighted criteria.
- Prioritisation and ranking by comparison between candidate items.
- Evaluation of qualitative and quantitative information.

It follows that, when seeking to appropriately apply a formal decision making technique, the nature of the A&A problem must first be understood.

4.2 Multi Attribute Decision Making (MADM)

4.2.1 The Multi Attribute Approach

In any decision making problem, when deciding between possible solution alternatives, those alternatives are evaluated against criteria judged to be important to the decision maker. The criteria are the 'attributes' that must be optimised. For example, when selecting between material alternatives for a ship structure, the decision maker will likely need to satisfy the criteria of high material strength and high resistance to sea water corrosion. In this case, the attributes of 'strength' and 'corrosion resistance' are the dimensions from which the problem must be viewed. In other words, the decision analyst must consider how effectively each material option satisfies the criterion for strength, then the analyst must consider how effectively each material option satisfies the criterion for corrosion resistance. Hence, the decision must be considered from the perspectives of all required attributes. Here, the attributes are independent of each other, meaning that a change in the value of one has no correlating influence on the other. It may be appreciated that in other situations, where decisions need to be considered from the perspectives of multiple attributes, some of those attributes could be interdependent or conflicting. This last point is illustrated by the universal desire to obtain the greatest level of some measure of performance whilst incurring the lowest level of some measure of cost. For the purpose of this thesis, decision problems will be structured to have independent attributes unless otherwise stated[23].

4.2.2 The Generic Decision Matrix

When seeking to apply quantitative techniques to a MADM problem, the decision is structured as a matrix having '*m*' rows and '*n*' columns, such as that shown below. Construction of a decision matrix follows a similar theme across MADM techniques (Yoon & Hwang, 1995). For the generic decision matrix, the value of *'x'* is the score given to each alternative (1 to *m*) when evaluated against each of the required attributes (1 to *n*). Scores are assigned by decision making analysts with subject matter expertise towards the decision problem.

Required Attributes (Criteria)

Design Alternatives

$$\begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & x_{2,3} & \cdots & x_{2,n} \\ x_{3,1} & x_{3,2} & x_{3,3} & \cdots & x_{3,n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m,1} & x_{m,2} & x_{m,3} & \cdots & x_{m,n} \end{bmatrix}$$

where each element can be expressed as:

$$x_{i,j} \quad \text{for } i = 1, \dots, m; \quad j = 1, \dots, n$$

[23] This thesis has focus upon pragmatically applying a bounded scope of established decision making techniques. It is envisaged that the application of a wider range of techniques, including those used to de-couple dependent attributes, could be the focus of further research.

4.2.3 The Treatment of Attributes

The following have universal application when giving consideration to attributes:

- **Attribute (Criteria) Weighting.** The attributes may be prioritised by giving each a weighting factor. A weight is the value assigned to each attribute to indicate its importance relative to the others under consideration. By normalising values, data that has been presented in diverse measurement units can be made compatible throughout the methodology. The weights are normalised using a method appropriate to the data types such that they conform to Eqn. (4.1).

$$\sum_{j=1}^{n} w_j = 1 \qquad j = 1, \ldots, n. \qquad \text{Eqn. (4.1)}$$

where:

w_j is the normalised weight of the j th attribute.

- **Monotonic Utility for Attributes.** The concept of monotonic utility involves the preference for an attribute to move in a single direction (either increasing or decreasing) towards the most desirable value (e.g. maximum performance). The concept can be envisaged by considering a non-monotonic utility, such as the temperature in a room, where the most desirable utility is located somewhere in the middle of the range, not the maximum or minimum.
- **Beneficial Attributes.** Beneficial attributes offer increasing monotonic utility (preference) in the direction of some most desirable maximum value. That is, the greater the attribute value, the greater its benefit and, therefore, the greater its attractiveness.
- **Cost Attributes.** For cost attributes, the greater the attribute value, the less its preference. In other words, high costs are generally less preferred. This involves decreasing monotonic utility in the direction of some most desirable minimum value.

It can, therefore, be appreciated that care must be taken when scoring against attributes to ensure that the nature of the attribute is understood (beneficial or cost), and that numerical manipulation of values is consistent with that attribute nature throughout the decision making methodology.

4.3 MADM Techniques

According to a number of academic sources including Hwang & Masud (1979), Yoon & Hwang (1995) and Triantaphyllou (2000), Multi Criteria Decision Making (MCDM) is a classification that comprises Multi Attribute and Multi Objective Decision Making (MADM and MODM). Whilst MADM involves selection focused upon the attributes required of the solution, MODM involves focus upon the alternative that best satisfies defined objectives (Yoon & Hwang, 1995).

It is evident from this discussion that decision analysis has been, and continues to be, the focus of considerable academic investigation involving the development and classification of a range of formal techniques. Furthermore, as argued by Triantaphyllou et al., (1997), there is no single decision methodology that has been universally accepted and can be universally applied. Rather, when electing to use a formal decision making technique, the decision analyst must postulate its suitability in relation to the nature of the decision problem. It follows, therefore, that understanding towards a number of MADM methodologies is required. Within the context of this thesis, the approach considered is that of MADM, as defined by Yoon & Hwang (1995). Accordingly, types of MADM techniques are shown within Figure 4.3.1.

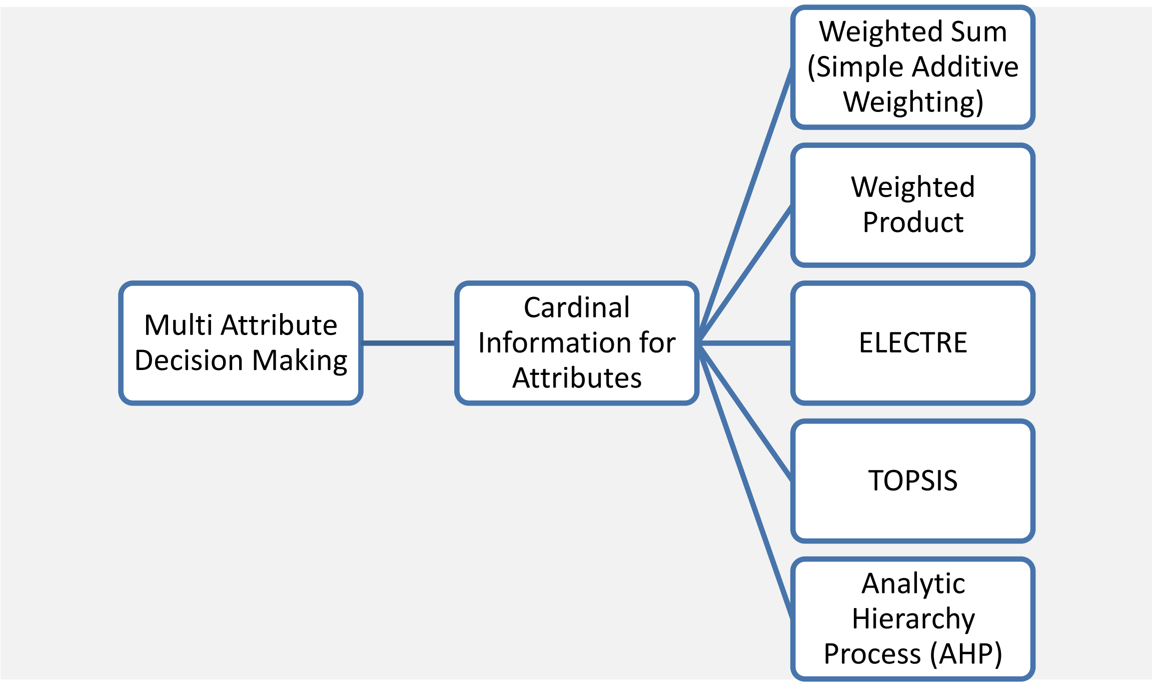


Figure 4.3.1. Commonly Encountered MADM Techniques [24]

[24] Adapted by the researcher from a taxonomy of MADM methods presented by Hwang & Yoon (1981).

Figure 4.3.1 has been adapted by the researcher from a taxonomy of MADM methods presented by Hwang & Yoon (1981). This approach has been taken because the methods shown have been consistently classified as MADM throughout the work of a number of authors including Yoon & Hwang (1995) and Triantaphyllou (2000). It is apparent from literature reviews (of their work and that of others) that these techniques, and variants of these techniques, form the basis of decision support tools that have been applied across a wide range of fields including finance, business, the environment, science and engineering. This view is supported within a survey of MCDM conducted by Aruldoss et al., (2013) and is further supported by Triantaphyllou (1997). It should be noted that throughout the work of these authors, the terms 'attribute' and 'criteria' often appear interchangeably with the consequence that 'MADM' and 'MCDM' appear interchangeably. Hence, the same approach has been adopted throughout this thesis. The techniques shown in Figure 4.3.1 are introduced below.

4.3.1 The Weighted Sum Approach - Simple Additive Weighting (SAW)

SAW is a versatile approach taken towards the solution of MADM problems. The method determines a decision outcome based on the addition of weighted performance scores for each decision option, where performance has been scored against the attributes required of the decision outcome. In its simplest form, the technique can be implemented using the template at Table 4.3.1.1.

During the 1990s, following decades of development towards systematic decision making, the assertion was made within a compendium of MADM techniques that "the SAW method is probably the best known and most widely used MADM method", (Yoon & Hwang, 1995). Contemporary references offer evidence of its continuing application across a wide range of disciplines, either as a stand-alone technique or as part of a hybrid methodology combined with other established decision making approaches. Examples include: the use of SAW to compare medical imaging processes (Azar, 2000); the use of Fuzzy Simple Additive Weighting for the selection of suppliers (Kaur & Kumar, 2013); and the use of SAW combined with the Analytic Hierarchy Process (AHP) for the selection of personnel (Afshari, Mojahed & Yusuff, 2010). It is arguably the case that the SAW technique has gained widespread acceptance owing to its intuitive and convenient approach.

Table 4.3.1.1. Template for Simple Additive Weighting [25]

Decision Title							
		Alternatives (A)					
		A_1		**A_2**		**A_3**	
Criteria (X)	weight	score	weighted score	score	weighted score	score	weighted score
	(w)	(v)	$(w) \times (v)$	(v)	$(w) \times (v)$	(v)	$(w) \times (v)$
X_1							
X_2							
X_3							
X_4							
Value of Alternative $V = \sum(w)(v)$							
Rank of Alternative							

As explained in a comparative study of MCDM techniques (Triantaphyllou, 2000), the underlying assumption for this approach is the 'additive utility assumption'. This means that the overall value for each alternative is assumed to be given by the combination (addition) of all its weighted scores, as shown in Table 4.3.1.1. This works effectively for single dimensional problems whereby the decision is viewed from the perspectives of criteria having single (quantitative) data types using the same unit. However, limitations arise when the method is applied to MCDM problems involving different data types and units. In these cases, the additivity assumption would be violated unless scores were quantified and normalised[26] to maintain data compatibility throughout the methodology.

4.3.2 The Weighted Product Approach – Weighted Product Method (WPM)

The Weighted Product approach (often referred to as the Weighted Product Method, WPM) involves the multiplication of terms rather than their addition, as in the case of the weighted sum approach (i.e. the SAW approach). Using the WPM, performance scores are raised to the power of the attribute weight. When comparing two alternatives, A_K and A_L, the approach is shown by Eqn.(4.2).

[25] The template is offered by the researcher based upon the established SAW technique.
[26] The purpose of normalisation is to allow comparison between incompatible scales of measurement by transforming measurements into dimensionless scales.

$$R\left({}^{A_K}/_{A_L}\right) = \prod_{j=1}^{n} \left({}^{a_{Kj}}/_{a_{Lj}}\right)^{w_j} \qquad j = 1, \dots, n \qquad \text{Eqn. (4.2)}$$

where:

$R\left({}^{A_K}/_{A_L}\right)$ is the ratio term returned for the comparison of A_K and A_L,

n is the total number of attributes,

a_{Kj} is the performance value of the of alternative A_K in terms of the j th attribute,

a_{Lj} is the performance value of the of alternative A_L in terms of the j th attribute and:

w_j is the normalised weight of the j th attribute.

Preference for alternative A_K over A_L would be indicated if the term $R(A_K / A_L)$ had a value greater than or equal to one. The highest value of the term for all alternatives indicates that which is most preferred.

The approach was introduced by Bridgeman (1922) and further advocated by Miller & Starr (1969), Starr (1972) and Yoon (1989). It is discussed within the MCDM comparative study made by Triantaphyllou (2000). An advantage of the method is its characteristic as a 'dimensionless analysis' since units of measure are eliminated by the use of ratio terms. This means that unlike other methods (SAW for example), performance parameters do not have to be manipulated by normalisation. Furthermore, the use of ratio terms means that the approach is naturally ordered for comparison whereby the decision analyst has the option of using relative values between alternatives, rather than quantitative values for all alternatives. Even so, the Weighted Product approach is less intuitive than the Weighted Sum approach. A review of literature suggests that the method has been adopted less widely than other established techniques. This view is supported by Yoon & Hwang (1995) and Aruldoss et al., (2013).

4.3.3 ELECTRE

ELECTRE (Elimination and Choice Translating Reality) was first introduced by Benayoun et al., (1966). The methodology is based upon a concept of 'outranking' between alternatives depending upon the level of satisfaction or dissatisfaction evaluated for one alternative over another. Satisfaction and dissatisfaction are quantified by indexes for ‘Concordance’ and ‘Discordance’ respectively.

As part of the methodology, Concordance and Discordance sets are created whereby, for a pair of alternatives, the Concordance set contains all the attributes for which one alternative is preferred over the other. Its compliment, the Discordance set, contains all the attributes for which that alternative is not preferred over the other. Concordance and Discordance indexes are calculated from their respective sets. It is evident that the Concordance index defines the amount of evidence to support the conclusion that one alternative outranks the other. Ultimately, outranking relationships emerge between alternatives whereby dominance becomes stronger with a higher Concordance index and a lower Discordance index.

It has been asserted that ELECTRE is particularly convenient for decision problems involving a large number of alternatives evaluated against a relatively small number of attributes (Lootsma, 1990). However, this should not necessarily be taken as a bounding statement for the technique since, as observed in a survey of MCDM methods and applications (Aruldoss et al., 2013), a number of variations of the ELECTRE method have been developed that deal with different types of decision problems.

4.3.4 TOPSIS

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) was first developed and published by Hwang & Yoon (1981). The technique is based on the concept that, for a problem with several solution options, each to be considered against specific criteria, the chosen option should have the shortest distance from the ‘Ideal Solution’ and the farthest distance from the ‘Negative Ideal Solution’. This concept was also proposed by Zeleny (1982) and subsequently enriched by Hall (1989), Yoon (1987) and Hwang, Lai & Liu (1993).

TOPSIS involves a multi criteria approach to decision making whereby selection conclusions are systematically derived towards a problem having several solution options, each of which is evaluated against key criteria. The technique involves identifying the Ideal Solution as the combination of all the best criteria evaluations attainable whilst the Negative Ideal Solution is a combination of all the worst criteria evaluations (Yoon & Hwang, 1995).

TOPSIS has become a well-established method and has found application across a wide range of fields to resolve a wide variety of down-selection problems. Examples, to name but a few, include evaluation and selection of initial training aircraft (Wang & Chang, 2007); outsourcing of third party logistics service providers (Bottani & Rizzi, 2006); material selection for components with weightings given to mechanical properties (Jee & Kang, 2000); evaluation of competitive companies (Deng et al., 2000); the assessment of service quality in the airline industry (Tsaur, 2002) and supplier selection in the semiconductor manufacturing industry (Deswal & Garg, 2015).

4.3.5 The Analytic Hierarchy Process (AHP)

Having been introduced and developed by Saaty (1977 and 1980), the Analytic Hierarchy Process (AHP) is now a well-established method. In common with the other multi criteria approaches, conclusions are systematically derived towards a problem having several solution options, each of which is evaluated against key criteria.

At the centre of the process is the concept of 'pairwise comparison'. The aim of pairwise comparison is to judge how strongly one solution alternative compares to another. Comparison between pairs of alternatives is translated into numerical values according to a scale presented by Saaty (1980) and adapted within Table 4.3.5.1.

The application of AHP is extensive, as illustrated by the references, numbering more than 1000, cited by Saaty (1994) when he published his description of the fundamentals of decision making using AHP. Acceptance of the method continued such that AHP has been used when modelling problems in fields that include politics, economics, social and environmental sciences (Berrittella et al., 2007). This view has been reiterated by Saaty (2008) and is supported within contemporary studies (Aruldoss et al., 2013).

Some of the benefits of AHP include the following (Cheng, 2002):

- AHP facilitates the structuring of an unstructured problem into a rational decision hierarchy.
- The methodology elicits more information from the experts or decision makers by employing focussed pairwise comparison.

- AHP can be used to assign weights to evaluation criteria.
- The methodology includes a process for assessing consistency that can validate the ratings given by experts and decision makers.

Table 4.3.5.1. AHP Scale used for Pairwise Comparison

Intensity	Definition	Explanation
1	Equally important	Equal comparison
2	Weakly greater	Subjective reasoning favours one over the other
3	Moderately greater	
4	Moderate plus	Subjective reasoning strongly favours one over the other
5	Strongly greater	
6	Strong plus	Dominance of one over the other has been demonstrated in practice
7	Very strong or demonstrably greater	
8	Very, very strong	Evidence of the highest possible affirmation for dominance of one over the other
9	Extreme	
Note: 2,4,6, and 8 are intermediate values used to compromise between adjacent scale values		

Alongside the benefits and widespread application of AHP, observations have been made by some authors, including Belton & Gear (1983) and Triantaphyllou & Mann (1989), concerning ranking inconsistencies that may occur when alternatives are scored closely together or when new alternatives are introduced into a decision problem. For this reason, as with other MADM techniques, AHP should be used as a 'decision support tool' with the final answer being subject to scrutiny by subject experts and decision analysts.

4.4 Conclusion

This chapter considered the nature of the decisions that take place towards proposals for As&As, then considered the characteristics of a collection of formal decision methodologies classified as MADM techniques. Ultimately, the aim is to select a technique that is appropriate to the decision problem. It will not escape the attention of the reader that selection of the most suitable MADM technique is itself a MADM problem. That is to say, a number of alternatives (SAW, WPM, ELECTRE etc) need to be evaluated from the perspective of the attributes associated with the decision making problem. In this context, the attributes have been explained in terms of the thinking that takes place during the DCB process. Hence, it is asserted by the researcher that, depending upon the type of decision within the DCB process, a formal decision technique should be able to accommodate a mix of expert judgement, numerical scoring, criteria weighting and comparison to establish preference. Furthermore, a technique should be capable of dealing with qualitative data types (in which case subjective reasoning is applied) or quantitative data types (in which case calculation is applied).

Table 4.4.1 presents a summary of the key characteristics for the five established MADM techniques discussed throughout Section 4.3.

Table 4.4.1 Summary of MADM Techniques Discussed in Section 4.3

Technique	Underlying Principle	Key Advantages	Key Disadvantages
Weighted Sum Method (Simple Additive Weighting)	Used for evaluating alternatives against weighted criteria using the additivity assumption whereby an overall outcome is the summation of weighted scores.	Relative to all other methods, this is arguably the most established. It involves a convenient and intuitive approach. Strong in single dimensional problems having quantitative data types expressed in the same unit.	Difficulty emerges when dealing with multi-dimensional problems involving different units and a mix of qualitative and quantitative data.
Weighted Product Method	Alternatives are compared relatively using ratio terms raised to the power of the attribute weight.	Offers dimensionless analysis since units of measure are eliminated by the use of ratio terms. Hence can be used for multi dimensional problems without the need for normalisation.	Less intuitive than the Weighted Sum approach and less widely adopted. Zero scoring should be ruled out due to problems with ratio computations.
ELECTRE	Based upon a concept of pairwise comparison and ‘outranking’ between alternatives, depending upon the level of satisfaction or dissatisfaction for one alternative over another.	Established method involving the systematic computation of concordance and discordance indices. A number of variations of the ELECTRE method have been developed that deal with different types of decision problem.	Involves relatively high cognitive demand and time-consuming computation. It was reported by Triantaphyllou (2000) that the method can eliminate less favourable options but may not always identify the most preferred.
TOPSIS	Developed as an alternative to ELECTRE and based on the concept that the	Highly established method involving systematic computation including	Involves relatively high cognitive demand and

	chosen option should have the shortest distance from the 'Ideal Solution' and the farthest distance from the 'Negative Ideal Solution'.	the clear application of weightings and normalisation techniques. Commonly applied as a hybrid technique (e.g. Fuzzy TOPSIS).	time-consuming computation.
Analytic Hierarchy Process (AHP)	Involves pairwise comparison between alternatives and translates comparisons into numerical values on a defined scale.	Highly established method. Involves systematic structuring of problem into a hierarchy that allows the importance of each element to become clear. The method checks for inconsistencies in decision logic. Commonly applied as a hybrid technique (e.g. Fuzzy AHP and AHP-TOPSIS).	Relatively high cognitive burden imposed as pairwise comparisons increase. Method can return irregularities in rankings for alternatives.

Having investigated the possible application of the five techniques, the following three have been chosen by the researcher for application to A&A decision making:

- SAW
- AHP
- TOPSIS

These have been chosen because between them, they satisfy the attributes discussed above. Hence, the SAW technique is based upon numerical scoring and weighted criteria. It is a convenient and intuitive approach. AHP is based upon comparison between pairs of candidate items and can deal with both qualitative and quantitative data types. The approach is notable for its structuring of a decision problem into a rational decision hierarchy. The method is well understood having been widely investigated over several decades. TOPSIS is a particularly well-established method, notable for its systematic computational approach towards quantitative performance measures and its unambiguous treatment of attributes (either monotonically increasing or monotonically decreasing in the directions of preferred utility). As discussed throughout the chapter, literature reviews indicate that all these techniques have wide and proven application. Furthermore, they consistently feature in the work of authors on the subject of Multi Criteria Decision Making.

It should be noted that the selected techniques do not rule out the application of alternative approaches. Indeed, as stated within Section 4.3, there is a wide range of possible approaches. These include hybrids, the use of ‘fuzzy’ approaches when dealing with decision parameters not clearly defined, the use of techniques that de-couple dependent attributes and the use of techniques that deal with a mix of qualitative and quantitative data types. However, the selected MADM techniques establish a pragmatic baseline by defining scope boundary around a range of established techniques appropriate in the context of A&A decision making. Wider investigation into the application of other decision approaches for As&As could form the focus of future research.

Chapter 5: Risk Based Reasoning for Fleet Time (FT) Implementation of Alterations and Additions (As&As) and the Application of Simple Additive Weighting (SAW)

Abstract

The integration of ship As&As within major Upkeep periods is standard practice across the RFA flotilla. An alternative approach sometimes taken is to implement certain As&As as part of a ship's 'Fleet Time Support', consisting of relatively short, but more frequent maintenance periods. This offers capability assurances in terms of safety and obsolescence management on a continuous basis. It also facilitates an agile and flexible response to rapidly changing operational requirements. However, limitations exist for the types of As&As that can be implemented in Fleet Time (FT), during short maintenance periods, whilst the ship is at notice to resume operations, often overseas, and with the crew remaining on board. It is sometimes the case that A&A proposals suitable for FT implementation present themselves as obvious candidates due to their combination of high priority and low complexity. However, the decision is generally less intuitive and requires robust investigation into the nature of A&A proposals. This chapter explains the reasoning that takes place at the point of considering A&A proposals as suitable FT candidates. It then demonstrates the application of the Simple Additive Weighting (SAW) technique to form decisions that have systematic and objective justification. In so doing, a decision making framework is proposed involving evaluation of A&A proposals against an attribute hierarchy of major criteria and sub-criteria.

5.1 Major Upkeep Periods v Fleet Time Support as A&A Fit Opportunities

In keeping with standard practice for commercial shipping, RFA vessels undergo a maintenance cycle having major refit periods at intervals of 5 years with an intermediate docking period. These are the major Upkeep periods for which a ship is removed from its 'Fleet Time' (FT) operations for survey and maintenance lasting up to several months. During this time, vessels are dry-docked and available for an extensive range of intrusive repair and conversion activities. It follows, therefore, that in parallel with Upkeep maintenance, the opportunity is taken to Upgrade and Update vessel capability by integrating design changes (i.e. As&As) into the major refit and docking periods. This has efficiency advantages since work packages for Upgrade, Update and Upkeep can all be integrated within a single programme. This involves a project management plan that addresses work-scope and funding overlaps, and which utilises common shipyard resource and facilities. The project plan can then be implemented by coordinating the combined activities of the Design Authority, the teams responsible for vessel availability, the logistics support, the shipyard engineers and the ship staff.

These coordination advantages mean that the integration of As&As within major Upkeep periods is normal practice, such that the vast majority are implemented in this way. Even so, an alternative practice is to implement certain As&As as part of a ship's FT Support. This consists of relatively short maintenance periods whilst crew remain embarked and whilst the ship stands at readiness to resume operations with a 'notice for sea' measured in hours or days. These are the Contractor Support Periods (CSPs) and Assisted Maintenance Periods (AMPs) which, compared to the major Upkeep periods, occur with a greater frequency of (nominally) 3 programmes per year. This greater access for maintenance purposes offers the opportunity to Upgrade and Update a vessel's functional capability on a more continuous basis. This is particularly desirable in the case of those As&As aimed at assuring safety and managing obsolescence. In addition, the FT implementation of As&As offers an agile response to rapidly changing operational requirements by facilitating frequent enhancements to platform capability, as deemed necessary by NCHQ (Naval Command Headquarters). Furthermore, a useful level of flexibility can be built into A&A programmes by using successive FT Support Periods to incrementally implement more complex, or more expensive, As&As over staged packages.

It can be appreciated, therefore, that the Upgrade and Update of RFA vessels between major Upkeep periods spreads engineering work more evenly across the refit cycle in terms of design effort, project management, cost and risk. For this reason, the implementation of As&As during FT remains a strategy aspiration for the through life support for RFA vessels. The relative advantages of implementing As&As during major Upkeep periods and FT are summarised within Table 5.1.1.

Table 5.1.1. Comparison of A&A Implementation During Upkeep Periods and Fleet Time [27]

A&A Within Major Upkeep Period	A&A During Fleet Time Support
Extensive scope of repair and conversion activities with wide access to ship systems, structure and layout for intrusive As&As.	Safety Assurance and Obsolescence Management by Update and Upgrade of a vessel's functional capability on a more continuous basis.
Upkeep and A&A work packages facilitated by relatively large budget.	Capability enhancement by offering an agile response to rapidly changing operational requirements.
Integrated project management plan for Upgrade, Update and Upkeep activities.	Fit Opportunity Flexibility by incrementally implementing complex or costly As&As over staged packages.
Accommodation of work scope and funding overlaps between Upkeep and A&A work packages.	Reduce risk at major Upkeep periods by spreading design effort, project management, engineering work and cost across the refit cycle.
Common shipyard resource and facilities directed toward Upkeep and A&A work packages.	
High degree of coordinated effort between design authority, Upkeep teams, shipyard workers and ship staff.	

5.2 Platform Assurance Associated with Fleet Time (FT) Implementation

As discussed within section 5.1, the driving factors for FT implementation of As&As can be understood in terms of the benefits and assurances offered to RFA ships on a continuous operational basis. These come in the form of safety, obsolescence management, capability enhancement and incremental fits. Ultimately, the implementation of As&As during FT seeks to deliver continuous ship capability whilst reducing the workload and project risk (cost and schedule) during major Upkeep periods. The assurances offered by implementing As&As during FT are summarised within Table 5.2.1.

[27] Table 5.1.1 is offered by the researcher following discussions with SQEP and own professional experience working with the RFA between 2008 and 2012.

Table 5.2.1. Platform Assurance for Fleet Time A&A Implementation [28]

Reason for FT A&A Implementation	Platform Assurance
Update and Upgrade on a continuous basis	Safety Assurance and Duty of Care
Update on a continuous basis	Obsolescence Management
Agile response to rapidly changing operational requirements	Capability Insertion and Enhancement (Upgrade)
Flexible implementation over staged work packages.	Incremental Fit (manage programme cost and schedule)

5.3 Constraints Towards the Fleet Time (FT) Implementation of As&As

Whilst the implementation of As&As during FT offers an agile and flexible response to the requirements of ship Upgrade and Update, it must be appreciated that implementation may not be possible during FT since maintenance periods are short, the ship is at notice to resume operations and the crew are living and working on-board. For example, it would not be desirable to implement As&As involving high habitability disturbance (heating, lighting, noise, fumes etc.). Similarly, it would not be possible to implement As&As that are intrusive towards ship structure or services, involving the large scale removal of deck plates or the shutting down of ship's power. Hence, in order to realise the benefits of implementing As&As during FT, it is first necessary to identify those factors that would permit and, more importantly, *prevent,* the implementation. These factors are the constraints that impose risk towards the successful implementation of As&As during FT. For the purpose of reasoning, modelling and decision making, it is proposed within this research project that the constraints be identified and treated as Risk Factors (RFs).

5.4 Risk Based Reasoning for Fleet Time (FT) Implementation of As&As [29].

Figure 5.4.1 proposes the decision-point process needed to determine the suitability of a supported A&A for implementation during FT. This builds upon the description previously given for the DCB process[30]. It offers a means by which

[28] Table 5.2.1 is offered by the researcher following discussions with SQEP and own professional experience working with the RFA between 2008 and 2012.
[29] 'Risk' is used here to describe the constraints associated with implementation of As&As during Fleet Time. It does not represent a calculation of Risk as (likelihood x consequence).
[30] DCB process - the Design Control Board process involves investigation of A&A proposals to facilitate informed decision making towards their acceptance (or otherwise) and the management of their implementation. Examination and explanation is given throughout Chapters 3 and 4.

clear and justifiable reasoning can be applied to consider the basis upon which the decision can be made to implement that A&A during FT.

Ultimately, the decision on whether any A&A is a suitable FT candidate must be derived by evaluating the benefits, in terms of platform assurances, against the Risk Factors constraining the scope of work that can be attempted during FT. It follows that benefits and risks should be identified and quantified, although in practice, comparison of benefits against risk is often based upon subjective opinion and judgement. This is justified when the following points are considered:

- At Figure 5.4.1, the researcher proposes how the decision-point reasoning for FT implementation of As&As would be conducted as an extension to the DCB process explained throughout Chapters 3 and 4. By definition, Design Control Boards are a forum for informed discussion leading to collective decision making by SQEP. Within this context, the exercising of qualitative engineering judgement is entirely consistent with the requirement to make robust and defensible engineering decisions.

- Quantitative data for benefit-risk analysis will only be available for A&A proposals where detailed investigations or feasibility studies have been performed by shipyard designers, consultants or specialist service providers. This is because the accumulation of data is both costly and time consuming, making a detailed approach impractical for large numbers of A&A proposals, especially when project milestones are approaching for ship refit. Following a principle of ‘proportionality’, the detail of analysis will only increase where A&A proposals are categorised as ‘major’ by virtue of high financial value, criticality towards vessel operations and high levels of perceived risk towards implementation.

From preceding discussions, it can be understood that consideration of A&A proposals as suitable candidates for FT implementation should follow a systematic reasoning process, during which proposals are evaluated against several risk-based criteria (attributes). It follows that an established MADM technique can be applied to form decisions that have systematic and objective justification. Accordingly, the application of the SAW technique will be examined.

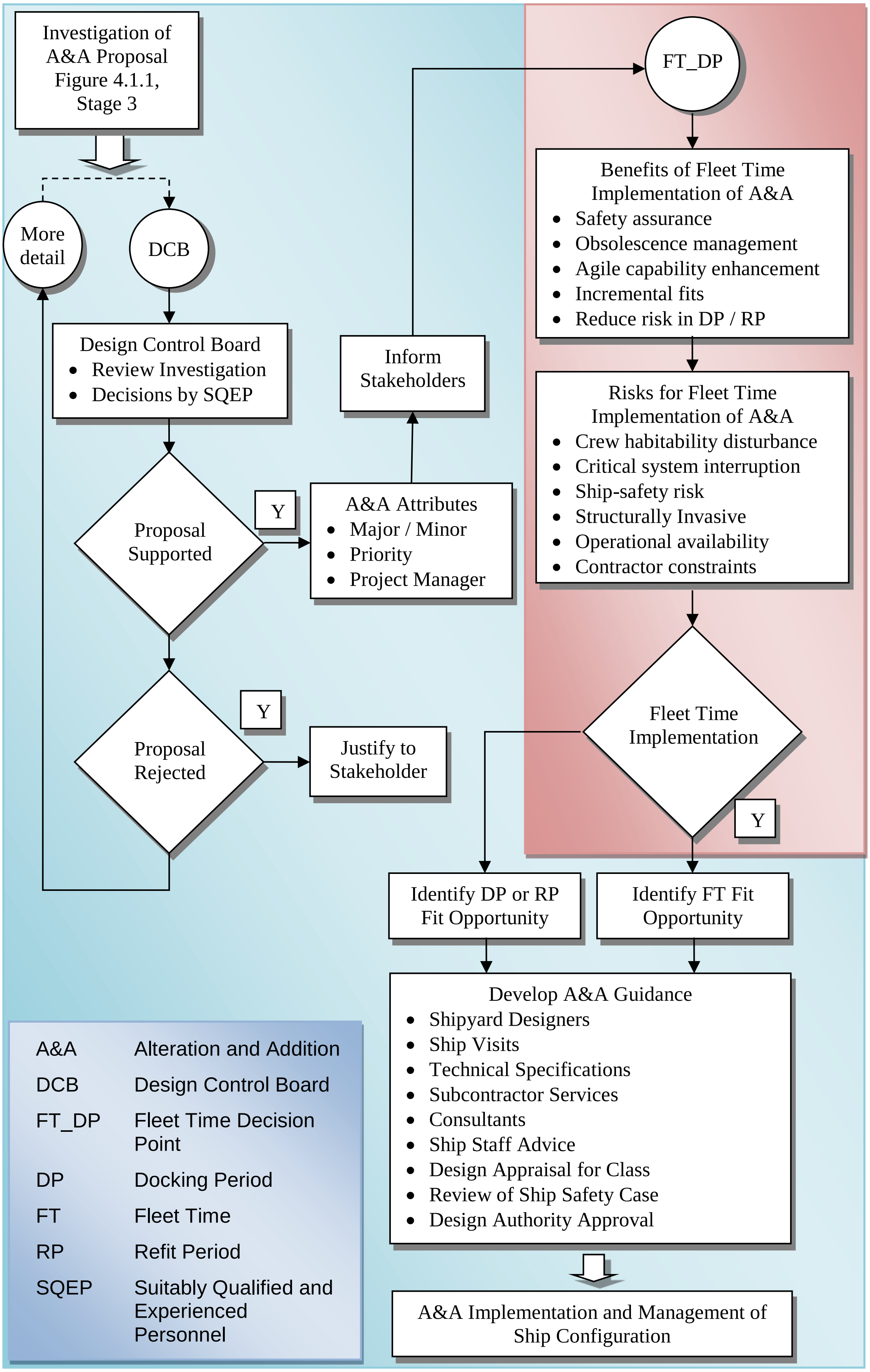


Figure 5.4.1. Proposed FT Decision Reasoning within the DCB Process

5.5 The Simple Additive Weighting (SAW) Approach to MADM Problems

The SAW approach was introduced within Chapter 4 (Section 4.3.1). To summarise, the method determines a decision outcome based on the addition of weighted performance scores for each decision option, where performance has been scored against the attributes (criteria) required of the decision outcome. The detail and application of the SAW approach are discussed below.

5.6 The Generic Simple Additive Weighting Approach

The generic SAW approach involves the following steps:

5.6.1 Step 1. Objective

The overall objective is clearly defined and treated as the decision making problem.

5.6.2 Step 2. Attribute Generation

The criteria relevant to the decision are identified. These are the attributes required of the **chosen solution.**

5.6.3 Step 3. Criteria (Attribute) Weighting

The criteria are prioritised by giving each a weighting factor. By normalising values, data can be made compatible throughout the methodology. Care must be taken if scoring against a mix of benefit and cost attributes to ensure that the nature of the attribute is understood (benefit or cost) and that the numerical manipulation of values is compatible throughout the decision making methodology.

The treatment of attributes was discussed within Chapter 4 (Section 4.2.3).

5.6.4 Step 4. Design Alternatives

A range of design options are considered during the concept studies for any design selection exercise. The credible alternatives are identified and developed for a particular scenario with the aim of ultimately selecting a single design solution.

5.6.5 Step 5. Scoring Matrix

The problem is structured as a decision matrix with design alternatives scored against each required attribute.

For the generic decision matrix shown below, the value of 'x' is the score given to each alternative ($i = 1, \dots, m$) with respect to each of the attributes in turn ($j = 1, \dots, n$).

Scores are assigned by decision making analysts with subject matter expertise towards the decision problem.

Generic Decision Matrix

Required Attributes (Criteria)

Design Alternatives

$$\begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & x_{2,3} & \cdots & x_{2,n} \\ x_{3,1} & x_{3,2} & x_{3,3} & \cdots & x_{3,n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m,1} & x_{m,2} & x_{m,3} & \cdots & x_{m,n} \end{bmatrix}$$

where each element can be expressed as:

$$x_{i,j} \quad \text{for } i = 1, \dots, m; \quad j = 1, \dots, n$$

5.6.6 Step 6. Weighted Performance Scores

For each decision option, the performance scores are multiplied by the criteria weightings. The resulting values (v) can be expressed by Eqn.(5.2).

$$v_{ij} = w_j r_{ij} \qquad i = 1, \dots, m; \quad j = 1, \dots, n. \qquad \text{Eqn. (5.2)}$$

where: r_{ij} represents the normalised values for $x_{i,j}$

5.6.7 Step 7. Additive Weightings

The weighted performance scores are added to give the value function (V) for each option using Eqn.(5.3).

$$V_{ij} = \sum_{j=1}^{n} w_j r_{ij} \qquad i = 1, \dots, m \qquad \text{Eqn. (5.3)}$$

5.6.8 Step 8. Decision Down-Select

The decision options are ranked according to the sum of their weighted scores. Ultimately, the decision analysts must make a decision regarding selection (or otherwise) of design alternatives, with the credibility of each based upon the ability to satisfy design criteria.

5.7 Application of SAW for Risk-Based Modelling of Fleet Time As&As

To demonstrate the application of the SAW technique, a test case compares 3 proposals for As&As to be implemented during fleet time. From previous sections, it can be appreciated that selection involves evaluating the benefits in terms of platform assurances against the Risk Factors constraining the scope of work that can be attempted during fleet time. Therefore, the test case identifies the Risk Factors as attributes (criteria) that are weighted to reflect the fact that some attributes will be considered by decision analysts to be more important than others.

Unless otherwise stated, investigations to support this demonstration have involved discussions between the researcher, groups and individuals who, by virtue of their experience, qualifications and responsibilities, can be regarded as Suitably Qualified and Experienced Personnel (SQEP). This approach is discussed within Appendix B.

5.7.1 Step 1. Objective

The decision making problem is to identify the most suitable proposals for design Alterations and Additions (As&As) during fleet time. The decision making methodology will consider the constraints imposed upon FT implementation and rank the A&A proposals accordingly.

5.7.2 Step 2. Attribute Generation

It is proposed by this research project that the constraints be grouped into four independent Risk Factors, as shown within Figure 5.7.2.1. This follows discussion within Sections 5.3 and 5.4 of the risks associated with implementing As&As during FT. These Risk Factors represent the criteria against which proposals for As&As can be judged for their suitability for implementation during

FT. The Risk Factors have been considered from the perspectives of the following key stakeholders:

- The ship staff required to live and work on board RFA vessels and occupy the same areas where As&As may be taking place.
- The MoD as owner, operator and Design Authority for those vessels, with responsibilities towards vessel availability and capability because of operational commitments
- The commercial shipyard responsible for the delivery of vessel Upgrade, Update and Upkeep, including the associated administrative, engineering, project management and logistic activities.

The factors were identified during discussions across the key SQEP stakeholders. Discussions at these levels led to the expansion of the four main Risk Factors as shown within Table 5.7.2.1.

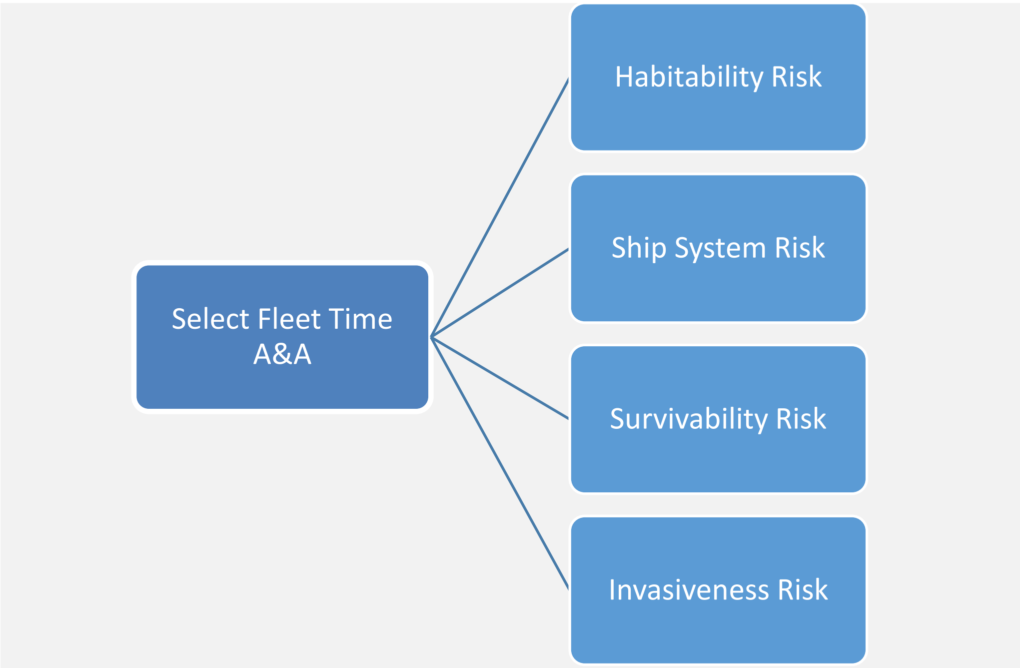


Figure 5.7.2.1. Proposed Risk Factors for FT Implementation of As&As

Table 5.7.2.1 indicates the following:

- **Habitability Risk Factor (HAB_RF)**. This is concerned with requirements to maintain acceptable conditions for crew, in terms of the domestic services and ambient conditions within living and working spaces.

- **System Risk Factor (SYS_RF)**. This is concerned with requirements to maintain essential ship services in terms of systems for electrical power generation and distribution, mechanical systems and systems for machinery control and surveillance.

Table 5.7.2.1. Risk Factors Applicable to Fleet Time As&As [31]

Habitability Risk Factor	Crew habitability disturbance - examples
HAB_RF Habitability Risk Factor. Concerned with requirements to maintain acceptable ambient conditions for crew living on-board.	• HVAC (heating ventilation air conditioning) • Domestic hot water • Lighting • Noise • Fumes • Access to cabins • Removal of deck-head and bulkhead panels in living areas • Loss of mess facilities • Loss of rest and recuperation facilities • Trip hazards
Ship System Risk Factor	**Continuance of ship support systems - examples**
SYS_RF System Risk Factor. Concerned with requirements to maintain essential ship services	• Stores Refrigeration plant • Cold storage rooms • Boilers • Sewage treatment plants • Lighting • Internal Communications • Electrical power generation • Intrusion into galley • Systems for Machinery Control and Surveillance • Loss of cooling (sea water / fresh water / chilled water)
Survivability Risk Factor	**Continuance of ship safety systems - examples**
SURV_RF Survivability Risk Factor. Concerned with requirements to maintain systems for ship safety, protection and damage control.	• Navigation, situational awareness and safe passage • Provision of Emergency power • Interruption to Fire Fighting Main or fire alarm systems • Removal of Close In Weapon Support (CIWS) systems • Provision of emergency fire and flood pumps
Invasiveness Risk Factor	**Invasiveness towards ship structure - examples**
INV_RF Invasiveness Risk Factor. Concerned with requirements to minimise disruption to ship construction and access routes.	• Removal of deck plates • Dismantling of machinery • Need to access ship tanks • Cutting of hull • Cutting of ship structure • Structural work required below the waterline

- **Survivability Risk Factor (SURV_RF).** This is concerned with the requirement to maintain systems for ship-safety in terms of preventing damage scenarios, minimising loss of capability in the event of sustaining

[31] Based on work experience and discussions with Suitably Qualified and Experienced Personnel (SQEP).

damage and recovering ship availability and capability from a damage scenario.

- **Invasiveness Risk Factor (INV_RF).** This is concerned with the requirement to minimise dismantlement of ship structure and minimise disruption to access throughout the vessel.

5.7.3 Step 3. Criteria (Attribute) Weighting

The criteria are prioritised by giving each a weighting factor, as shown within Table 5.7.3.1. Ranking has been assigned on the basis of discussion between the researcher and subject experts within the RFA Design Authority. It should be noted that the ranking shown depends upon the preference of the decision maker and may be subject to alternative expert judgement. It should also be noted that, whilst the criteria weights have been based upon discussion between experts, the MADM review conducted in Chapter 4 indicated that hybrid approaches are commonly used, whereby the weights could be determined, for example, using the AHP method[32].

Table 5.7.3.1. Weighting of Major Risk Criteria

	Risk Criteria Scoring			
Major Criteria	rank	score (r)	RR (1/r)	normalised weight (RR)
Habitability Risk	4th	4	0.250	0.120
Ship System Risk	3rd	3	0.333	0.160
Survivability Risk	1st	1	1.000	0.480
Invasiveness Risk	2nd	2	0.500	0.240
Sum		10	2.083	1.000
Notes: (1) highest risk weightings identify the highest priority (2) RR = Rank Reciprocal				

Prioritisation of criteria has been achieved by ranking from 1st to 4th and scoring accordingly. The Rank Reciprocal (RR) method has been used whereby normalisation is achieved by dividing each reciprocal term by the sum of the reciprocals (Stillwell et al., 1981). This is shown by Eqn.(5.4). As discussed by

[32] Whilst the use of hybrid techniques has not been adopted within this thesis, it is envisaged that the approach could form the focus of future research.

Yoon & Hwang (1995) and by Roszkowska (2013), the method is an established means for weighting and normalising ranked criteria.

$$w_j = \frac{\frac{1}{r_j}}{\sum_{k=1}^{n} \frac{1}{r_k}} \quad \text{Eqn. (5.4)}$$

where:

r_j is the rank of the j th attribute, and n is the total number of attributes.

5.7.4 Step 4. Design Alternatives

Three A&A proposals are evaluated with the objective of ranking them in terms of the risks that would constrain their implementation during FT. The design alternatives are detailed within Table 5.7.4.1.

Table 5.7.4.1. Alterations and Additions Proposed for FT Implementation [33]

Name	Proposal Description	Justification	Explanation of Requirement	Comment on FT Implementation
CCTV	To fit an additional CCTV monitor adjacent to the radar sited on the bridge.	To achieve a SIGNIFICANT improvement in effectiveness.	When the "Darken ship shutters" are closed on the bridge, the Helicopter Control Officer cannot easily see the flight deck CCTV display to react in a safe and timely manner.	Not technically demanding and does not require major ship systems to be shut down. Short time to implement. System components accessible Remote from cabin spaces.
LADDER	Address ladder steepness within the Main Machinery Space.	To overcome a SIGNIFICANT hazard to safety.	The proposal follows an accident on the ladder leading to Engine Room.	Steep ladders require extensive redesign. Areas of engine room need isolating. Several days required to implement. Engine room unusable during installation.
EXHAUST	Harbour Generator - Manufacture and fit a resilient bulkhead transition piece for the generator exhaust.	To overcome a SIGNIFICANT deficiency in habitability.	Noise and vibration levels in the cabins above the generator are uncomfortable for occupants and borderline acceptable for crew accommodation.	Not technically demanding but generator must be shut down during installation. Bulkhead modifications are required. Work will occur in areas adjacent to crew sleeping areas.

[33] From actual records between 2008 and 2012 relating to 9 of the total 13 ships within the RFA flotilla.

The alternatives can be summarised as follows:

- Major alterations to the main ladder leading to a ship's engine room.
- Structural alterations to a bulkhead within an accommodation area with the aim of reducing ambient noise levels from a generator exhaust routed through the area.
- The installation of an additional CCTV with the ship's bridge area to monitor flight-deck operations.

5.7.5 Step 5. Scoring Matrix

Each proposal is evaluated against the criteria that would constrain FT implementation. The scoring matrix is shown within Table 5.7.5.1. Since the criteria do not contain quantitative measures, scoring is performed on a judgement basis by the engineering stakeholders considered to be Subject Matter Experts by virtue of engineering qualifications and experience.

Table 5.7.5.1. Scoring Matrix for A&A Fleet Time Implementation

Scoring								
Low Risk 1	**Alternatives (A)**							
Medium Risk 2	**A1**		**A2**		**A3**			
High Risk 3	**Ladder**		**Exhaust**		**CCTV**			
Criteria (X)	score (v)	Normalised (v_1)	score (v)	Normalised (v_2)	score (v)	Normalised (v_3)	max score (v_max)
Habitability Risk	1	0.333	3	1.000	1	0.333	3
Ship System Risk	3	1.000	2	0.667	1	0.333	3
Survivability Risk	3	1.000	2	0.667	2	0.667	3
Invasiveness Risk	3	1.000	2	0.667	1	0.333	3
Note: Linear normalisation is used for scoring (v / v_max)							

Scores have been assigned numerical values based upon a simple evaluation of the risks to FT implementation, i.e.:

- Low Risk =1.
- Medium Risk =2.
- High Risk =3.

Linear normalisation has been applied to the scores using Eqn. (5.5). This is commonly used with the SAW technique (Yoon & Hwang, 1995).

$$r_{ij}=\frac{x_{ij}}{x_j^*} \qquad i = 1, \dots, m; \quad j = 1, \dots, n. \qquad \text{Eqn. (5.5)}$$

where x_j^* is the maximum value of the j th attribute.

5.7.6 Step 6. Weighted Performance Scores

For each decision option, the normalised values within the scoring matrix are multiplied by the normalised criteria weightings according to Eqn. (5.2). The weighted scores are shown within Table 5.7.6.1.

Table 5.7.6.1. Weighted Scoring Matrix for A&A Fleet Time Implementation

		Alternatives (A)					
		A1		**A2**		**A3**	
		Ladder		**Exhaust**		**CCTV**	
Criteria (X)	weight	score	weighted score	score	weighted score	score	weighted score
	w	v_1	(w) x (v_1)	v_2	(w) x (v_2)	v_3	(w) x (v_3)
Habitability Risk	0.120	0.333	0.040	1.000	0.120	0.333	0.040
Ship System Risk	0.160	1.000	0.160	0.667	0.107	0.333	0.053
Survivability Risk	0.480	1.000	0.480	0.667	0.320	0.667	0.320
Invasiveness Risk	0.240	1.000	0.240	0.667	0.160	0.333	0.080
Value of Alternative $V = \sum (w)(v)$			0.920		0.707		0.493
Rank of Alternative			**1**		**2**		**3**

5.7.7 Step 7. Additive Weightings

Using Eqn. (5.3), the weighted performance scores are added to give the value function (V) for each option, as shown within Table 5.7.6.1.

5.7.8 Step 8. Decision Down-Select

As demonstrated within Table 5.7.6.1, the SAW technique has resulted in the A&A proposals being ranked according to the sum of their weighted scores. Because cost criteria have been applied throughout the analysis, involving high values being associated with high risk, the A&A proposals are ranked in descending order from the option with the highest risk to that with the lowest risk. It should be remembered that the objective was tied to identifying A&A proposals with low risk for implementation during fleet time.

5.8 Development of a Risk-Based Attribute Hierarchy

The comparison of A&A proposals described thus far involves a simple evaluation against four risk-based attributes. Whilst this treatment returned effective results for the test case, it may be postulated that a more rigorous consideration, involving a wider range of criteria, would more accurately reflect the broad scope of scenarios encountered in practical situations. For this reason, it is proposed that the Risk Factors shown within Table 5.7.2.1 be developed into a hierarchy of attributes involving the four major criteria and a second tier of sub-criteria. The proposed attribute hierarchy[34] is shown within Figure 5.8.1. Weights can be assigned throughout the hierarchy as a continuance of the process described within Section 5.7.3. The results are shown within Table 5.8.1.

For example, the normalised (RR) weight for Habitability Risk is:

w = 0.120 = (0.250 / 2.083).

The approach has been extended to the sub-criteria and weights at the end of each 'branch' are obtained by multiplying through the hierarchy. For example, under the major criteria of 'Habitability Risk', the weight for 'Domestic Systems' has been calculated as follows:

Normalisation (RR) = 0.3333 = 0.500 / (0.500 + 1.000), using Eqn. (5.4)

Then: w = 0.040 = (0.333 x 0.120):

Before the weights can be applied to influence the decision making, each A&A alternative is evaluated against the major and sub-criteria following the process described within Section 5.7.5 The resultant matrix at Table 5.8.2 shows scores for each A&A proposal against all criteria within the attribute hierarchy.

[34] The hierarchy and weights were proposed by the researcher and offered to senior engineers having responsibility for RFA and RN ship maintenance. The details were offered within a draft paper for which feedback was requested. It has since been reviewed. No objections were received towards the hierarchy.

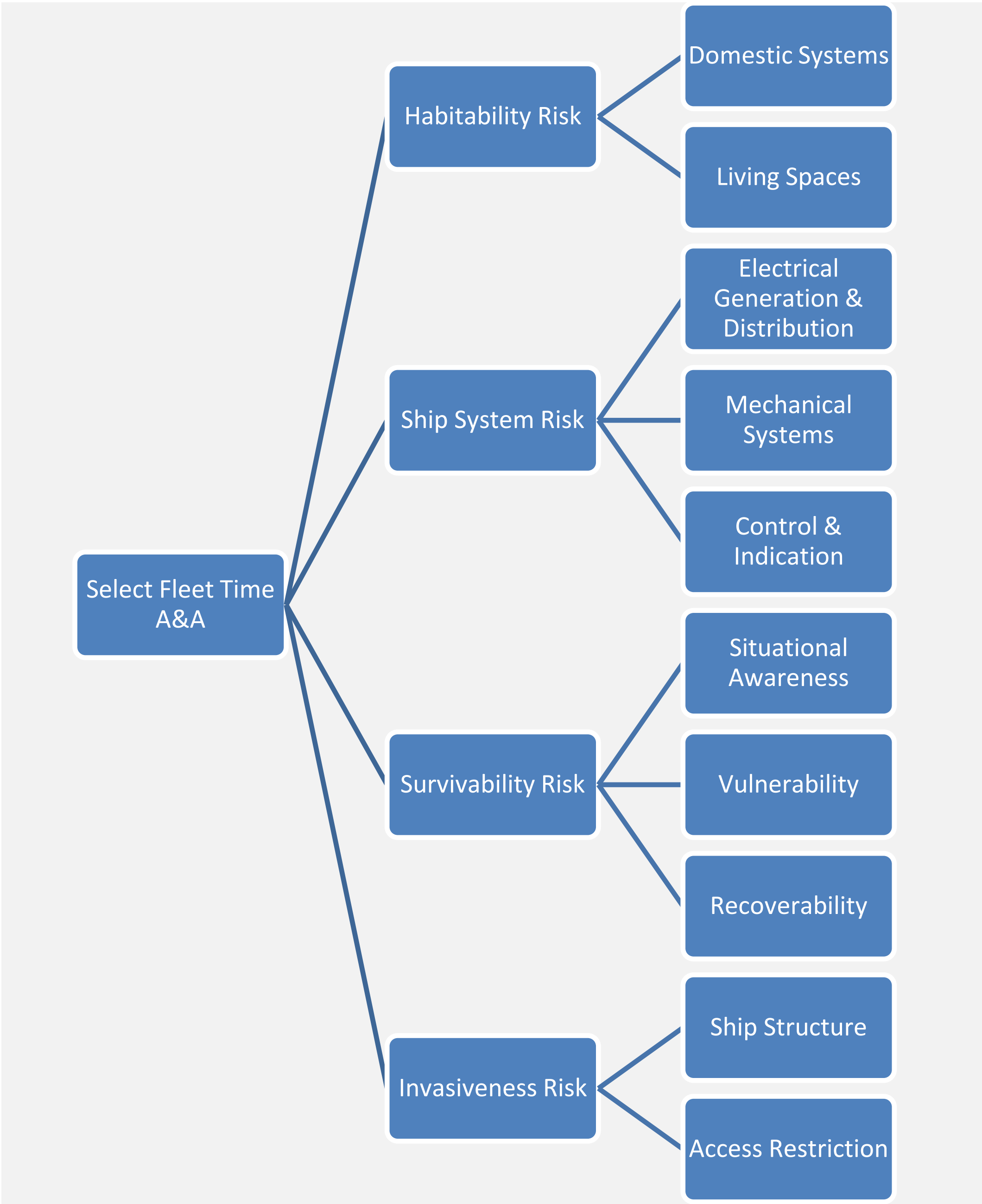


Figure 5.8.1. Proposed Criteria Hierarchy for A&A Implementation in FT

Having established the criteria weightings and produced a scoring matrix, a weighted scoring matrix is derived in accordance with Section 5.7.6. Finally, the weighted performance scores are added using Eqn. (5.3) to give the value function (V) for each option. The results are shown within Table 5.8.3.

As previously, the A&A proposals are ranked in descending order from the option with the highest risk to that with the lowest risk. This ranking is consistent with that derived in the previous case.

It is evident that the results are in trend with those calculated within Table 5.7.6.1 for the simple decision hierarchy. In fact, it is reasonable to accept that the results within Table 5.8.3 are the more reliable since they have considered the decision problem from the perspectives of a wider range of attributes.

Table 5.8.1. Criteria Weighting for the Attribute Hierarchy

	Major Risk Criteria			Risk Sub-Criteria			
Criteria (X)	rank	RR (1/r)	normalised weight (RR)	rank	RR (1/r)	normalised (RR)	**weight (w)**
Habitability Risk	4	0.250	0.120				
Domestic Systems				2	0.500	0.3333	**0.040**
Living Spaces				1	1.000	0.6667	**0.080**
Ship System Risk	3	0.333	0.160				
Electrical				2	0.500	0.3333	**0.053**
Mechanical				2	0.500	0.3333	**0.053**
C&I				2	0.500	0.3333	**0.053**
Survivability Risk	1	1.000	0.480				
SA				1	1.000	0.5455	**0.262**
Vulnerability				2	0.500	0.2727	**0.131**
Recoverability				3	0.333	0.1818	**0.087**
Invasiveness Risk	2	0.500	0.240				
Structure				1	1.000	0.6667	**0.160**
Access				2	0.500	0.3333	**0.080**
Sum		2.083	1.000				**1.000**

Notes:
(1) The highest weightings identify the highest risk priority
(2) Where attributes are tied in ranking, the mean rank is used
(3) Rank Reciprocal (RR) normalisation has been used for ranked weightings

Table 5.8.2. Scoring Matrix for A&A Fleet Time Implementation

Scoring	Note: Linear normalisation is used for scoring (v / v_max)						
Low Risk 1 Medium Risk 2 High Risk 3	**Alternatives (A)**						
	A1		**A2**		**A3**		
	Ladder		**Exhaust**		**CCTV**		
Criteria (X)	score (v)	normalised	score (v)	normalised	score (v)	normalised	max score (v_max)
	v_1		v_2		v_3		
Habitability Risk							
Domestic Systems	1	0.333	1	0.333	1	0.333	3
Living Spaces	1	0.333	3	1.000	1	0.333	3
Ship System Risk							
Electrical	3	1.000	2	0.667	1	0.333	3
Mechanical	3	1.000	2	0.667	1	0.333	3
C&I	3	1.000	1	0.333	1	0.333	3
Survivability Risk							
Susceptibility	1	0.333	1	0.333	2	0.667	3
Vulnerability	3	1.000	2	0.667	1	0.333	3
Recoverability	3	1.000	2	0.667	1	0.333	3
Invasiveness Risk							
Structure	3	1.000	2	0.667	1	0.333	3
Access	3	1.000	2	0.667	1	0.333	3

Table 5.8.3. Ranking of A&A for Fleet Time Implementation using SAW

		Alternatives (A)					
		A1		A2		A3	
		Ladder		Exhaust		CCTV	
Criteria (X)	weight	score	weighted score	score	weighted score	score	weighted score
	w	v_1	(w) x (v_1)	v_2	(w) x (v_2)	v_3	(w) x (v_3)
Habitability Risk							
Domestic Systems	0.040	0.333	0.013	0.333	0.013	0.333	0.013
Living Spaces	0.080	0.333	0.027	1.000	0.080	0.333	0.027
Ship System Risk							
Electrical	0.053	1.000	0.053	0.667	0.036	0.333	0.018
Mechanical	0.053	1.000	0.053	0.667	0.036	0.333	0.018
C&I	0.053	1.000	0.053	0.333	0.018	0.333	0.018
Survivability Risk							
SA	0.262	0.333	0.087	0.333	0.087	0.667	0.175
Vulnerability	0.131	1.000	0.131	0.667	0.087	0.333	0.044
Recoverability	0.087	1.000	0.087	0.667	0.058	0.333	0.029
Invasiveness Risk							
Structure	0.160	1.000	0.160	0.667	0.107	0.333	0.053
Access	0.080	1.000	0.080	0.667	0.053	0.333	0.027
Value of Alternative $V = \sum(w)(v)$			0.745		0.575		0.421
Rank of Alternative			1		2		3

5.9 Conclusion

The decision on whether an A&A proposal is a suitable candidate for implementation during Fleet Time must be derived by evaluating the benefits offered to the vessel against the constraints (risks) of doing so. The basis upon which evaluation may be made objectively has been proposed by a systematic Fleet Time (FT) decision-point reasoning process. The benefits have been expressed in terms of the capability assurances offered to the platform. These are safety assurance, obsolescence management, agile capability enhancement and the ability to incrementally implement design change.

The constraints relate to the difficulties of performing As&As during short maintenance periods whilst the ship is at short notice to resume operations, often overseas and with the crew living and working on board. Based upon discussions with Suitably Qualified and Experienced Personnel (SQEP), this chapter has demonstrated how these constraints can be expressed as four major criteria. These give consideration, from the perspective of all stakeholders associated with the A&A proposals, towards the risks associated with implementing As&As during FT. Furthermore, sub-criteria have been developed from the major risk criteria to propose an attribute hierarchy against which A&A proposals can be evaluated.

Generation of multiple attributes in this way means that the comparison of A&A proposals can be treated as a Multi Attribute Decision Making (MADM) problem. It follows, therefore, that an established MADM technique can be applied to form decisions that have systematic and objective justification. Accordingly, this chapter has applied the SAW approach. This was chosen because it is arguably the case that the SAW technique has gained widespread acceptance due to its intuitive and convenient approach.

Using the SAW technique, analysis was performed towards a test case by evaluating three A&A proposals against weighted criteria. In the first instance, for simplicity, the A&A proposals were evaluated against only the four major criteria. Then, following the reasoning that a wider range of criteria would more accurately reflect the broad scope of practical scenarios, the A&A proposals were evaluated against the complete attribute hierarchy.

In both cases, the decision making objective was met in that the analysis clearly distinguished between A&A proposals in terms of the risk associated with implementation during Fleet Time. Furthermore, the results were consistent across each analysis in terms of the ranking of A&A proposals. This gives confidence that in either case, a decision analyst would be presented with an effective approach. Since the approaches are differentiated by the depth to which criteria are considered, the applicability of one approach or the other can be determined according to the complexity of the decision making problem. Hence, the simpler approach can be applied where the decision appears to be more intuitive, and vice-versa.

It is the view of the researcher, based upon first-hand shipyard experience between 2008 and 2012 working alongside SQEP responsible for A&A

implementation, that selection of Fleet Time As&As is often based upon intuitive subjective judgement, supported by investigation into the nature of the A&A proposals. Whilst there is no suggestion that this approach is ineffective, the systematic treatment presented in this chapter represents an extension to the decision making process previously followed. In particular, the proposal of criteria as a risk-based attribute hierarchy presents an objective framework against which A&A proposals can be evaluated. Treatment in this way becomes useful where, for example, the aim is to establish a routine of conducting As&As to vessels whilst they remain in service.

Therefore, it is proposed that the approach presented provides a means by which selection of A&As for FT implementation can be made objectively. Evaluation against a comprehensive attribute hierarchy means that selection decisions are given thorough consideration. The decisions are, therefore, likely to be robust relative to the more intuitive thinking that might otherwise occur. It is certainly the case that adoption of the approach presented provides a means by which decisions can be systematically derived and documented.

To determine the degree of acceptance of the approach presented, this chapter will form the basis of an academic paper that will be offered to the design authority responsible for the implementation of As&As to RFA vessels.

In addition, to further explore the systematic treatment that has been implemented, a subsequent chapter will investigate the merits (or otherwise) of applying an alternative MADM technique, namely, the Analytic Hierarchy Process (AHP). A possible benefit involves the comparison of A&A proposals against each other rather than against an attribute hierarchy.

Chapter 6: Reasoning for the Implementation of Alterations and Additions (As&As) during Fleet Time (FT) using the Analytic Hierarchy Process (AHP)

Abstract

This chapter follows the discussions throughout Chapter 5 of the As&As that are implemented during Fleet Time (FT) within short maintenance periods whilst the vessel remains in, or near, its theatre of operation. Chapter 5 demonstrated how the SAW technique may be applied, as part of a systematic risk-based process, to make decisions towards As&As suitable for FT implementation. Having selected three examples of A&A proposals, it was shown how this decision can be made by ranking the As&As according to the risks that would constrain their implementation during FT. This chapter investigates an alternative decision making approach by testing the application of the Analytic Hierarchy Process (AHP) to the same three A&A proposals. By using the same problem to compare the approaches taken by SAW and AHP, this chapter investigates their relative merits when applied to A&A decisions of this type. It also tests, by consistency, the credibility of the results previously obtained.

6.1 The AHP as a Structured MADM Approach

This section illustrates the AHP by building upon the introduction offered within Chapter 4. Having been developed by Saaty (1977 and 1980), the AHP is an established method used as part of a formal decision making strategy. It takes the MADM approach, whereby conclusions are systematically derived towards a problem having several solution options, each of which is evaluated against key criteria. To illustrate this, in Figure 6.1.1, Saaty & Vargas (2012) consider the objective of choosing a specific boat design.

Two possible variants are considered (monohull or multihull), each of which is considered in terms of its attributes towards a particular scenario (racing or cruising). It can be appreciated therefore, that the AHP involves a decision being structured in terms of its clearly defined objective, the criteria that must be considered and the alternatives that offer possible solution.

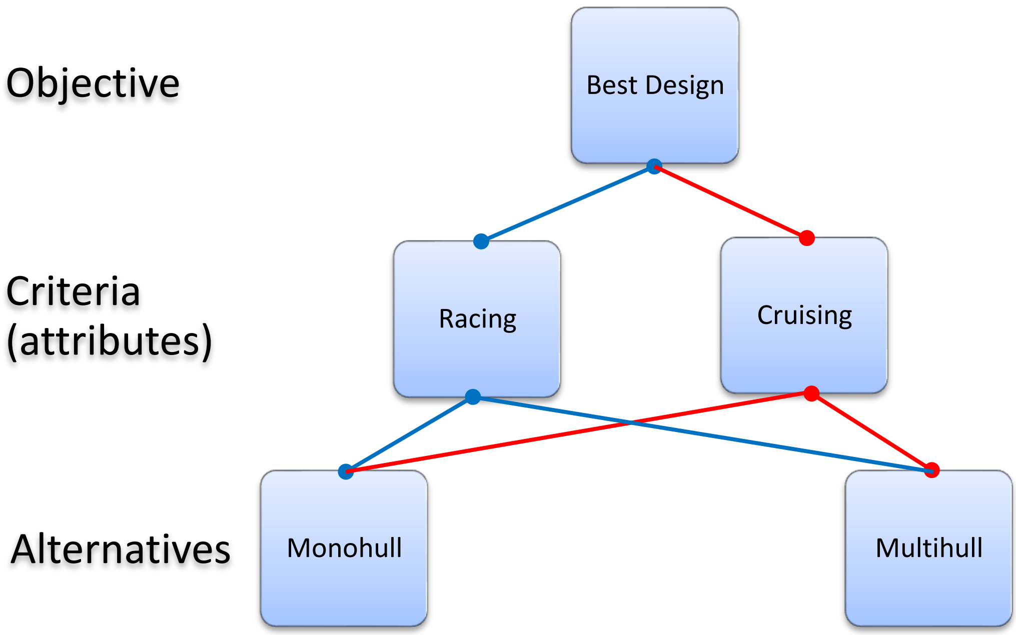


Figure 6.1.1. A Simple AHP Structured Boat Design Decision [35]

In his publication of the AHP, Saaty (1980) describes the process as having 15 distinct steps, as reproduced in full within Appendix C. To take a pragmatic approach within the context of this discussion, they have been adapted by the researcher as follows:

- **Step 1**. The overall objective is clearly defined and treated as the focus for the problem requiring solution. In this example, the objective is to determine optimum boat design by choosing between two credible options.
- **Step 2**. The objective is put into context whereby the solution options are identified for a particular scenario. In this example, the solution options are identified as being monohull and multihull design variants.
- **Step 3**. Criteria (attributes) relevant to the decision are identified.
- **Step 4**. The problem is formally structured in terms of objective, criteria and alternatives. In this example, in order to determine the best boat design, the effectiveness of each hull form option will be judged against racing and cruising criteria.

[35] Reprinted / adapted by permission from Springer Nature: Springer, Models, Methods, Concepts & Applications of the Analytic Hierarchy Process, by Thomas L. Saaty, Luis G. Vargas 2012.

- **Step 5.** The criteria are prioritised, i.e. ranked by giving each a weighting factor. In this example, weighting values would be derived for the racing criterion and the cruising criterion according to which is judged to be more important for the way the boat will be operated.

- **Step 6**. Pairwise comparison of solution options then occurs whereby options are scored against each other in terms of each criterion. Pairwise comparison will be demonstrated throughout this chapter.

- **Step 7.** For each option, composite scores from Steps 5 and 6 are obtained. The highest scoring option, and therefore the preferred solution, is that which is determined to be most favourable in terms of the most highly weighted criteria. The scoring mechanism will be demonstrated throughout this chapter.

When choosing between design options, the attributes of the final design must be selected and prioritised to optimise the design towards its intended purpose. This involves the criteria, and any sub criteria, being appropriately weighted to reflect their relative importance. As an extension to Figure 6.1.1, a decision can be structured using AHP to consider layers of criteria and sub-criteria. This is illustrated within Figure 6.1.2.

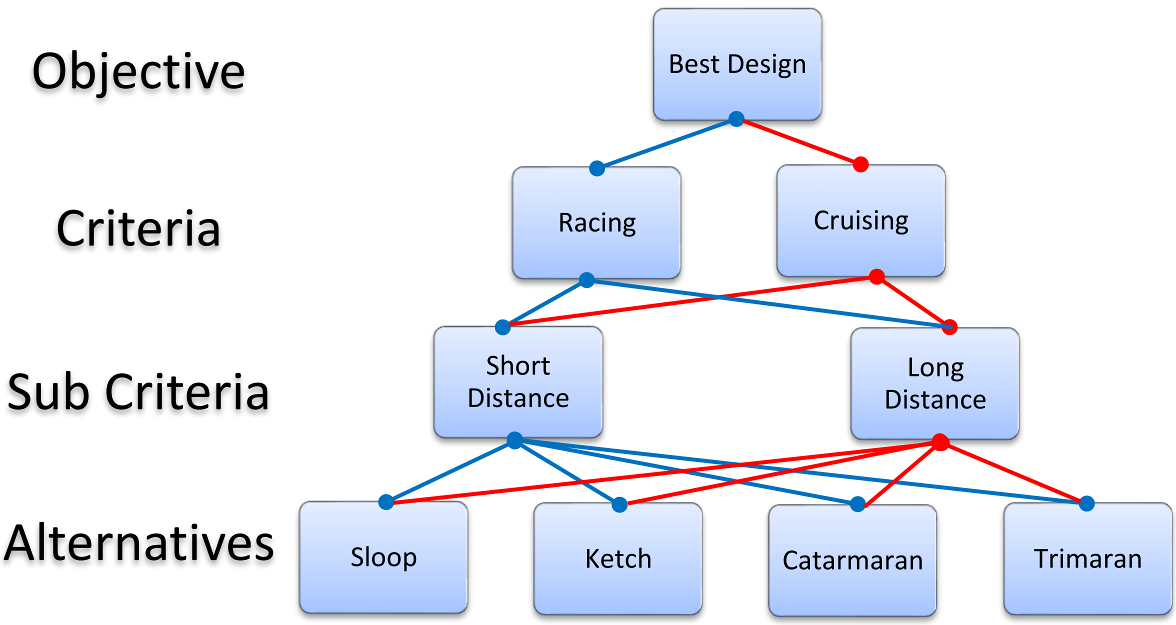


Figure 6.1.2. An AHP Decision Structured with Criteria and Sub Criteria [36]

[36] Reprinted / adapted by permission from Springer Nature: Springer, Models, Methods, Concepts & Applications of the Analytic Hierarchy Process, by Thomas L. Saaty, Luis G. Vargas 2012.

6.2 Review of Decision Reasoning for Fleet Time (FT) As&As

The concept of FT implementation of As&As was introduced within Section 5.1 as a means of offering agile ship Upgrade and Update. The benefits, in terms of assurances towards safety management, obsolescence management and capability enhancement, were discussed within Section 5.2. The Risk Factors were discussed within Section 5.3. These constrain the scope of work that can be undertaken during FT when maintenance periods are short, the ship is at short notice to resume operations and the crew is living and working on-board. As discussed within Section 5.4, systematic reasoning must be applied when deciding whether to implement As&As to RFA vessels during FT.

To support a formal decision approach using the SAW technique, Section 5.7.2 systematically identified the attributes against which A&A candidates may be evaluated to decide upon their suitability for FT implementation. For the purpose of investigating the effectiveness of that approach, Section 5.7.4 described three A&A candidates to be used as part of a test case.

As detailed throughout Section 5.7, the attributes used for A&A evaluation were compiled by the researcher based on professional experience and discussions with Suitably Qualified and Experienced Personnel (SQEP). The test case candidates were taken from actual A&A proposals investigated by the researcher during professional experience of the Upgrade and Update of RFA vessels using the DCB process. The approach is described within Appendix B

6.3 Risk Based Reasoning for FT implementation of As&As Using the AHP

For the purpose of the following AHP evaluation, the same test case will be considered. The candidates are shown within Table 5.7.4.1. As previously, the inverse approach will be taken whereby the most suitable is determined as that with the least constraining risk in terms of the Risk Factors shown within Table 5.7.2.1. The AHP will be used to systematically evaluate and quantify the risk for each proposal, thereby allowing proposals to be ranked according to risk.

6.4 Structuring the Problem

Figure 6.4.1 shows the steps taken when using the AHP. The objective is to identify the risk associated with the Fleet Time implementation of the three A&A proposals described within Table 5.7.4.1.

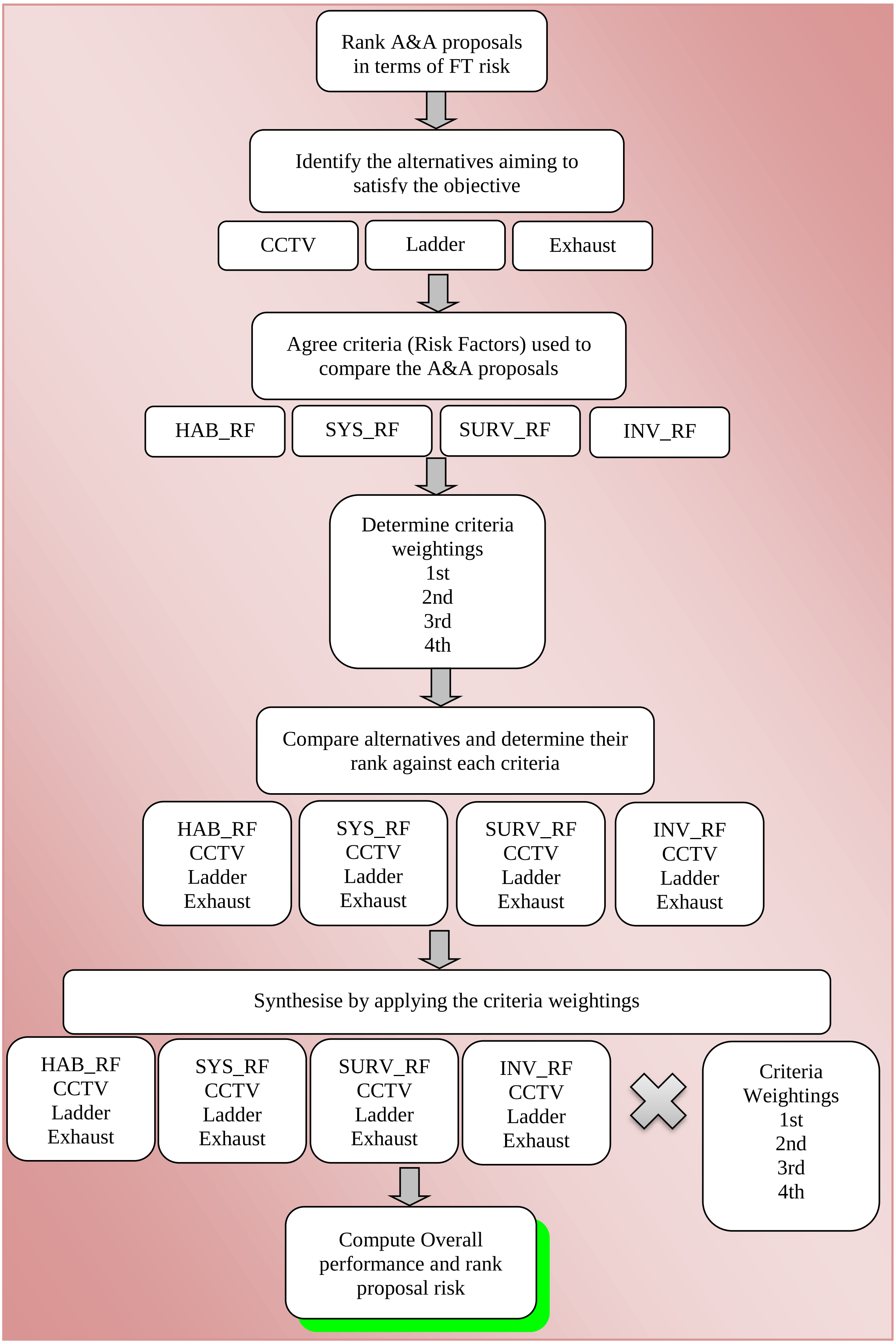


Figure 6.4.1. AHP Algorithm to Compare Risk Associated with FT As&As

As previously performed (Chapter 5), the criteria have been identified as the constraints (Risk Factors) during FT towards A&A implementation. These are the need to minimise habitability disturbance (HAB_RF), the need to maintain ship systems (SYS_RF), the requirement to maintain critical ship safety and survival systems (SURV_RF) and the inability to perform work that is intrusive towards ship structure (INV_RF).

6.4.1 Reciprocal Matrix by Pairwise Comparison

The aim of pairwise comparison is to judge how strongly one alternative compares to another. As discussed within Section 4.3.5, when using the AHP, comparison between pairs of alternatives is made in numerical terms according to a scale presented by Saaty (1980) and offered within Table 4.3.5.1.

Comparison is made to produce a matrix that quantifies the preference for one option over another, as demonstrated within Table 6.4.1.1. By convention, pairwise comparison is made between an alternative appearing in the left-hand column with each alternative appearing in the top row.

Comparison can be made unambiguously where reliable quantitative data exists that supports ratio measurement between alternatives. Conversely, the assignment of values to indicate preference for one alternative over another is often subjectively made by expert opinion, or based upon some practical observation. For the sake of illustration, the researcher has performed this judgement for the examples given. Judgement is based upon first-hand knowledge of the A&A proposals from their previous investigations during DCBs, and the application of documented A&A procedures for RN and RFA vessels (Royal Navy, 2003). The approach is described within Appendix B.

Table 6.4.1.1.shows how the matrix is developed to determine the weights assigned to the criteria (RFs). For illustration, it can be appreciated that when comparing the importance of ‘Survivability’ (SURV) with itself, the numerical value returned must have the value of ‘1’, indicating equal importance. However, the importance of ‘Survivability’ has been judged to be moderately greater than that of ‘Systems’ (SYS) and has therefore been assigned a value of ‘3’. Similarly, the importance of ‘Survivability’ is judged to be strongly greater than ‘Invasiveness’, and the importance of ‘Survivability’ is judged to be at the high extreme of the scale when compared to ‘Habitability’. The respective numerical values have been assigned. It follows that the reciprocal judgements hold true, such that

reciprocal values are entered into the matrix as shown. For this reason, this type of matrix may be referred to as a ‘Reciprocal Pairwise Matrix’.

Table 6.4.1.1. Development of the Criteria Weightings Reciprocal Matrix

Risk Factor	SURV	SYS	INV	HAB
SURV	1	3	5	9
SYS	1/3			
INV	1/5			
HAB	1/9			
Risk Factor	**SURV**	**SYS**	**INV**	**HAB**
SURV	1	3	5	9
SYS	1/3	1	4	6
INV	1/5	1/4	1	4
HAB	1/9	1/6	1/4	1

6.4.2 Computation of a Vector of Priorities

It should be remembered that the aim is to quantify the constraints, i.e. Risk Factors, in terms of their relative weightings. In mathematical terms this is achieved by computing the principle eigenvector. When normalised, this becomes the vector of priorities (the weighting vector, ‘w’). When using the AHP, it has been demonstrated by Saaty (1980) and Anderson, et al. (2003) that a good approximation is achieved using the following steps:

- Calculating the sum of the values in each column of the reciprocal pairwise matrix.
- Dividing each element in the matrix by its column summation. The resulting matrix is referred to as the normalised pairwise matrix.
- Computing the average value of the elements in each row of the normalised pairwise matrix. The average values of each element indicate the priority for criteria.

This computation is described within Eqn. (6.1) and Eqn. (6.2), (based upon the generic decision matrix given within Section 4.2.2).

When this technique is applied to the reciprocal pairwise matrix for criteria weightings, the priority vector is derived, as shown within Table 6.4.3.1. To put this in context, this gives the relative weightings for the Risk Factors that constrain the implementation of As&As during Fleet Time.

$$A = (a_{ij}) = \begin{bmatrix} 1 & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & 1 & \cdots & a_{2,n} \\ \cdot & \cdot & \cdots & \cdot \\ a_{n,1} & a_{n,2} & \cdots & 1 \end{bmatrix} \qquad \text{Eqn. (6.1)}$$

$$w_k = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \qquad \text{Eqn. (6.2)}$$

where:

w_k is the weighting vector of an element k in the reciprocal pairwise matrix and:

$k = 1, 2, \ldots n$.

6.4.3 Dealing with Consistency

The AHP recognises, and is capable of dealing with, the type of inconsistency that can occur when subjective human judgement is used to perform numerous pairwise comparisons. The principle can be appreciated when considering that if item 'A' is preferred over item 'B', and item 'B' is preferred over item 'C', then item 'A' should be preferred over item 'C' (transitive property). If not, then the comparisons are not logically consistent.

Table 6.4.3.1. Development of the Risk Factor Criteria Weightings

Risk Factor	SURV	SYS	INV	HAB
SURV	1	3	5	9
SYS	1/3	1	4	6
INV	1/5	1/4	1	4
HAB	1/9	1/6	1/4	1
Sum	1.64	4.42	10.25	20.00

Risk Factor	SURV	SYS	INV	HAB	Sum	Priority Vector (Risk Factor weightings)	
SURV	0.61	0.68	0.49	0.45	2.23	0.56	56%
SYS	0.20	0.23	0.39	0.30	1.12	0.28	28%
INV	0.12	0.06	0.10	0.20	0.48	0.12	12%
HAB	0.07	0.04	0.02	0.05	0.18	0.04	4%
Sum	1.00	1.00	1.00	1.00		1.00	

The AHP provides a measure of consistency by introducing the Consistency Ratio (CR) shown within Eqn. (6.3). As described by Saaty (1980) and Yang et al. (2001), a CR value greater than 0.1 indicates inconsistency such that pairwise judgements should be reviewed. In this respect, Saaty (1980), explains that the measure of consistency enables the judgements to be iterated by experienced participants, engaging in dialogue and making trade-offs to achieve compromise.

$$CR = {}^{CI}/_{RI} \qquad \text{Eqn. (6.3)}$$

where:

CR is the Consistency Ratio,

CI is the Consistency Index obtained from Eqn. (6.4) and:

RI is the random index. This is the Consistency Index for a randomly generated reciprocal matrix (see below)

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \text{Eqn. (6.4)}$$

where:

λ_{max} is the principal eigenvalue of an 'n x n' comparison matrix 'A' that is calculated using Eqn. (6.5).

$$\lambda_{max} = \frac{\sum_{k=1}^{n} \frac{\sum_{k=1,j=1}^{n} w_k \, a_{kj}}{w_k}}{n} \qquad \text{Eqn. (6.5)}$$

As explained by Saaty (1980), the principal eigenvalue is obtained from the summation of products between each element of the priority vector and the sum of columns. For the RF criteria (Table 6.4.3.1), this gives:

Principle eigenvalue	λ_{max}	4.27	
Consistency Index	CI	0.089	(λ-n)/(n-1)
Random Index	RI	0.9 for n = 4	

Noting that the Random Index is the CI for a randomly generated reciprocal matrix, as offered by Saaty (1980) and reproduced within Table 6.4.3.2.

Table 6.4.3.2. Random Index (RI) Values for a Matrix of Size 'n'

n	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56

This returns CR = 0.099, i.e. 9.9%. Since CR < 0.1, the pairwise judgements, and hence the weights assigned to the RFs, are considered consistent.

6.4.4 Comparison of A&A Proposals

Following the same methodology, pairwise comparisons are made for each A&A alternative with respect to each criterion. The results are shown within Table 6.4.4.1 such that the A&A proposals can be ranked in terms of the following:

- The impact of each upon the need to maintain ship safety and survivability systems (SURV).
- The impact of each upon ship support systems (SYS).
- The impact of each upon crew habitability (HAB).
- The invasive nature (INV) of each towards the ship structure and systems.

Table 6.4.4.1. Comparison of As&As wrt Risk Factors Using the AHP

SURV	LADDER	EXHAUST	CCTV	SURV	LADDER	EXHAUST	CCTV	SURV Priority Vector
LADDER	1	5	3	LADDER	0.65	0.56	0.69	0.633
EXHAUST	1/5	1	0.33	EXHAUST	0.13	0.11	0.08	0.106
CCTV	1/3	3	1	CCTV	0.22	0.33	0.23	0.260
Sum	1.53	9.00	4.33					
SYS	**LADDER**	**EXHAUST**	**CCTV**	**SYS**	**LADDER**	**EXHAUST**	**CCTV**	**SYS Priority Vector**
LADDER	1	7	8	LADDER	0.79	0.85	0.57	0.738
EXHAUST	1/7	1	5	EXHAUST	0.11	0.12	0.36	0.197
CCTV	1/8	1/5	1	CCTV	0.10	0.02	0.07	0.065
Sum	1.27	8.20	14.00					
INV	**LADDER**	**EXHAUST**	**CCTV**	**INV**	**LADDER**	**EXHAUST**	**CCTV**	**INV Priority Vector**
LADDER	1	6	9	LADDER	0.78	0.83	0.60	0.739
EXHAUST	1/6	1	5	EXHAUST	0.13	0.14	0.33	0.201
CCTV	1/9	1/5	1	CCTV	0.09	0.03	0.07	0.060
Sum	1.28	7.20	15.00					
HAB	**LADDER**	**EXHAUST**	**CCTV**	**HAB**	**LADDER**	**EXHAUST**	**CCTV**	**HAB Priority Vector**
LADDER	1	1/5	6	LADDER	0.16	0.14	0.50	0.268
EXHAUST	5	1	5	EXHAUST	0.81	0.71	0.42	0.647
CCTV	1/6	1/5	1	CCTV	0.03	0.14	0.08	0.084
Sum	6.17	1.40	12.00					

6.4.5 Synthesis of A&A Rankings with Weighted Criteria

At this stage, the AHP has been used to assign weightings to the criteria that could constrain the implementation of As&As during FT. The A&A alternatives have themselves been ranked with respect to each criterion. As can be appreciated from Figure 6.4.1, the final stage is to synthesise by matrix-vector multiplication, as shown within Table 6.4.5.1.

Table 6.4.5.1. Synthesis of A&A Rankings with Criteria Weightings

	SURV	SYS	INV	HAB		Risk Factor	Criteria Weighting
LADDER	0.633	0.738	0.739	0.268		SURV	0.556
EXHAUST	0.106	0.197	0.201	0.647	X	SYS	0.280
CCTV	0.260	0.065	0.060	0.084		INV	0.119
						HAB	0.045

e.g. for ladder

(SURV weight x SURV Rank for Ladder) + (SYS weight x SYS Rank for Ladder) + (INV weight x INV Rank for Ladder) + (HAB weight x HAB Rank for Ladder)

The overall results are given within Table 6.4.5.2. This shows the relative risk of implementing the three A&A proposals during FT. In particular, compared to the other As&As, the proposed alterations to the machinery room ladder would be highly unsuitable during FT maintenance periods and should therefore await a major docking period.

Table 6.4.5.2. Risk Quantification for FT Implementation using the AHP [37]

A&A	Comment	Risk Quantification
LADDER	**Involves the greatest constraints (highest risk)**	**0.659**
EXHAUST		**0.167**
CCTV		**0.174**

6.5 Conclusion

This chapter has demonstrated how the AHP can be applied towards proposals to implement As&As for RFA vessels during their FT maintenance periods. This follows the same study conducted within the previous chapter using the SAW

[37] This is a quantification, using the AHP, of the constraints imposed by implementing the A&A during Fleet Time. It is not a calculation of 'Risk' as (likelihood x consequence).

technique. In each case, application of the decision techniques represents a novel approach towards the kind of decisions that, particularly for low value or low criticality As&As, are otherwise likely to be performed intuitively, using informed judgement by SME. Should this judgement be contentious, the SAW and AHP techniques would provide a means of systematically structuring and evaluating a problem to arrive at robust decisions.

The AHP involves deriving weightings for criteria based upon comparison of their relative importance. In this example, the need to maintain ship survivability systems returned the highest weighting. This was progressively followed by the requirement to maintain ship support systems, the need to avoid intrusive work and the need to minimise crew habitability disturbance. Based upon these criteria, and following the AHP, it has been shown that major alteration of the engine room ladder involved the greatest constraints for FT implementation. Application of the AHP in this way therefore demonstrated a structured decision making approach towards identifying A&A proposals likely to be unsuitable for FT implementation.

The findings for AHP in this exercise are consistent with those of the same exercise previously conducted using the SAW technique. Whilst this offers mutual assurance towards the methodologies applied, it cannot in itself be taken as conclusive proof towards their suitability. Indeed, had it been the case that the results did not follow the same trend, then some other means would be needed to determine the more reliable result. Additional assurance could include:

- Benchmarking using test cases for which the outcome is already known;
- Learning from experience of decisions previously taken for problems of a similar nature, i.e. during the implementation of As&As for other vessels;
- Gaining understanding of the decision dynamics by sensitivity analysis, i.e. evaluating the decision outcome in response to changes in the weightings and numerical scoring;
- Applying an additional decision technique to assess the majority trend.

Finally, an observation offered by the researcher is that, whilst the SAW technique offered a convenient and intuitive approach, the AHP involves a higher cognitive burden. Therefore, in situations where a timely and pragmatic approach is sought by practical engineers, it may be the case that the effort associated with the AHP is not considered proportional in this application.

Chapter 7: The Application of TOPSIS to Select Construction Materials for a Marine Heat Exchanger

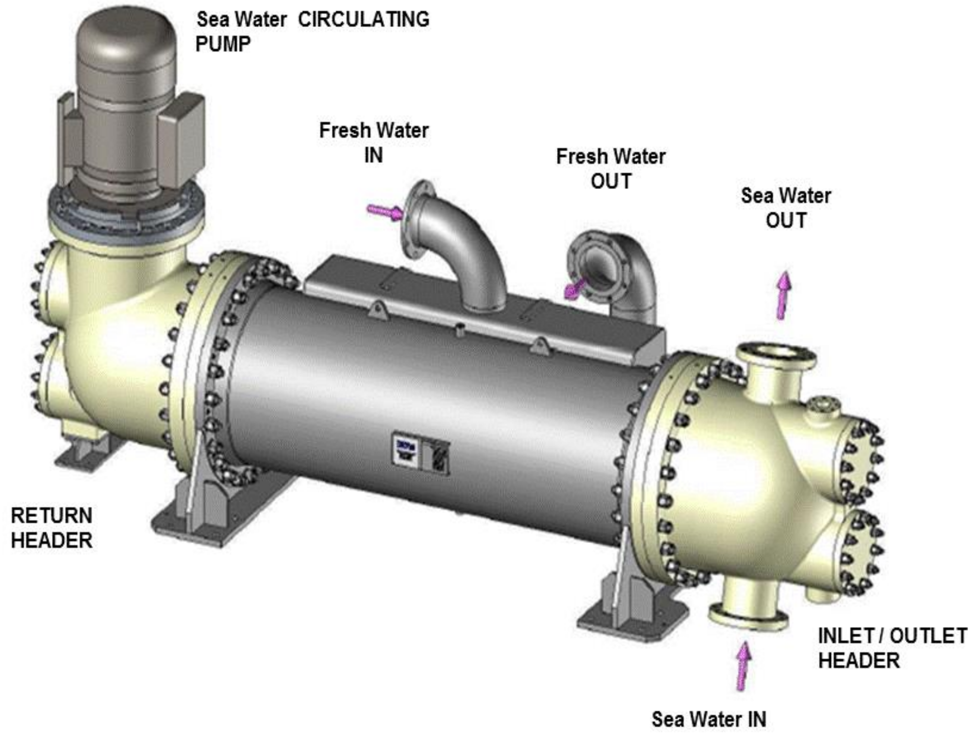
Abstract

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is based upon the concept that, for a problem with several solution alternatives, each to be considered against specific criteria (attributes), the chosen alternative should have the shortest distance from the 'Ideal Solution' and the farthest distance from the 'Negative Ideal Solution'. This chapter examines the hypothesis that a decision making methodology based upon TOPSIS can be applied to down-selection problems of the type encountered when conducting ship design exercises or implementing design Alterations & Additions (As&As). The hypothesis is tested against an adaptation of a design exercise conducted to select the material types for the sea water heat exchangers of a naval vessel. The chapter first introduces the attributes required of the material types, with particular reference to the Microbiologically Influenced Corrosion (MIC) known to have been experienced by RN vessels within non-tidal sea water basins. Material options are then discussed and a test case is structured as a Multiple Attribute Decision Making (MADM) problem. The focus then shifts to the implementation of the TOPSIS-based methodology. As analysis is performed, key characteristics of the technique emerge, particularly in relation to the treatment of attribute types (benefit and cost) and to the effect upon the decision outcome of varying the attribute weightings. These characteristics are discussed throughout the methodology and conclusion.

7.1 Consideration of Heat Exchanger Materials as a MADM Design Problem

Within the context of this study, a marine heat exchanger is a ship's component that cools the temperature of a fresh water medium by transferring heat energy to sea water across a separating metal membrane. The fresh water is circulated as a cooling medium around ship systems, with heat being transferred from consumers throughout the vessel, ultimately into the surrounding sea. Figure 7.1.1 and Figure 7.1.2Figure 7.1.2. Internal Arrangement of a Shell and Tube

Heat Exchanger show the generic form and construction of a ‘shell and tube’ heat exchanger.



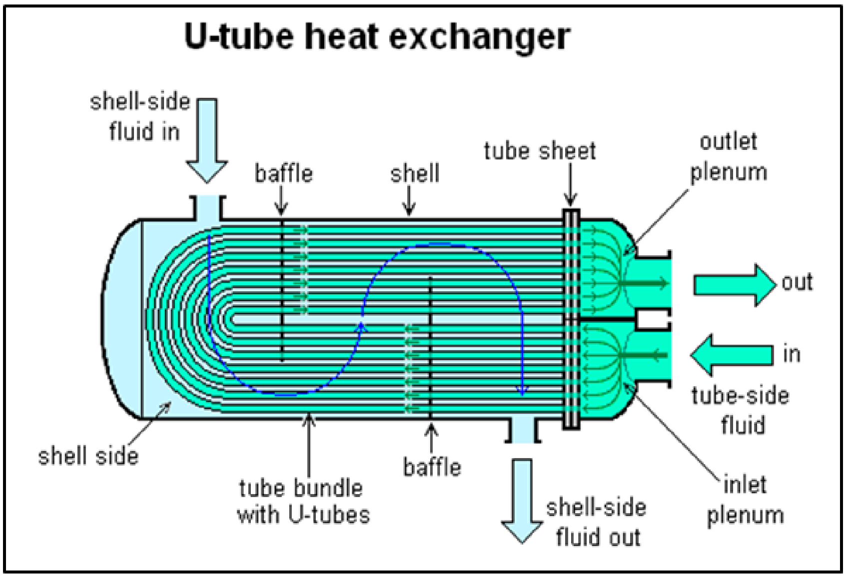
CAD Image supplied with the Coutesy of Naval Group

Figure 7.1.1. A Common Form of Marine Shell and Tube Heat Exchanger [38]

During design of the propulsion and auxiliary systems of naval and commercial vessels, heat exchangers are specified in terms of construction materials, heat duty, number of units and the operating regime. Typically, they are installed to last the service life of the vessel, with maintenance during Upkeep periods to restore thermal effectiveness by internal cleaning and repairs. Even so, once the vessel has entered service, As&As (Alterations and Additions) may be implemented to sea water cooling systems where, for example, changes in operational requirements have led to increased thermal loads or unforeseen high rates of internal corrosion and erosion. This situation is especially likely where vessels require outfitting for a change in role or where elderly vessels require

[38] Image supplied courtesy of Naval Group (formerly DCNS), a leading company in defence naval systems.

extensions to their service life. In such cases, As&As may include material changes, heat exchangers being uprated and changes to cooling system layout.



source: https://commons.wikimedia.org/wiki/File:U-tube_heat_exchanger.PNG
Free Documentation License

Image of Tube Sheet reproduced with permission from Copper Development Association
https://www.copper.org/applications/marine/cuni/

Image of a Tube Bundle provided by Standard Xchange Heat Transfer Company
http://apkthermal.com/standard-xchange/standard-shell-and-tube/

Figure 7.1.2. Internal Arrangement of a Shell and Tube Heat Exchanger [39]

[39] Copper Development Association – extensive source of information for copper-based materials including marine alloys.
Standard Exchange - experience includes a range of heat exchangers, particularly for US commercial and naval vessels.

Any such A&A would be treated as a 'major' design exercise given the criticality of cooling systems to ship safety and operation, the intrusive nature of implementation towards the vessel structure and adjacent systems, the required subject matter expertise, the high material and labour costs and the impact towards Upkeep planning in terms of scheduling and budgetary control.

Whether performed at the ship design phase or as an A&A during the service life of the vessel, the characteristics of the design exercise are the same insofar as decisions will need to be made towards selection of design solutions. This will involve selection across several design alternatives that must be evaluated against the multiple attributes (i.e. criteria) required of the chosen alternative. Further to the arguments presented within Chapter 4, it follows that selection between several options for heat exchanger materials can be treated as a Multiple Attribute Decision Making (MADM) problem.

7.2 Heat Exchanger Material Attributes

7.2.1 Physical (Thermal) Properties

For the operation of a heat exchanger to be both efficient and thermally effective, the tube bundle must be constructed from a material with high thermal conductivity and have its contact surface area maximized, whilst the water pumped through the heat exchanger encounters minimum flow resistance. Furthermore, in order to minimize stress and fatigue during thermal cycling, the coefficient of thermal expansion must be low. It must also be compatible with that of the materials used for the surrounding construction, including the tube sheet, baffles and tube supports.

7.2.2 Mechanical Properties

Compared to vessels of the RN, operating profiles for commercial vessels are generally well defined, involving fixed ocean transits or routines within a limited range from base. Environmental challenges will be encountered of course, although these can usually be predicted for the known area of operations. This means that requirements for ship systems can be defined according to a limited scope of operations. On the other hand, an RN surface vessel might be required to operate across a wide range of theatres, often involving environmental extremes. Similarly, vessels of the RFA are required to operate in, or around, the same environments in support of those operations. Furthermore, for submarines, environmental hazards extend to the high sea water pressures experienced during diving operations. Therefore, sea water heat exchangers must have appropriate tensile and creep properties. Mechanical properties must include adequate ductility across the temperature range, good fatigue behaviour and high fracture toughness to avoid fast fracture in the presence of component cracking during its long service life.

7.2.3 Corrosion Resistance

The materials in contact with sea water, particularly the tube sheets and tube bundles, must have low corrosion rates to maintain wall-thinning within the corrosion allowance. Furthermore, whilst the use of sacrificial anodes is commonplace, component selection throughout the heat exchanger and connecting pipework should be such that materials are galvanically compatible in order to avoid corrosion between dissimilar metals. In addition, the selection of materials that are susceptible to biofouling will result in reduced heat exchanger effectiveness or failure due to internal growth of marine organisms and degradation of tube surfaces.

7.2.4 Supply Risks

Reliability towards the supply of major components is an important aspect for the selection of materials, particularly where a manufacturer may be required to work with novel materials for which there is limited experience within the supply chain. Indeed, for defence contracts involving bespoke, high value equipment with a long lead time, it is common practice to engage with suppliers over a series of design review meetings to identify manufacturing risk and gain assurance towards a robust schedule for item production and test. Such engagement would run parallel to negotiations aimed at equipment cost and other commercial terms and conditions.

7.2.5 Operating Experience and LFE

A great deal of practical knowledge and data is gained from the in-service use of materials and systems in terms of operating procedures, maintenance regimes and failure characteristics (modes of failure and rates of failure). Collectively, this is referred to as 'LFE' (Learning from Experience). It follows that, whilst there is potential for performance or cost benefits associated with the introduction of novel materials or new technology, the risk of introduction may be unacceptable for vessels required to support continuous operational objectives. Furthermore, a 'Training Needs Analysis' would need to be conducted for significant departures from established practice. For these reasons, decisions involving the selection of design options would typically favour equipment for which there is proven in-service experience, substantial LFE and a high 'Technology Readiness Level'.

7.3 Heat Exchanger Material Alternatives Common to RN Vessels

7.3.1 Titanium Based Design Alternatives

Titanium is an option for the header material (plenum castings) and the tube bundle material (seamless tubes) of sea water heat exchangers. Compared to copper alloys commonly used for the same application, titanium offers good corrosion resistance and high strength. It also has a lower thermal expansion coefficient. Furthermore, titanium has a lower density (specific gravity) meaning that component weight could potentially be reduced.

Against this is the fact that titanium is less effective at transferring heat (has a lower thermal conductivity coefficient and a higher specific heat capacity). This means that, for a given heat load, either a larger surface area would be needed at the heat exchange membrane or the membrane thickness would need to be reduced to compensate for the reduction in heat transfer effectiveness.

Furthermore, a considerable disadvantage of titanium for sea water applications is its poor resistance to biofouling compared to copper-based alloys. Consequently, titanium-based heat exchangers would require anti-fouling measures and increased cleaning regimes during maintenance, all having the potential to impose an increased cost burden throughout service life.

7.3.2 Copper Based Design Alternatives

Copper has excellent resistance to corrosion in the atmosphere, fresh water and sea water. The addition of nickel to copper improves its strength and durability and, therefore, its resistance to erosion and cavitation. In sea-water, copper-nickel alloys have good anti-fouling properties compared to titanium, offering resilience to biofouling that might otherwise severely restrict flow through the heat exchanger tube sheet within a matter of weeks (Powell & Mitchels, 2000).

The two most commonly utilised copper-nickel alloys are CuNi 90:10 (meaning 90% copper - 10% nickel) and CuNi 70:30. By increasing the nickel content, the alloy can be made less soft, so more resistant to erosion and the effects of shear stresses in water flowing through the tubes. This facilitates greater sea water flow rates such that cooler dimensions can be reduced for a given rate of heat transfer.

According to the Copper Development Association (CDA), the most commonly used copper alloys in sea water applications are copper-nickel alloys and nickel aluminium bronzes (CDA, 2016). When applied to the construction of sea water heat exchangers, the alloys of copper-nickel (CuNi) are commonly used for the heat exchanger tubing whilst Nickel Aluminium Bronze (NAB) is commonly used for the plenum castings (headers) where higher strength is required.

7.4 Microbiologically Influenced Corrosion (MIC) and Macro-Fouling

In a paper presented at the MoD 9th International Naval Engineering Conference and Exhibition, INEC 2008, it is stated that “The Royal Navy (RN) has suffered significant platform downtime in recent years as a result of MIC related defects in sea water cooled shell and tube heat exchangers” (Nicklin, 2008). The paper goes on to present the impact to RN submarines of MIC and macro-fouling within sea water heat exchangers and the remedial measures taken by the UK MoD to ensure platform operational availability.

The resistance of copper-nickel alloys to corrosion in sea water is attributed to the formation of a thin, protective surface layer upon exposure to clean sea water. Initially, an oxide layer forms within a matter of days, then takes 2-3 months to fully mature (Powell & Mitchels, 2000). To form the protective layer, new copper alloy tubing, or that which has been freshly cleaned and descaled, must be exposed to clean oxygenated sea water. This condition cannot be assumed for the water in Upkeep dockyards within the UK which are typically located in estuarine areas, making use of non-tidal basins for maintenance berths. The stagnant water that such basins encourage allows anaerobic bacteria to thrive and their metabolic by-products to accumulate. This can give rise to MIC which is the deterioration at a metal surface resulting from chemical attack associated with the metabolic activity of micro-organisms. For copper-based tubing, sulphide ions metabolised by bacteria are especially threatening. An otherwise protective oxide layer formed on the surface of tubing in the presence of sulphide ions will be weak, making the metal vulnerable to accelerated corrosion during subsequent service, even following a return to clean sea water. For this reason, the tubing within sea water heat exchangers must undergo passivation and conditioning processes to ensure an effective coating prior to service.

Compared to other metals, the susceptibility of copper-nickel alloys towards MIC is a negative attribute. Even so, their greater positive attributes have resulted in their widespread adoption for sea water shell and tube heat exchangers, including those fit to RN surface ships and submarines. It can be appreciated, therefore, that authorities responsible for the commissioning, refit and maintenance of RN vessels must implement an effective management strategy in order to ensure that heat exchangers meet their design life intent. This involves understanding MIC and the need for effective conditioning (passivation) of sea water heat exchangers prior to operational service. As reported by Nicklin (2008), this was dramatically demonstrated within the RN submarine flotilla when, following Upkeep periods in 2005 and 2006, a total of 8-months operational availability across 2 submarine platforms was lost as a result of tube wall pitting related to MIC. Consequent tube wall breaching was observed much sooner than anticipated during service, corresponding to a nominal corrosion rate of 2 mm/year. The extreme nature of this can be appreciated when it is considered that once adequately conditioned, corrosion rates for copper alloys can be as little as 0.02 mm/year (Kirk & Tuthil, 1991).

Such experience points to the highly negative operational and cost impact of MIC upon RN vessels. For this reason, there has been an impetus to implement conservative protection measures during vessel commissioning and Upkeep periods including the total exclusion of dock basin sea water from heat exchangers. In practice, this has involved the use of portable dockside coolers and the closed loop circulation of fresh water through the sea water side of heat exchangers. In addition, whilst not sustainable as a long-term policy, an expedient measure on occasions has been to supply heat exchangers with mains fresh water on a ‘once through’ basis. Indeed, this approach was adopted by the UK MoD in 2006 because of severe disruption of the RN submarine programme due to the MIC threat which, at that time, had not been fully evaluated.

Other cleaning and prevention measures involve water treatment options including de-scalers, chlorination and the use of chemicals to passivate copper alloy and so inhibit microbiological effects. For example, the addition of Ferrous ions (Fe^{2+}) helps to form a protective layer and reduce the corrosion of copper-nickel alloys. This would typically be achieved by the addition during heat exchanger commissioning of Ferrous Sulphate ($FeSO_4$). Nicklin (2008) makes reference to a water treatment study conducted by the Defence Science and Technology Laboratory (DSTL). This compared the effectiveness of clean sea water, mains fresh water, fresh water dosed with Ferrous ions and fresh water containing Sodium Dimethyl Dithiocarbonate (SDD). The comparison demonstrated that oxygenated sea water free of sulphide pollution produced the most effective copper oxide coating. Whilst the SDD demonstrated benefits, its use would be overshadowed by environmental concerns. Indeed, legislation aimed at safeguarding the marine environment has a restricting effect on the use of chemical treatments, particularly near to land and waterways.

In addition to equipment failure due to corrosion, a well documented threat is that of macro-fouling throughout sea water ship systems including hull valves, pipework, pumps and heat exchangers. The fitting of hull gratings and sea chests acts to reduce the hazards to equipment of coarse seaborne debris such as sand, gravel and marine vegetation, by providing a screened reservoir of water at the intake that could be dosed with biocides. Even so, the risk remains that fine particles and embryonic marine organisms will be transported into a system giving rise to erosion, sedimentation and the growth of attaching waterborne species (biofouling). An extreme, although not uncommon, example of crustacean biofouling is shown in Figure 7.4.1.

Compared to other metals with marine application, including titanium, the Copper-Nickel alloys have established themselves as having significant resistance to marine biofouling. This is largely attributed to the continuous release of Cu^+ ions during the natural corrosion of copper that cannot be tolerated by marine micro-organisms (Schleich & Steinkamp, 2003). Indeed, this is sometimes referred to as the ‘toxicity’ of copper to micro-organisms. During a study of marine biofouling involving continuous exposure of metal surfaces to UK coastal sea water, the development of slime films was documented for titanium, copper and copper-nickel (Blunn & Jones, 1984). Periodic microscopic inspection of the slime films showed them to be formed from bacteria, corrosion products and algae. Depending on number-of-weeks exposure, film thickness was in the order of µm x10 to µm x100. The comparison clearly demonstrated the resistance of pure copper compared to the susceptibility of titanium to bacterial slime formation. The biofouling properties of Cu-Ni (90:10) were intermediate between titanium and pure copper. When referring to copper alloys within the technical summary, the study described the "antifouling nature of the toxic surfaces".

Figure 7.4.1. Biofouling at a Flange of a Sea Water Pipe [40]

The environmental factors known to affect the extent of marine biofouling include sea water temperature and light levels. In turn, these are largely dependent upon geographic location, season of the year, distance from the shoreline and depth of sea water (Schleich & Steinkamp. 2003). For vessels of the Royal Navy this establishes a baseline principle whereby the degree of macro-fouling would be

[40] Image reproduced with the permission of Cathelco: http://www.cathelco.com/mgps-overview/understanding-bio-fouling/. The company website describes extensive experience in marine anti - fouling systems for ships and offshore installations.

related to the theatre of operations. Therefore, for example, an RN submarine operating at depth in cold oceanic waters should experience a lower bio-related maintenance burden than an RFA surface ship supporting warm water operations interspersed by lengthy periods in port. Since the 1990s, international political events have been the impetus for increasing deployment of RN vessels on littoral (close to shore) operations in warm climates, as opposed to their previous ‘cold war’ operations in the North Atlantic. Indeed, Nicklin (2008) makes the assertion that “the modern operating profile of UK submarines has led to massively increased occurrences of biofouling”. There is, therefore, cause for concern that deployed vessels may suffer degraded heat exchanger performance or the need to return to port for more frequent maintenance of sea water systems. In either case, this potentially results in reduced operational availability and increased operational costs.

7.5 TOPSIS for Decision Making with Multiple Attributes

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) was first developed and published by Hwang & Yoon (1981). The technique is based on the concept that, for a problem with several solution options, each to be evaluated against multiple criteria, the chosen option should have the shortest distance from the ‘Ideal Solution’ and the farthest distance from the ‘Negative Ideal Solution’. The Ideal Solution is quantified as being the combination of all the best criteria evaluations attainable whilst the negative ideal solution is a combination of all the worst criteria evaluations (Yoon & Hwang, 1995). TOPSIS was introduced with further detail and supporting references in Chapter 4.

7.6 A Proposed Generic MADM Approach Based on TOPSIS

A proposed decision making approach is shown within Figure 7.6.1. This is offered by the researcher as a combination of personal professional experience and the TOPSIS methodology presented by Yoon & Hwang, (1995).

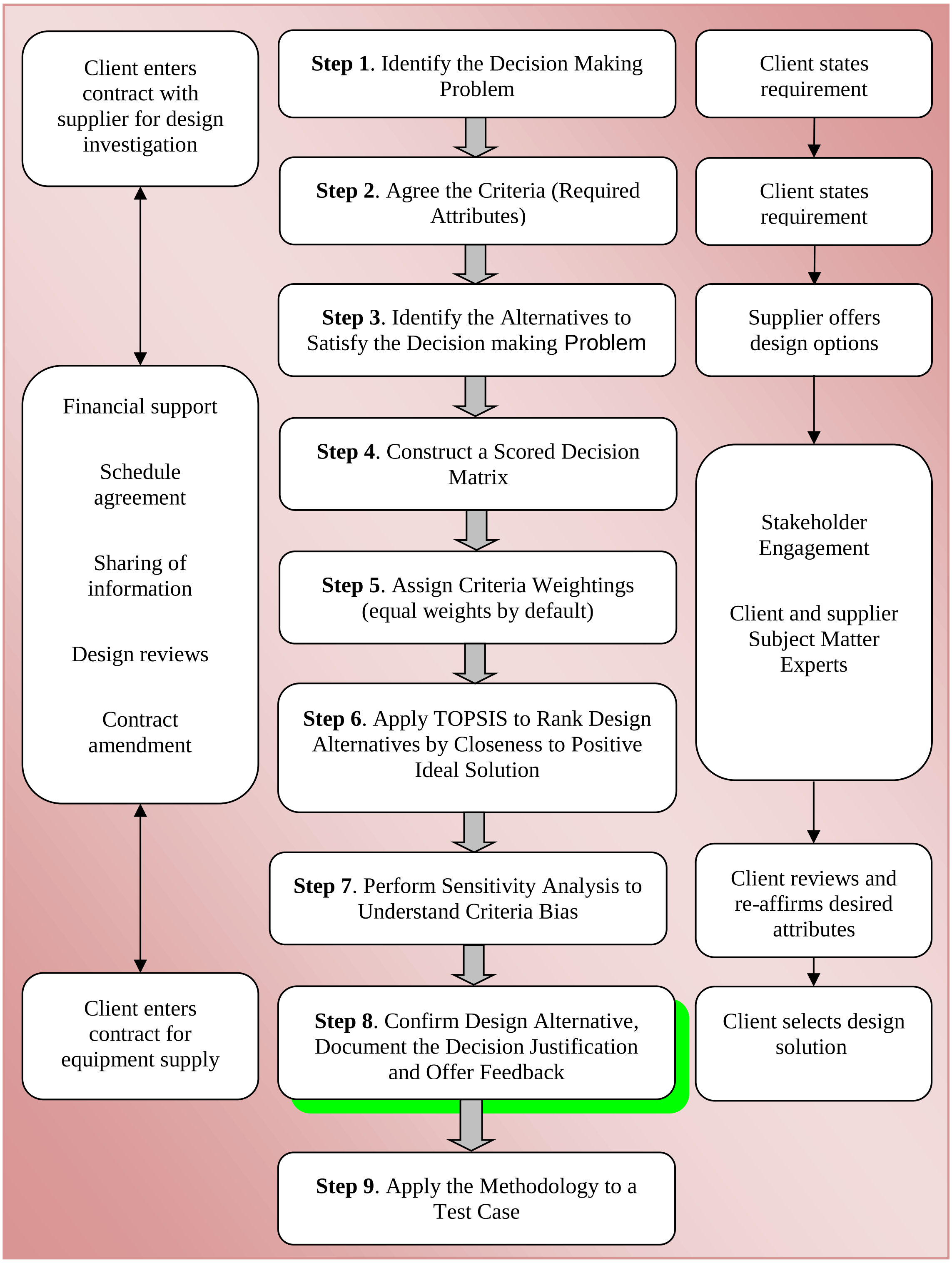


Figure 7.6.1. Generic MADM Approach based upon TOPSIS

The approach assumes that a client has formed a contract with a supplier, perhaps an equipment provider or a design service provider, to develop a design solution that will satisfy a number of stated requirements. The interaction between client and supplier is shown throughout the process[41].

It can be appreciated that, once contractual (and so financial) agreement is reached, the interaction between client and supplier extends to the discussion and exchange of information between respective experts. This in turn leads to the progressive development of a solution, communicated via regular design reviews. Hence there is continuous dialogue between a range of client and supplier stakeholders having specific interest in the various aspects of the process. In order that the client gains assurance towards a successful outcome, progress through the process is likely to be reviewed via a series of formal milestones. Depending upon the contractual terms and conditions, such milestones are likely to be contractually linked to financial payments, thus providing the incentive for delivery. The steps of the generic process are explained below.

7.6.1 Step 1. Objective

The overall objective is clearly defined and treated as the decision making problem. The objective is based upon the requirements of the client.

7.6.2 Step 2. Required Attributes

The criteria relevant to the decision are identified. These are the attributes required of the chosen solution that are important to the client.

7.6.3 Step 3. Design Alternatives

A range of design options are considered during the concept studies for any design selection exercise. The credible alternatives are identified and developed for a particular scenario with the aim of ultimately selecting a single design solution. The design options are provided by the supplier in response to the requirements stated by the client.

7.6.4 Step 4. Decision Matrix

The problem is structured as a decision matrix with design alternatives scored against each required attribute. This was introduced within Chapter 4. The value

[41] It is the experience of the researcher that this interaction is typical in situations where the UK MoD has contracted a capability provider for the procurement of new equipment or the in-service support of existing equipment.

of ‘x’ is the score given to each alternative (1 to m) when evaluated against each of the required attributes (1 to n). Scores are assigned by decision making analysts with subject matter expertise towards the decision problem.

Generic Decision Matrix

Required Attributes (Criteria)

Design Alternatives

$$\begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} & .. & x_{1,n} \\ x_{2,1} & x_{2,2} & x_{2,3} & .. & x_{2,n} \\ x_{3,1} & x_{3,2} & x_{3,3} & .. & x_{3,n} \\ . & . & . & .. & . \\ . & . & . & .. & . \\ x_{m,1} & x_{m,2} & x_{m,3} & .. & x_{m,n} \end{bmatrix}$$

where each element can be expressed as:

$x_{i,j} \qquad \text{for } i = 1, \dots, m; \quad j = 1, \dots, n$

7.6.5 Step 5. Criteria (Attribute) Weighting

The criteria are prioritised by giving each a weighting factor and normalised such that they conform to Eqn. (7.1).

$$\sum_{j=1}^{n} w_j = 1 \qquad\qquad j = 1, \dots, n. \qquad\qquad \text{Eqn. (7.1)}$$

where w_j is the normalised weight of the j^{th} attribute

Care must be taken when scoring against attributes to ensure that the nature of the attribute is understood (beneficial or cost) and that the numerical manipulation of values is compatible throughout the decision making methodology. The treatment of attributes was introduced and discussed more extensively within Chapter 4.

It is proposed by the researcher that the attributes are initially assigned the same weight, thereby providing a baseline against which the effect of criteria bias can be explored. This is addressed further within the sensitivity analysis of Step 7.

7.6.6 Step 6. Similarity to the Positive Ideal Solution Using TOPSIS

The design alternatives are evaluated with respect to the weighted criteria using the TOPSIS methodology. This leads to the calculation of positive and negative ideal solutions. Following the TOPSIS methodology, the alternatives are ranked in terms of their proximity to the positive or negative ideal solutions. The preferred solution is that determined most favourable in terms of its similarity (closeness) to the positive ideal solution. TOPSIS involves the following manipulation:

Normalisation of Decision Matrix. Scores are normalised to maintain data compatibility throughout the methodology. The scores within the decision matrix are normalised according to Eqn. (7.2).

$$r_{ij}=\frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad i = 1, \dots, m; \quad j = 1, \dots, n. \qquad \text{Eqn. (7.2)}$$

Normalisation is implemented with respect to each attribute column.

Weighted Normalised Scores. The Criteria weightings are applied to the normalised scores according to Eqn. (7.3).

$$v_{ij} = w_j r_{ij} \qquad i = 1, \dots, m; \quad j = 1, \dots, n. \qquad \text{Eqn. (7.3)}$$

Ideal Solutions. The Ideal Solution (IS) and Negative Ideal Solution (NIS) are generally denoted by the superscripts (*) and ($^-$) respectively. The Ideal Solution is the set of most beneficial values against each attribute whilst the opposite is true for the Negative Ideal Solution. The sets are extracted from the weighted normalised scores.

Separation (S) from Ideal Solutions. If a single design alternative returned the highest value against all weighted criteria then this would conveniently emerge as the Ideal Solution. However, this is unlikely to occur in practical situations where design compromise is normally encountered. Therefore, for each criterion, the design alternatives must be evaluated by considering its distance (separation) from both the Ideal Solution and the Negative Ideal Solution.

Separation from the Ideal Solution is calculated using Eqn. (7.4).

$$S_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^*\right)^2} \qquad i = 1, \dots, m. \qquad \text{Eqn. (7.4)}$$

Separation from the Negative Ideal is calculated using Eqn. (7.5).

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \qquad i = 1, \dots, m. \qquad \text{Eqn. (7.5)}$$

where:

v_{ij} is the weighted normalised value (Eqn.(7.3));

v_j^* is the ideal value for the j th criterion;

v_j^- is the negative ideal value for the j th criterion.

Similarity (Closeness) to the Ideal Solution. Ultimately, the aim is to identify the design alternative most similar to the Ideal Solution, that is to say, the alternative with the shortest distance to the Positive Ideal Solution and the farthest distance from the Negative Ideal Solution. Using Eqn. (7.6), the values returned for separation from Positive and Negative Ideals (S^* and S^-) are used to calculate a final value representing the design alternative closest to the Positive Ideal. The calculated values allow the design alternatives to be ranked in order of preference.

$$C_i^* = \frac{S_i^-}{(S_i^* + S_i^-)} \qquad i = 1, \dots, m. \qquad \text{Eqn. (7.6)}$$

7.6.7 Step 7. Criteria Sensitivity Analysis – Understanding Bias

The weight indicates criterion importance relative to the other criteria under consideration. As the value of the weight increases, the relative importance also increases. It can therefore be appreciated that the assignment of weights reflects the preferences of the decision-maker such that the decision outcome will be biased in the direction of the criteria weighting. In order to understand this dynamic, and so guard against undue decision bias, analysis should be performed to determine sensitivity of the decision outcome to changes in criteria weighting. This forms part of an approach informally referred to as a 'common-sense check'. In other words, the decision maker should endeavour to fully understand the mechanism by which a decision has been derived and the practical implications. The decision should thus become the focus of objective expert judgement to ensure it offers a realistic outcome, in trend with reasonable expectations for the given context. The output of a methodology should not be accepted without question.

7.6.8 Step 8. Confirm the Chosen Design Alternative

The decision analyst must decide upon selection (or otherwise) of design alternatives based upon their ability to satisfy required criteria. The proposed selection methodology serves to inform that decision whilst guarding against unconscious bias. In the final analysis, the decision maker confirms the required criteria weightings and evaluates the decision outcome. To facilitate understanding of, and justification for, any decision outcome, the basis upon which the decision was derived must be documented and communicated across the stakeholder communities. It is highly likely that a formal record of that basis will be sought at some time in the future when, for example, LFE is sought for subsequent projects.

7.6.9 Step 9. Apply to a Test Case

The generic methodology will be applied to the selection of construction materials for a sea water heat exchanger.

7.7 Test Case – Material Selection for a Marine Heat Exchanger

The test case considers selection of construction materials for heat exchangers within a ship sea water cooling system. From the previous sections, it is apparent that selection of the most suitable materials involves identifying the material options, then evaluating those options with respect to attributes known to be important for the material application. Some attributes will be considered by the decision analyst to be more important than others. For this reason, the attributes are weighted. Following the generic approach discussed within Section 4.3.2, the test case is structured as a systematic decision making process based upon the application of the TOPSIS methodology. This is shown within Figure 7.7.1.

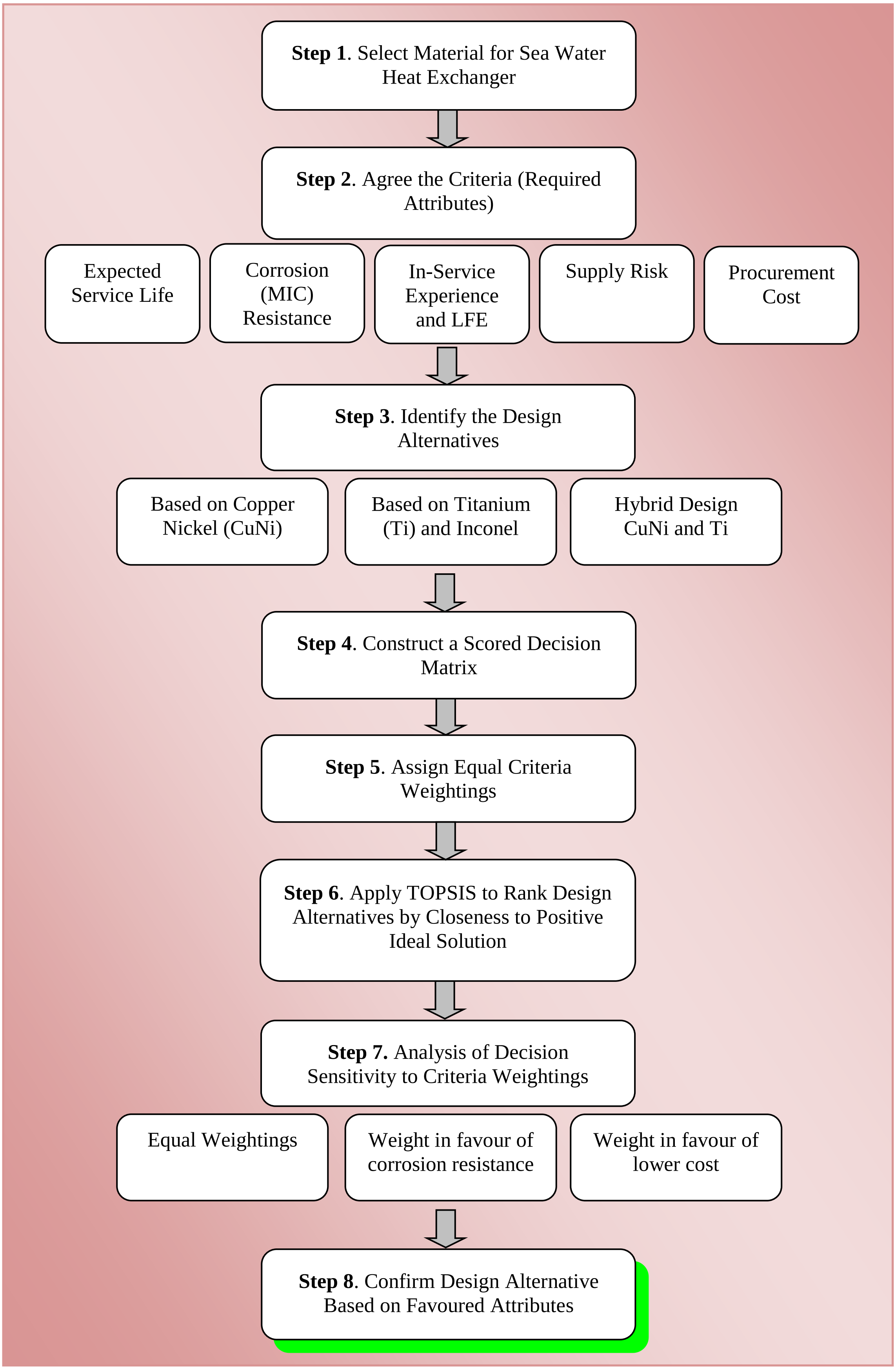


Figure 7.7.1. The Generic MADM Approach Applied to Test Case

The chosen test case is based upon a material selection exercise performed for the sea water heat exchanger of a vessel during 2011[42]. Attributes were identified from the requirements stated by the client. This involved formal discussion between Suitably Qualified and Experienced Personnel (SQEP)[43] representing both client and supplier. Design alternatives were developed by the supplier and scored during workshops attended by the client and supplier. At conclusion of the original selection exercise, a decision was recommended, based upon summation of scores, although no criteria weightings were applied and the TOPSIS methodology was not followed. Therefore, application of the generic methodology proposed within this text represents an extension to the decision process previously performed.

7.7.1 Step 1. Objective

The decision making problem is to identify the most suitable construction materials for a sea water heat exchanger.

7.7.2 Step 2. Required Attributes

The chosen solution must have positive attributes in terms of expected service life due to favourable mechanical properties and resistance to corrosion, particularly MIC. There should be considerable in-service experience by virtue of its application across similar platforms and an extensive database of LFE. Supply risk should be low indicating that manufacturing processes are well understood, delivery schedules are robust and installation procedures are well established. Procurement costs associated with the chosen material should be low. These attributes are summarised as:

- Expected Service Life
- Corrosion Resistance (resistance to MIC)
- In Service Experience (extent of LFE)
- Supply Risk
- Procurement Cost (not necessarily through-life cost)

[42] General discussion of the design exercise is offered here although no 'Official-Sensitive' details are given. Adaptation has been made to the design alternatives and criteria to illustrate the arguments whilst protecting information related to a specific vessel or commercial organisation.
[43] In this context, SQEP typically involves a mix of senior engineers with lead responsibility towards technical systems together with operators having practical experience towards those systems. The mix should have the diversity to consider the selection problem from a wide range of perspectives.

It should be noted that only the first three are benefit attributes whereby their highest values are assigned the highest scores. On the other hand, ‘supply risk’ and ‘procurement cost’ involve decreasing monotonic utility, meaning that preference is for low values trending in the direction of a minimum. To maintain a consistent approach throughout this problem, the highest benefit is assigned the highest score. Therefore, score inversion is applied to the cost attributes whereby low cost and low risk are assigned high scores.

7.7.3 Step 3. Design Alternatives

Construction material options were considered for a sea water cooling system comprising shell-and-tube heat exchangers. The proposed material options were based upon those firmly established within the marketplace for which technical characteristics were understood and costing data was available. Options involved sea water cooling systems based upon either of two material types: copper or titanium. In addition, a proposal to integrate heat exchangers constructed from each material was examined with the aim of combining the qualities of both within a hybrid system. The alternatives are described below:

- **Copper-Nickel Based System.** This involves the use of traditional copper-nickel alloys having CuNi (70:30) tube bundles with headers constructed from NAB (Nickel Aluminium Bronze). Connecting pipework would be CuNi for galvanic compatibility. Copper-based alloys would be used throughout the sea water cooling system. Whilst copper-based systems have well-established marine application and demonstrate resilience to biofouling, a key challenge is likely to be the need to manage susceptibility to MIC in non-tidal basins.
- **Titanium Based System.** This involves the use of titanium (Ti) as the construction material for the heat exchangers with nickel-based (typically Inconel 625) pipework for galvanic compatibility. Whilst titanium offers favourable mechanical properties and resistance to MIC, likely key challenges will be the need to manage biofouling during service and difficulty when working with Inconel during manufacture.
- **Hybrid System.** This is a proposal involving a combination of copper-based and titanium heat exchangers. The aim is to utilise the particular

benefits of materials, in terms of corrosion resistance (titanium) or resilience to biofouling (copper), by operating heat exchangers selectively in response to a range of threatening environmental conditions. Whilst this proposal suggests an innovative means to combine the qualities of both material types, key challenges are likely to be integration of the different systems across the vessel and the accurate sizing of heat exchangers to accommodate heat loads across a range of operational scenarios.

7.7.4 Step 4. Decision Matrix

The scores assigned to the heat exchanger material selection are shown within Table 7.7.4.1. They are based upon the original selection exercise. As for the attributes discussed within Section 7.7.2, care was exercised to implement a consistent approach whereby the highest benefit was assigned the highest score[44]. Scoring was performed on a judgement basis between engineering stakeholders considered to be Subject Matter Experts by virtue of engineering qualifications and experience (see Section 7.7).

Table 7.7.4.1. Scored Matrix for the Selection of Heat Exchanger Materials

		Criteria				
		Service Life	Resist MIC	Experience	Supply Risk	Cost
Material Options						
CuNi and NAB	**A**	1	1	5	5	5
Ti and Inconel	**B**	5	5	1	3	1
Ti and CuNi Hybrid	**C**	3	1	4	2	3

7.7.5 Step 5. Criteria Weighting

As a baseline, the material attributes are assigned the same weighting factor, as shown within Table 7.7.5.1. The criteria weights are normalised so that they conform to Eqn. (7.1).

Table 7.7.5.1. Assignment of Baseline Criteria Weights

	Service Life	Resist MIC	Experience	Supply Risk	Cost
Weights (w)	0.2	0.2	0.2	0.2	0.2

[44] For scoring against the 'Cost' attribute, the lowest costs have been assigned the highest scores. Note that costs have been expressed in relative form using the 5-point scale consistently used to score against all criteria. The treatment of cost is further discussed within Section 7.8.

7.7.6 Step 6. Application of TOPSIS

The decision alternatives are evaluated with respect to the weighted criteria using the TOPSIS methodology.

Normalisation of Decision Matrix. Scores are normalised to maintain data compatibility throughout the methodology. The scores within the decision matrix are normalised using Eqn. (7.2).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad i = 1, \ldots, m; \quad j = 1, \ldots, n. \qquad \text{Eqn. (7.2)}$$

Normalisation is implemented with respect to each attribute $(j = 1, \ldots, n.)$.

Normalised scores are shown within Table 7.7.6.1, where the first element is calculated as:

$$r_{1,1} = 0.1690 = \frac{1}{\sqrt{(1^2+5^2+3^2)}}$$

Table 7.7.6.1. Normalisation of Scores for the Decision Matrix

Squares (sq)		Service Life	Resist MIC	Experience	Supply Risk	Cost
	A	1	1	25	25	25
	B	25	25	1	9	1
	C	9	1	16	4	9
Sum Sq		35	27	42	38	35
Root Sum Sq		5.92	5.20	6.48	6.16	5.92
Normalisation						
		Service Life	Resist MIC	Experience	Supply Risk	Cost
	A	0.1690	0.1925	0.7715	0.8111	0.8452
	B	0.8452	0.9623	0.1543	0.4867	0.1690
	C	0.5071	0.1925	0.6172	0.3244	0.5071

Weighted Normalised Scores. The criteria weightings are applied to the normalised scores using Eqn. (7.3)

$$v_{ij} = w_j r_{ij} \qquad i = 1, \ldots, m; \quad j = 1, \ldots, n. \qquad \text{Eqn. (7.3)}$$

Weighted normalised scores are shown within Table 7.7.6.2, with the first element calculated as:

$$v_{ij} = 0.0338 = 0.2 \times 0.1690$$

Table 7.7.6.2. Weighted Normalised Scores for the Decision Matrix

	Service Life	Resist MIC	Experience	Supply Risk	Cost
A	0.0338	0.0385	0.1543	0.1622	0.1690
B	0.1690	0.1925	0.0309	0.0973	0.0338
C	0.1014	0.0385	0.1234	0.0649	0.1014

Ideal Solutions. Extracted from the weighted normalised scores, the Ideal Solution (IS) is the set of the most beneficial values against each attribute whilst the opposite is true for the Negative Ideal Solution (NIS). These are shown below:

Ideal Solution $\mathrm{IS} = \{0.1690,\ 0.1925,\ 0.1543,\ 0.1622,\ 0.1690\}$

Negative Ideal Solution $\mathrm{NIS} = \{0.0338,\ 0.0385,\ 0.0309,\ 0.0649,\ 0.0338\}$

Separation (S) from Ideal Solutions. For each attribute, the design alternatives must be evaluated by considering its distance (separation) from both the Ideal Solution and the Negative Ideal Solution.

Separation from the Ideal Solution is calculated using Eqn. (7.4).

$$S_i^* = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^*\right)^2} \qquad i = 1, \dots, m. \qquad \text{Eqn. (7.4)}$$

Separation from the Negative Ideal Solution is calculated using Eqn. (7.5).

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2} \qquad i = 1, \dots, m. \qquad \text{Eqn. (7.5)}$$

where:

v_{ij} is the weighted normalised score (Eqn. (7.3));

v_j^* is the ideal value for the j th criterion;

v_j^- is the negative ideal value for the j th criterion.

Using these equations, separation from Positive and Negative Ideal Solutions has been calculated as shown within

Table 7.7.6.3. The value for S^*_A is calculated as follows:

$$S_A^* = 0.2049 = \sqrt{[(0.0338 - 0.1690)^2 + \ldots + (0.1690 - 0.1690)^2]}$$

Table 7.7.6.3. Separation of Alternatives from Ideal Solutions

Separation from Positive Ideal							
	$(v_{i,1}-v_1^*)^2$	$(v_{i,2}-v_2^*)^2$	$(v_{i,3}-v_3^*)^2$	$(v_{i,4}-v_4^*)^2$	$(v_{i,5}-v_5^*)^2$	**Separation**	
A	0.01829	0.02370	0.00000	0.00000	0.00000	**0.20491**	**S^*_A**
B	0.00000	0.00000	0.01524	0.00421	0.01829	**0.19425**	**S^*_B**
C	0.00457	0.02370	0.00095	0.00947	0.00457	**0.20802**	**S^*_C**
Separation from Negative Ideal							
	$(v_{i,1}-v_1^-)^2$	$(v_{i,2}-v_2^-)^2$	$(v_{i,3}-v_3^-)^2$	$(v_{i,4}-v_4^-)^2$	$(v_{i,5}-v_5^-)^2$	**Separation**	
A	0.00000	0.00000	0.01524	0.00947	0.01829	**0.20736**	**S^-_A**
B	0.01829	0.02370	0.00000	0.00105	0.00000	**0.20747**	**S^-_B**
C	0.00457	0.00000	0.00857	0.00000	0.00457	**0.13310**	**S^-_C**

Similarity (closeness) to the Ideal Solution. Ultimately, the aim is to identify the design alternative most similar to the Ideal Solution, that is to say, the alternative with the shortest distance to the Positive Ideal Solution and the farthest distance from the Negative Ideal Solution. Using Eqn. (7.6), the values returned for separation from Positive and Negative Ideals (S^* and S^-) are used to calculate final values representing how close each design alternative is to the Ideal Solution. The values allow design alternatives to be ranked, as shown within Table 7.7.6.4.

$$C_i^* = \frac{S_i^-}{(S_i^* + S_i^-)} \qquad i = 1, \dots, m. \qquad \text{Eqn. (7.6)}$$

For the first alternative, similarity to the ideal solution is calculated as:

$$C_A^* = 0.5030 = \frac{0.20736}{(0.20491 + 0.20736)}$$

It is evident that, based upon the chosen attributes and the scores judged applicable to each of the design alternatives, the design based upon titanium and inconel materials has emerged as the solution closest to the Ideal Solution.

Table 7.7.6.4. Closeness of Alternatives to the Ideal Solution

Design Alternative		Closeness Scoring		Rank
CuNi and NAB	**A**	0.5030	C^*_A	2
Ti and Inconel	**B**	0.5164	C^*_B	1
Ti and CuNi Hybrid	**C**	0.3902	C^*_C	3

Furthermore, the TOPSIS methodology has output a ranked order for the design alternatives such that their relative preference can be evaluated.

In this respect, it can be appreciated from Eqn (7.6) that the strongest alternative is that closest to:

$C_i^* = 1$, where there is no separation from the Ideal Solution, i.e. $S_i^* = 0$

The opposite is true for the least preferred solution i.e. $C_i^* = 0 \text{ and } S_i^- = 0$

7.7.7 Step 7. Criteria Sensitivity Analysis – Understanding Bias

The assignment of criteria weights reflects the preferences of the decision-maker(s) such that the decision outcome will be biased in the direction of that weighting. This bias should not be unconscious. Rather, it should reflect a conscious effort to prioritise the most important attributes and should be clearly understood as such. For this reason, the proposed methodology includes a sensitivity analysis whereby the effect of changing criteria weightings is observed for the decision outcome. The attributes are initially assigned the same weight, thereby providing a baseline against which the effect of criteria preference can be explored. The sensitivity analysis is shown in Table 7.7.7.1 and discussed below.

Table 7.7.7.1. Sensitivity of Design Selection to Criteria Weighting

Weighting of Criteria						
	Case 1 Equal Weighting		Case 2 Corrosion Resistance		Case 3 Low Cost and Risk	
Service Life	0.2		0.3		0.1	
Corrosion (MIC) Resistance	0.2		0.35		0.1	
In-Service Experience	0.2		0.15		0.15	
Supply Risk	0.2		0.1		0.3	
Cost	0.2		0.1		0.35	
Ranking of Alternatives						
	RANK	C*	RANK	C*	RANK	C*
CuNi and NAB	2	0.5030	3	0.2697	1	0.7410
Ti and Inconel	1	0.5164	1	0.7392	3	0.2942
Ti and CuNi Hybrid	3	0.3902	2	0.3019	2	0.4055

For Case 1, all criteria received equal weighting resulting in the titanium-based design emerging as that closest to the Ideal Solution. Even so, the banding of values for C* around a central value indicates that the case for choosing this solution is not made emphatically. For Case 2, the titanium-based alternative emerges as the clear preference once the decision is weighted in favour of corrosion resistant material attributes (long design life based upon resistance to MIC). On the other hand, once the criteria are weighted in favour of low procurement cost and low supply risk, the copper-based design alternative emerges as the clear preference[45]. This is demonstrated by Case 3.

7.7.8 Step 8. Confirm the Chosen Design Alternative

Ultimately, the decision analyst must decide upon selection (or otherwise) of design alternatives, based upon the need to satisfy prioritised design attributes. The proposed selection methodology serves to inform that decision whilst guarding against unconscious bias towards attributes. In the final analysis, the decision maker confirms the required criteria weightings and evaluates the decision outcome.

7.8 The Influence of Cost Engineering

As demonstrated within Section 7.7.7, the decision outcome could be made to have a bias towards 'procurement cost' by preferably weighting the cost attributes. Scoring for design alternatives against the cost attributes can most accurately be performed when quantitative data exists that is definitive in nature, such as firm quotations offered by suppliers. If such data is not available, or is only partly available, then cost estimation must take place that includes assumptions and a degree of uncertainty. This has the consequence of reducing the fidelity of the scores assigned for the design alternatives, meaning that the reliability of the decision outcome is less robust.

Records for the original selection exercise indicate that the following cost types were estimated: UPC (Unit Procurement Cost) and TLC (Through Life Costs). Unit Procurement Cost is concerned with procurement of equipment units without necessarily considering the costs that will be encountered during service, including maintenance costs during Upkeep or costs associated with Upgrade and Update. These costs are likely to be particularly significant where a long service life for the vessel is anticipated or where in-service experience has highlighted high supportability demands.

---

[45] At the time of design consideration, cost analysis revealed lower procurement cost and lower supply risk associated with the copper-nickel alternatives.

Whilst the decision-maker is free to select decision alternatives based on either the UPC or TLC, it should be appreciated that the full cost of ownership includes both. Indeed, other forms of cost may be included within the full cost of ownership, such as the costs associated with decommissioning and disposal of equipment at the end of its service life. These costs are likely to be significant where, for example, environment legislation impacts upon material dismantling and disposal.

For the test case, Unit Procurement Cost has been used as the attribute for cost. During the original selection exercise, UPC was estimated[46] for each design alternative, as shown in relative form within Figure 7.8.1.

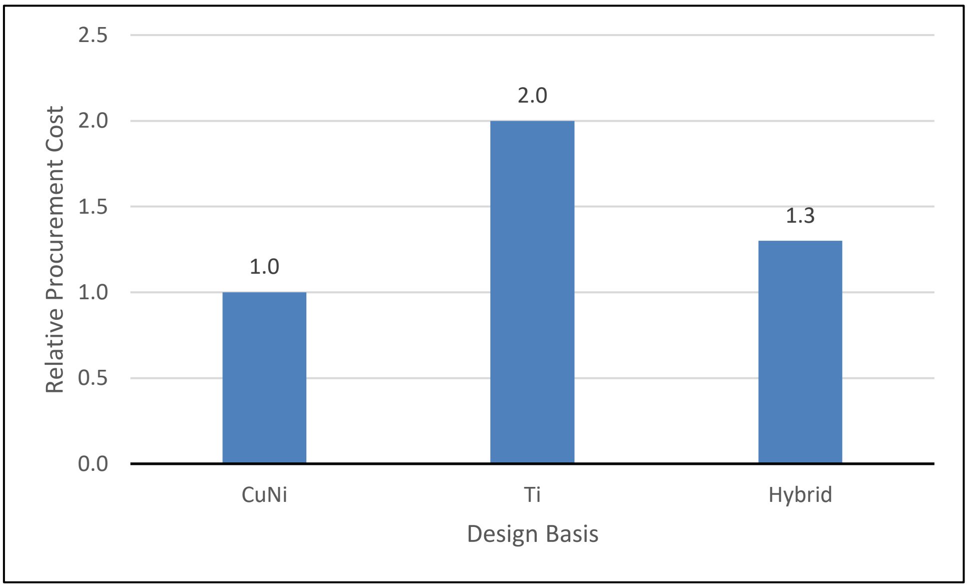


Figure 7.8.1. Cost Estimate Comparison for Heat Exchanger Design Types

Where available, estimates were informed by ROM costs (Rough Order of Magnitude costs) offered by suppliers together with data from previous contracts for similar heat exchangers. Adjustments were assumed for parameter differences including raw material cost, heat exchanger capacity and quantity of units. Costs were considered for entire ship sets of heat exchangers and connecting pipework. Since the design alternatives involve the use of different materials, assumptions were made towards the impact on component production of their differing mechanical properties. It is not clear from original records

[46] Although based upon the actual design selection exercise and showing the same trends, actual data has not been reproduced to protect commercially sensitive information. Figure 7.8.1 has been offered by the researcher to illustrate the arguments within the text. It has been adapted from the actual costing exercise.

whether the procurement cost included installation and testing. No information is given towards allowances for anticipated scrap rates or whether procurement cost includes a value for production risk.

It is apparent from the discussion that procurement cost is a clear discriminator between the design alternatives and that there is reasonable basis for the cost estimates. However, many assumptions have been made, meaning that there must be uncertainty associated with the cost estimation. This observation is significant because it has been demonstrated that, depending upon the preference of the decision maker, the selection of a design alternative may be based upon its cost. This points to the requirement for robust cost estimation when including ‘procurement cost’ as an attribute for design alternatives.

7.9 Conclusion

This chapter has examined the hypothesis that a decision making methodology based on TOPSIS can be applied to down-selection problems of the type encountered when conducting ship design exercises or implementing As&As once the ship has entered service. This hypothesis is founded on the premise that TOPSIS is a well-established method used as part of formal decision making and has found application across a wide range of fields to resolve a wide variety of down-selection problems. The origins of TOPSIS have been offered within this chapter and it has been demonstrated how the technique can be applied and adapted within a proposed ‘generic methodology’.

A test case for the generic methodology considers selection of construction materials for heat exchangers within a sea water cooling system. Selection involves identifying the material options, then evaluating those options with respect to criteria (attributes) known to be important for the material application. The test case is based upon a material selection exercise performed for the sea water heat exchanger of an RN vessel during 2011. The original selection exercise involved down-selection based upon summation of scores although no criteria weightings were applied and the TOPSIS technique was not followed. Therefore, application of the generic methodology proposed within this chapter represents an extension to the decision making process previously followed.

Attributes were identified based on client preferences. Key considerations included the need to mitigate against corrosion, particularly Microbiologically

Influenced Corrosion (MIC), known to be a threat to the operational availability of RN vessels berthed, or undergoing Upkeep periods within, non-tidal sea water basins at some locations around the UK. Reference has been made to evidence for this threat, particularly in terms of experience from 2006 onwards within the RN submarine flotilla. Other criteria involved the desire to select design types for which comprehensive in-service experience was available, the desire to minimise supply risk and the desire for low procurement cost. In practical situations, it is rarely the case that all desired attributes can be satisfied by a single design alternative. For this reason, attribute prioritisation must be applied in the form of criteria weightings.

The test case demonstrated the suitability of TOPSIS as a technique for the solution of decision making problems where multiple required attributes (criteria) must be taken into consideration. This suitability was reinforced within the generic methodology by the inclusion of a sensitivity analysis whereby the effect of changing criteria weightings was observed upon the decision outcome. This clearly demonstrated that the decision outcome will be biased in the direction of the criteria weighting. This bias is undesirable if made unconsciously but highly desirable if properly understood and consciously made to reflect the preferences of the decision maker(s).

The sensitivity analysis demonstrated that the decision outcome could be made to have a bias towards ‘procurement cost’ by preferably weighting the cost attributes. This led to discussion of the cost engineering that had occurred for the original selection exercise. It was apparent that the cost estimates had reasonable basis. Even so, numerous assumptions had been made with the consequence of uncertainty being associated with the estimates. This is significant because it was shown that procurement cost was a clear discriminator between the design alternatives such that the selection of a particular alternative may be based upon its cost. This points to the requirement for robust cost estimation when including ‘procurement cost’ as an attribute for design alternatives. For this reason, cost engineering and the treatment of cost uncertainty will form the focus of a more detailed consideration within Chapter 8.

Chapter 8: Cost Engineering Principles in the Context of Alterations and Additions (As&As)

Abstract

In previous chapters, the concept of As&As within the RFA context has been explained and the associated decision making has been explored. The application of TOPSIS was investigated in Chapter 7, whereupon it was demonstrated by a sensitivity analysis that the decision outcome could be biased towards ‘procurement cost’ by preferably weighting the cost attribute. This demonstrates the need for robust cost estimation when including ‘procurement cost’ as an attribute for design alternatives. For this reason, Cost Engineering, including the treatment of cost uncertainty, forms the focus of this chapter. As discovered during the literature review of formal decision making techniques (Chapter 4), it is apparent that the scope of Cost Engineering is vast. Therefore, it is the view of the researcher that an exhaustive investigation into the field of ‘Costing' is both impractical and unnecessary in the context of this thesis. Rather, this chapter considers the Cost Engineering approach typically applied to MoD engineering projects and demonstrates how that approach can be applied to the acceptance, development and implementation of As&As for RFA vessels. Within this chapter, the term ‘cost’ relates to ‘financial cost’ unless otherwise stated.

8.1 The UK Defence Procurement Context

Defence expenditure analysis (UK Government, 2017b) revealed that the UK MoD spent nearly £19 billion with industry in 2015/16. This accounted for over 40% of all Government procurement and represented the fifth largest global defence budget. Furthermore, as discussed within Chapter 2, the Strategic Defence and Security Review (SDSR) in 2015 committed the UK to spending a minimum 2% of GDP on defence over the following decade. This represents £178 billion on defence equipment and support over that period. The analysis indicated that shipbuilding and ship repairing claimed the second highest spend by industry sector (£3 billion). Interestingly, sectors related to ‘the business of defence’ rank as highly as those providing hardware systems, with the highest spending (£4.4 billion) being for ‘Technical, Financial and Other Business Services’.

The scale and complexity of the programmes associated with these high levels of spending means that the MoD must seek contractual arrangements with the largest and most able suppliers of defence capability worldwide. Based upon the defence expenditure analysis for 2015/16, Figure 8.1.1 indicates the top ten suppliers and their proportion of MoD spend (UK Government, 2017b).

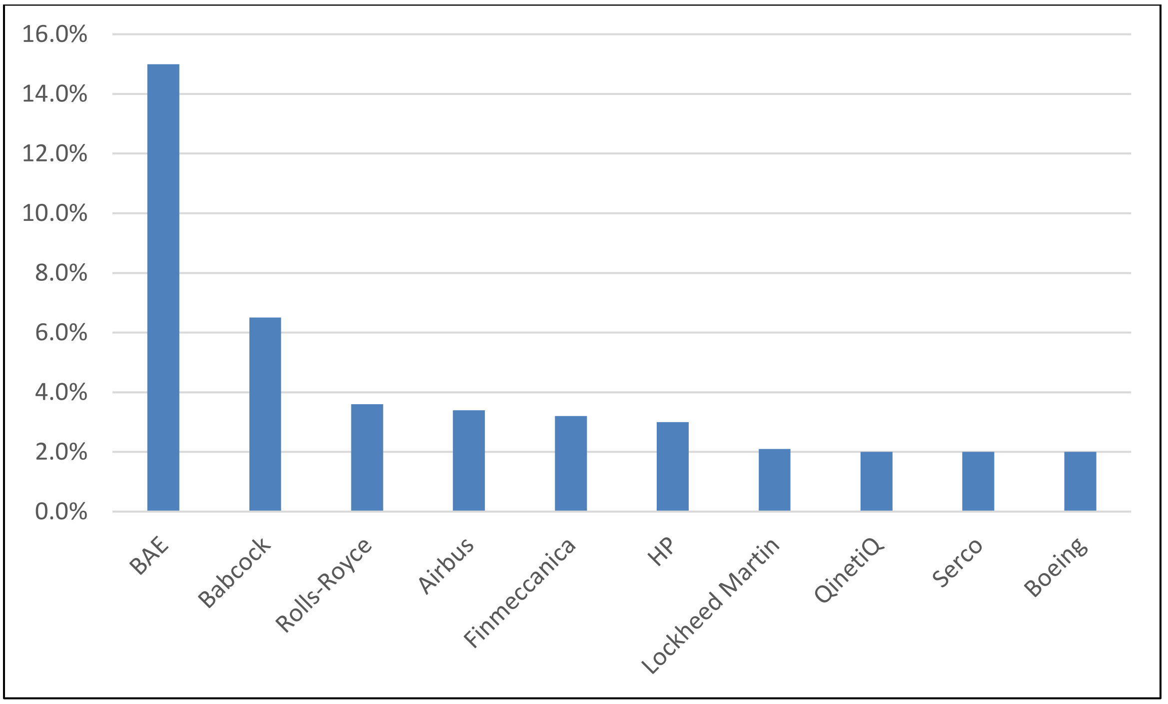


Figure 8.1.1. Proportion of Spend for Top 10 MoD Suppliers in 2015/16

In many cases, these industries represent the sole suppliers of defence capability for contracts. Indeed, just over 47% (£8.8 billion) of payments were made against non-competitive contracts. In the case of BAE Systems, the largest defence supplier (by spend), only 7% of contracts were made on a competitive basis.

The issue of non-competitive pricing is significant because lack of competition could impact upon the value for money to the UK taxpayer. The guiding principles are related to the following fundamental concepts:

- Value for money.
- A fair and reasonable price.
- Making the UK armed forces better able to meet the challenges of tomorrow.

Even so, it should be appreciated that single source procurement (i.e. procurement made on a non-competitive basis) may be appropriate for the following reasons:

- Only a single contractor is able to deliver the scope and volume for the required capability (due to scale of operation, technological complexity or global facilities).
- There are strong reasons related to maintaining or developing a national supply capability (sustaining a national manufacturing base).
- The required capability is associated with highly specialised or unique science and engineering.
- There are reasons for selecting particular suppliers related to national security.

Where they are appropriate, non-competitive contracts must be subject to challenge to ensure that contract awards deliver value for money to the UK taxpayer whilst also offering a fair and reasonable price to the contractor. This is the focus of competition policy that can be defined as "a set of measures employed by government to ensure a fair, competitive market environment for all enterprise participants" (Falvey et al., 2008). Furthermore, it has been stated by an intergovernmental group of experts on competition law and policy (UNCTAD, 2012) that "the starting point for achieving best value for money in government procurement is a regulatory framework that is based on the principle of competition and that submits public spending to the adherence to competitive procurement methods."

Such policy was developed and implemented by the UK Government following an independent review (Currie, 2011) of the existing MoD single source contract arrangements. A Government White Paper was produced aimed at 'Better Defence Acquisition' that subsequently formed the foundations of the 2014 Defence Reform Act (UK Government, 2014) and the Single Source Contract Regulations (National Archives, 2014). The Defence Reform Act (DRA) and Single Source Contract Regulations (SSCR) have since provided the legal framework for single source procurement by the MoD.

More widely, 'Public Procurement Policy' (UK Government, 2015) consists of multiple directives, regulations, policies and guidance relating to all aspects of the procurement of supplies, services and works for the UK public sector. The policy provides, and is subject to, a legal framework of domestic and international obligations, including EU directives.

Related to the policy are the 2011 'EU Defence and Security Public Contracts Regulations (DSPCR)' (UK Government, 2013). These establish rules for the procurement of defence and sensitive security equipment and services by contracting authorities in the UK.

It can be appreciated from this discussion that, given the need for capability procurement, and considering the economic significance of public procurement (in terms of value and support to industry), competition acts to deliver value for money, whilst also providing economic opportunities for bidders. This point was illustrated generically within a United Nations discussion paper (UNCTAD, 2012) when it was reported in 2012 that public procurement accounted for up to 30% of GDP in developing countries and approximately 15% of GDP in OECD[47] countries. It was asserted that governments use this purchasing power to deliver key policy objectives whilst driving markets towards innovation and sustainability.

8.2 Commercial Context for the Upgrade, Update and Upkeep of RFA Vessels

It will become evident throughout this section that competitive market mechanisms apply to the procurement and support of RFA ships, such that the SSCRs do not strictly apply. Nevertheless, in common with the single source commercial objectives, contracts for RFA through-life support aim to implement the guiding principles of 'value for money' and 'a fair and reasonable price'. For this reason, aspects of the policy and framework discussed above are similarly applicable.

The commercial and cost engineering context associated with the Upgrade, Update and Upkeep of RFA vessels can be illustrated by the major refit of RFA Fort Victoria conducted during 2014 by the UK shipyard, Cammell Laird. According to published information (Cammell Laird, 2017) the work cost £49.5m and was completed over 10 months, utilising labour-hours of 450 shipyard workers and requiring supply-chain services and materials worth millions of pounds. The work formed part of a through-life support contract established in 2008 to maintain 2 'clusters' of RFA ships, representing 9 of the 13 ships within

[47] OECD - Organisation for Economic Co-operation and Development, formed in 1960 by 18 European countries plus the United States and Canada, and consisting of 35 member states in 2017. Provides a forum in which governments can seek solutions to common economic, social and environmental problems. Sets international standards on a range of related topics.

the flotilla at that time. A similar contract was awarded for the remaining cluster of RFA ships to another UK shipyard, A&P, in Falmouth.

In 2016, with existing contractual arrangements set to expire in 2018, details of RFA through-life support requirements were published within the contract for Future In-Service Support (FISS), (UK Government, 2017c). This contract, which is valued at £940m for the period between 2018 and 2028, applies to RFA in-service support packages, and is composed of three lots as follows:

- **Lot 1 - Estimated value £320m over the 10 year duration:** RFA Wave Knight, RFA Wave Ruler, RFA Fort Austin, RFA Fort Rosalie and RFA Fort Victoria.
- **Lot 2 - Estimated value £275m over the 10 year duration:** RFA Lyme Bay, RFA Mounts Bay, RFA Cardigan Bay, RFA Argus and HMS Scott[48].
- **Lot 3 - Estimated value £345m over the 10 year duration:** RFA Tidespring, RFA Tiderace, RFA Tidesurge and RFA Tideforce.

The in-service support is to include worldwide engineering support, rectification of Operational Defects and the planning, management and implementation of maintenance periods[49]. Specifically with regard to As&As, contractual arrangements will also include the design, planning, implementation and technical services for the Upgrade and Update work packages. Running concurrently will be other related contracts, such as that for the planning, procurement and supply of technical coating services (Government Online, 2017). The technical coating services are to include internal and external coatings, an on-site technical advisor, coating survey capability together with associated research and development.

In addition to these support contracts, the A&P Group has announced award of the MoD contract to customise and outfit the four new Tide class tankers and co-ordinate their military Capability Assessment Trials (A&P, 2017). The A&P Group has developed multiple design specifications for military equipment Upgrades including fabrication, pipework and system modifications. This has been achieved

[48] HMS Scott is not an RFA vessel but is an RN Ocean Survey Vessel included within the Commercially Supported Shipping Design Authority.

[49] Maintenance periods include, but are not be limited to, Refit Periods (RPs); Docking Periods (DPs); Contractor Support Periods (CSPs); Annual Certification Periods (ACEs); and Assisted Maintenance Periods (AMPs).

whilst working alongside the ship designer (BMT Defence), ship builder (DSME, Daewoo Shipbuilding and Marine Engineering), UK industry contractors and the MoD Design Authority (CSS, Commercially Supported Shipping).

8.3 Consideration of Cost for As&As throughout the DCB Process

Chapter 3 described the decision making that occurs in response to A&A proposals for the Upgrade and Update of RFA vessels. It was explained that informed reasoning and expert judgement is applied by Suitably Qualified and Experienced Personnel (SQEP) throughout a Design Control Board[50] (DCB) process. An adaptation of this process was offered at Figure 3.5.1. Based upon implementation of that process, it is the experience of the researcher that cost consideration is made as follows:

8.3.1 The Relationship between A&A Cost and External Investigation

Following receipt of an A&A proposal, a decision is made towards the need for its further investigation (Figure 3.5.1, Stage 3). If required, in-house discussion and referrals to experts within the RFA, or wider MoD, will not usually require additional funding. However, funding will be required for commercial investigations that involve the services of consultants, subcontractors or specialist service providers. These might involve, for example, feasibility studies being undertaken or visits to ships being conducted.

8.3.2 The Relationship between A&A Cost and Assigned Properties

Once an A&A proposal has been supported (Figure 3.5.1, Stage 5), a decision is made concerning its scale and complexity. That is to say, it is judged either 'major' or 'minor' depending upon properties such as technological complexity, requirement for specialist services, time required to implement and impact upon ship certification. Furthermore, decisions are made regarding the priority and required levels of project management for the development and implementation of the A&A. When evaluating the priority, the ship functionality to which the A&A is related must be considered along with the vessel role and the category of urgency. It can be appreciated that the assignment of A&A properties (major / minor / priority) directly correlates with the cost of its development and

[50] The DCB Process is introduced in Chapter 3 and further discussed within Chapter 4.

implementation. Hence, a major A&A pertaining to a critical ship function, the Upgrade or Update of which is mandatory, will demand high levels of project management, skilled labour and material resources – all of which are costly.

8.3.3 The Relationship between A&A Cost and Design Options

During the detailed design phase (Figure 3.5.1, Stage 6), a number of activities are directed towards developing the design guidance (specification) that will be used to implement the A&A and provide assurances towards the vessel, including ship class, certification, configuration management and safety case. As demonstrated within Chapter 7 (by the comparison of material options for the Sea Water Heat Exchanger), when faced with several possible solutions, high cost can both discriminate between alternatives and be a consequence of selecting a particular alternative.

It is evident, therefore, that 'cost' is related to the various decisions that are directed towards As&As. Funding will be required to finance the external investigation of an A&A proposal, whereupon it may become evident that its scope will be demanding in terms of technological complexity, project management and spending. This, in turn, would drive the decision to class the A&A as 'major' indicating that its development and implementation will be expensive. At the design phase, during development of the A&A solution, high cost will likely discriminate between design alternatives when consideration is given to either the Unit Procurement Cost (UPC) or the subsequent Through Life Cost (TLC), or to both.

This reasoning extends beyond the consideration of individual As&As since in practice, multiple As&As will be implemented as Work Packages[51] during the Upkeep periods for a vessel. It follows that clear argument exists for the need to consider the costs associated with As&As alongside all other aspects. Therefore, 'Cost Engineering' expertise must be applied in order to compile robust cost estimates to inform A&A decision making.

[51] The concept of 'Work Packages' for Upgrade, Update and Upkeep has been discussed within Chapter 3.

8.4 The Nature of Cost Engineering

Cost engineering is defined by the Association of Cost Engineers (ACostE, 2017), as "the engineering practice devoted to the management of project cost, involving such activities as estimating, cost control, cost forecasting, investment appraisal and risk analysis." Furthermore, according to AACE International (formerly the Association for the Advancement of Cost Engineering), the practice involves the application of scientific principles and techniques and also includes analysis of profitability (AACE, 2017). Cost Engineering has been grouped together with Scheduling (Dow, 2004) to provide the definition of 'Project Controls' as the means of managing performance by providing consistent, accurate and timely information to a project team.

Standard text books (for example Ostwald & McLaren, 2004) and training material (for example ICEAA, 2017) generally agree on the inclusion of core principles related to the following:

- Costs directly associated with a product or service including estimates for materials and labour.
- Business overhead costs indirectly incurred to support the delivery of that product or service.
- Analysis of the uncertainties and risks associated with cost estimates.
- Application of profit margins to manufacture or service-delivery costs in order to derive the selling price for the product or service.

Details relating to the cost engineering elements that combine to form a cost estimate are given within Appendix D.

8.5 The Intelligent Customer

Within the context of the procurement of defence capability (including As&As), this text considers Cost Engineering from the perspective of the client within the client-supplier relationship discussed within Chapter 7. In other words, the client is offered a price quotation in response to an Invitation to Tender (ITT) for some aspect of required capability, such as the provision of design services, the procurement of new equipment or the in-service support of existing assets. The client must act as the 'intelligent customer' to judge if the price is fair and reasonable.

Depending upon the value, criticality and risk associated with the required capability, the MoD customer may decide to commission an Independent Cost Estimate (ICE), to examine the basis upon which the supplier's estimate has been derived. As discussed within Section 8.1, this approach is taken in the case of single source suppliers where there is no competition within the marketplace acting to drive down, or at least regulate, the price demanded for a product or service.

An ICE would be facilitated via contractual 'terms & conditions'. These could include the application of a 'Recovery Rates Programme' and the application of DEFCON 643. Details for each can be accessed by prospective suppliers via the UK Government's Acquisition System Guidance (ASG), the main source of policy and guidance on acquisition for the MoD and industry partners (UK Government, 2012).

A Recovery Rates Programme would be conducted by the MoD Cost Assurance and Analysis Service (CAAS) to gain assurance that a contractor's cost recovery rates (of the type discussed within Appendix D) represent the basis of agreeing upon fair and reasonable prices. This would typically form part of an audit routine conducted annually to coincide with the financial year, for rolling non-competitive contracts. The aim is to gain agreement with the contractor towards rates for direct labour, overheads and materials. Furthermore, by applying a programme of periodic reviews, trends can be identified (and controls implemented) for increases in recovery rates that might indicate cost escalation due to any, or all of, the following:

- Inadequate cost control.
- Inefficient use of labour, materials or facilities.
- Reduced profitability.
- Unexpected delays in delivery schedules.

DEFCON 643 requires that the prime contractor or subcontractor shall comply with the following:

- Maintain records of the costs for production or services (including details of times taken and wage rates paid) as available from normal accounting procedures.

- Provide the details of those cost records in an agreed recognisable format.
- Facilitate visits to contractors' premises for examination of the processes involved in manufacture and service-provision, in order to estimate their associated costs.
- Maintain and provide as requested, up-to-date details of the project plans for manufacture or provision of services with respect to any aspect that might significantly affect the costs.

It is evident that the client (in this case the UK MoD) is not necessarily required to derive a cost estimate from first principles. Even so, the client may decide to do so, or engage a third party to do so. Rather, the client is required to investigate and understand the content of the estimate, to such a level that costs can be judged as 'Appropriate, Attributable to the contract and Reasonable (AAR)'.

For this reason, it is asserted by the researcher that, in order to support the decision making applied to As&As, the fundamental principles of Cost Engineering should be understood to a level sufficient for a pragmatic and practical consideration of the associated costs.

8.6 Cost Estimating Techniques

A number of techniques are generically recognised by organisations concerned with the systematic estimation of cost. The Project Management Institute (PMI), has produced 'The Project Management Body of Knowledge (PMBOK)' that identifies the following techniques (PMI, 2013):

8.6.1 Expert Judgment

This involves Subject Mater Expertise (SME) towards the project under scrutiny and the application of experience gained from previous projects.

8.6.2 Analogous Estimating

In this case, the basis of estimate is derived from previous projects of a comparable nature. Typically, actual cost data from similar programmes is used to provide a cost baseline that is adjusted to reflect differences in, for example, size, complexity and work scope.

8.6.3 Parametric Estimating

This technique derives accurate cost estimates based upon the relationships between unit cost data and the variables applicable to a particular project. Examples for shipbuilding might be an estimate for the total cost of sheet steel based upon a forecast of the quantity of units needed multiplied by its unit cost.

8.6.4 Bottom-Up Estimating

This involves compiling high-level estimates based upon a detailed understanding of the subordinate work packages that combine to form the overall Work Breakdown Structure (WBS) for the project.

8.6.5 Three-Point Estimating (3PE)

This estimates a cost-range whereby a deterministic Most Likely (ML) value is bounded within an uncertainty range between an optimistic minimum (Min) and a pessimistic maximum (Max). In other words, the ML cost is considered to lie between the best-case estimate and the worst-case estimate. Typically, 3PEs are treated as having a triangular Probability Distribution Function (PDF), as demonstrated by Figure 8.6.5.1 and Eqn. (8.1), (Garvey, 2000).

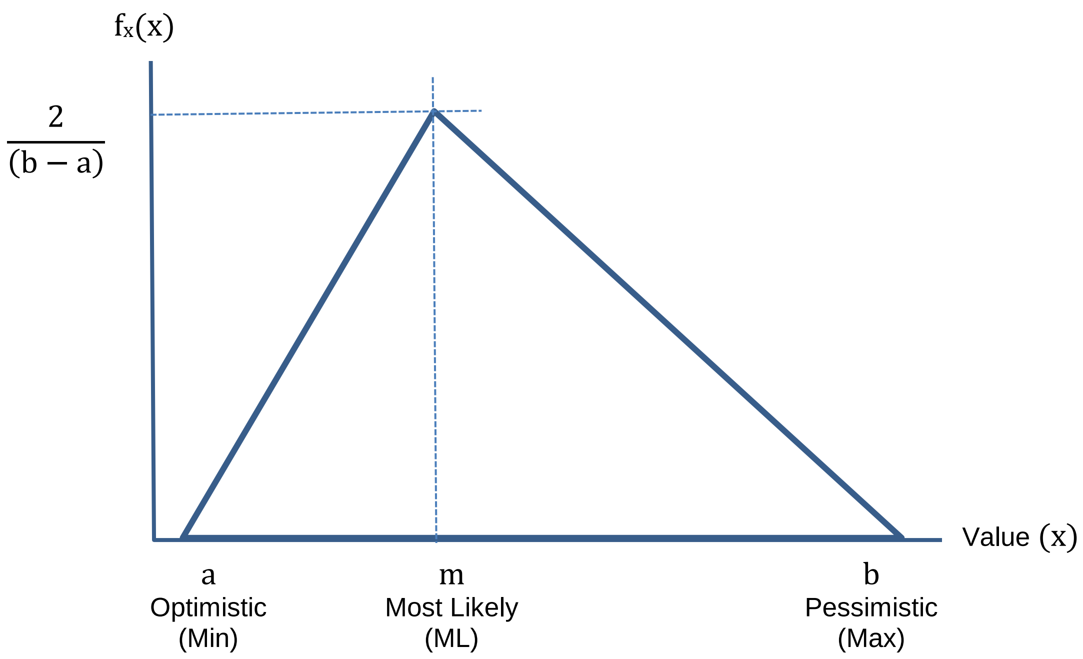


Figure 8.6.5.1. The Generic Triangular Distribution for a 3PE

$$f_x(x) = \begin{cases} \dfrac{2(x-a)}{(b-a)(m-a)} & \text{if } a \le x < m \\ \dfrac{2(b-x)}{(b-a)(b-m)} & \text{if } m \le x \le b \end{cases} \qquad \text{Eqn. (8.1)}$$

where: $-\infty < a < m < b < \infty$

8.6.6 Reserve Analysis

This involves the identification of allowances and the determination of management funding reserves to accommodate possible cost overruns due to uncertainty. Typically, cost allowances are accepted within the cost baseline for engineering processes known to involve the likelihood of cost increase, whilst the exact value of that increase cannot be pre-determined. For example, cost estimates for a manufacturing process may include allowances for engineering re-work and material scrappage. In this case, whilst it is reasonable to accept the likelihood of re-work and scrap, the levels of re-work and scrap, and therefore the associated cost, cannot be predicted with certainty. Alternatively, management funding reserves may be excluded from the cost baseline, but included within the project budget, then be withheld for the purposes of (1) programme control and (2) unforeseen work that might adversely impact the project.

8.6.7 Cost of Quality

In this case the project cost estimate includes estimates of the activities associated with quality control. These will likely include the cost of activities that offer assurance that requirements have been satisfied, together with the measures and re-work that must take place in the event of non-conformance. It can be noted that the term ‘cost of poor quality’ may be used in relation to costs associated with non-conformance.

8.6.8 Project Management Software

For all but the simplest cost scenarios, contemporary cost engineering makes use of computer applications that provide spreadsheet modelling capability and cost simulation tools. These are discussed from Section 8.8 onwards.

8.6.9 Vendor Bid Analysis

As discussed throughout Section 8.5, this involves examination of the basis of estimate offered by a vendor (capability supplier) in response to a bid invitation (i.e. an ITT). The aim is for the intelligent customer to determine that the price is fair and reasonable.

8.6.10 Group Decision Making Techniques

Team-based approaches may be used to inform the cost estimate and ensure that it is robust. Specific techniques will depend upon the programme management processes that have been established by a particular organisation. Typically, this will involve the application of formal documented processes to offer Quality Assurance towards the project deliverables. At the level of collective working, decision making is likely to involve discussion between SME, brainstorming sessions, peer review and project review panels. Indeed, the theme of collective decision making based upon informed judgement runs throughout this entire thesis and is implemented via the DCB process discussed within Section 8.3

8.7 Uncertainty Associated with Cost Estimates

For any cost engineering project, costs will be developed within a cost model. This takes a range of cost variables at the input, applies numerical computation to reflect engineering processes, historical trends and market conditions, then offers a likely cost consequence at the output.

When building estimates of costs within the model, 'uncertainty' is the inability to be definite with regards to the underlying data and, therefore, the outcome of the cost estimation method. It follows that uncertainty exists where there are shortfalls in available data, unquantified errors in data or lack of understanding towards the parameters that impact upon a system. For this reason, using probabilistic techniques, uncertainty analysis is conducted to gain confidence towards the reliability of conclusions and decisions founded upon uncertain information. Indeed, Garvey (2000) describes cost uncertainty analysis as the process of assessing the cost impacts of the uncertainties associated with the engineering definition for a system and the estimation methodology applied.

Cost uncertainty analysis has its origins in 'operations research', a discipline that deals with the application of advanced analytical methods to help make better decisions (INFORMS, 2018). Notable examples of early work come from the cost studies for military systems conducted at the RAND[52] Corporation during the 1950s (Hitch, 1955) and the 1960s (Dienemann, 1966). Contemporary examples can be sourced from a vast field of disciplines, as discussed throughout Section 8.9 and Section 8.10.

When compiling cost estimates for any project, cost uncertainty is greatest during the early concept phase when 'Rough Order of Magnitude' (ROM) costs are typically produced at short notice based upon limited technical, programme and cost data. As project maturity develops, the detail of project activities is identified so that uncertainty is reduced. In the experience of the researcher, organisations typically have maturity stages and metrics against which the progress of a product can be monitored and controlled. It follows that the uncertainty at each of these stages progressively falls within a smaller range as maturity is developed. The principle is demonstrated within Table 8.7.1. This is offered by the researcher based upon a formal AACE cost classification system (AACE, 2005), consisting of five classes of cost estimate, as given within Appendix E.

Table 8.7.1. Types of Cost Estimate with Associated Uncertainty

Readiness Level	Project Definition	Estimate Use	Type	Uncertainty Range
Low	0% to 2%	Concept Screening	Rough Order of Magnitude (ROM)	-20% to -50% +30% to +100%
Medium	10% to 40%	Budget Authorisation	Part-detailed estimate to reflect principles of operation, draft technical solution and project plan	-10% to -20% +10% to +30%
High	50% to 100%	Bid for Project	Detailed baseline	-3% to -10% +3% to +15%

8.8 Monte Carlo Analysis – A Stochastic Approach to Uncertainty Analysis

Stochastic modelling is a form of analysis based upon probability techniques using one or more random input variables. The Monte Carlo method uses a stochastic approach. Hence, given a collection of input variables, each having an

---

52 RAND Corporation - established in 1948 to provide research services for the US Air Force. Contemporary services are focussed upon research and analysis to support public policy worldwide.

uncertainty range and probability distribution, Monte Carlo simulation performs analysis to return a probability distribution that allows an analyst to judge the likelihood of a particular outcome.

The process is referred to as a ‘simulation’ because the method involves repeatedly sampling input values at random then calculating a possible result each time. Because of the diversity of possible samples for the input values, results would be considered unreliable for a small number of iterations through the process. Therefore, simulations involve thousands, tens-of-thousands or more, recalculations before convergence is accepted. For this reason, analysis is performed using a computer algorithm.

As a development of prior statistical sampling approaches, the Monte Carlo method was developed by scientists working on the US atomic programmes of the 1940s and 1950s. Their contribution was to recognise the potential for newly invented computers to conduct huge numbers of calculations on samples that, using traditional analytical approaches, would have been unacceptably time consuming, labour intensive and prone to error. Working with John von Neumann and Nicholas Metropolis[53], Stanislaw Ulam, (a Polish-born mathematician) developed algorithms for computer implementations, as well as exploring ways of transforming non-random problems into random forms suitable for solution via statistical sampling. A paper was published on the Monte Carlo method by Metropolis & Ulam (1949).

The underlying principles and the application to cost uncertainty analysis can be illustrated by Figure 8.8.1 and Figure 8.8.2. These have been adapted by the researcher based upon work carried out by the RAND Corporation during the 1960s to improve the estimation of costs for future military systems (Dienemann, 1966).

Since then, Monte Carlo methods have been applied across a wide range of fields to a vast number of problems having a probabilistic interpretation. Maritime examples are referenced by McNamara et al. (2017). These relate to the use of Monte Carlo to assess the efficiency of a marine cooling system (McNamara,

[53] Due to similarities between the statistical simulation and games of chance, Metropolis is credited with naming the method ‘Monte Carlo’ after the city in Monaco famed for its casinos and games of chance.

2013) and the application of Delay-Time Analysis to system maintenance and inspection regimes (Cunningham et al., 2011).

Examples of the wider application are offered throughout Sections 8.9 and 8.10. These include downloadable papers offered at the website for Palisade (2017a), particularly with respect to the Palisade risk assessment products (see Section 8.10.1).

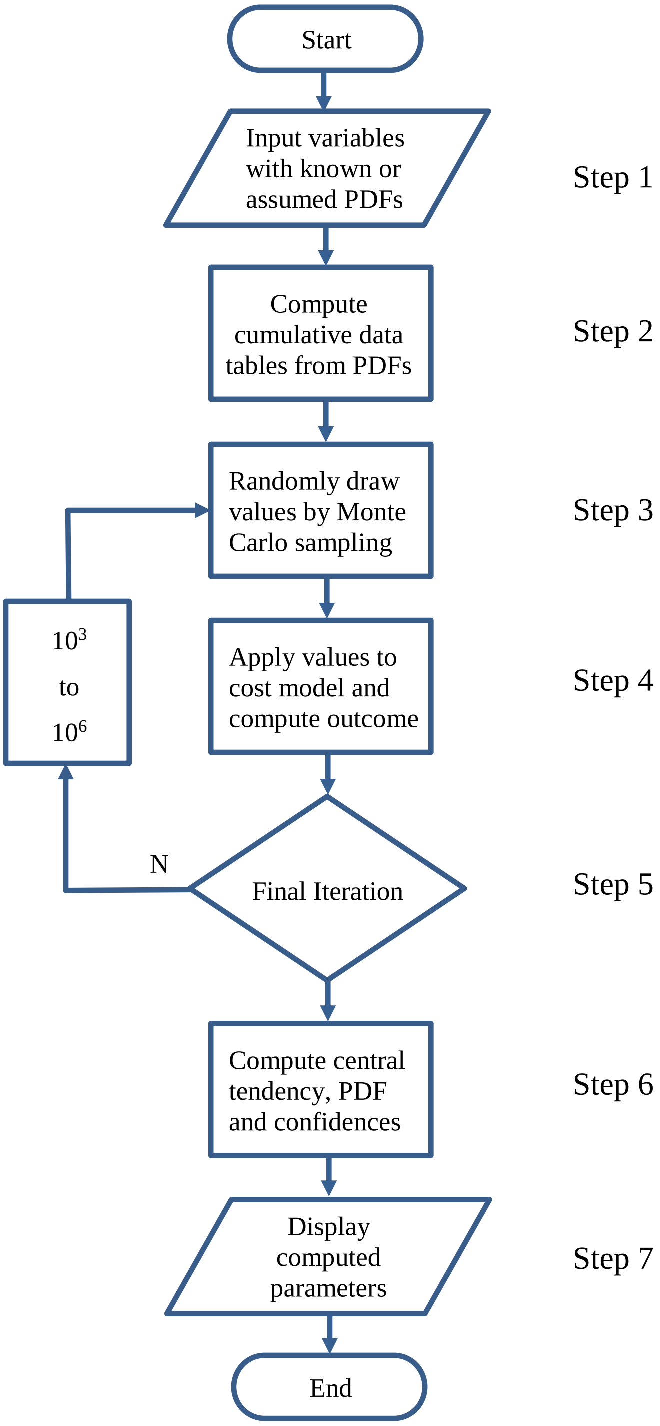


Figure 8.8.1. Monte Carlo Algorithm for Cost Uncertainty Analysis

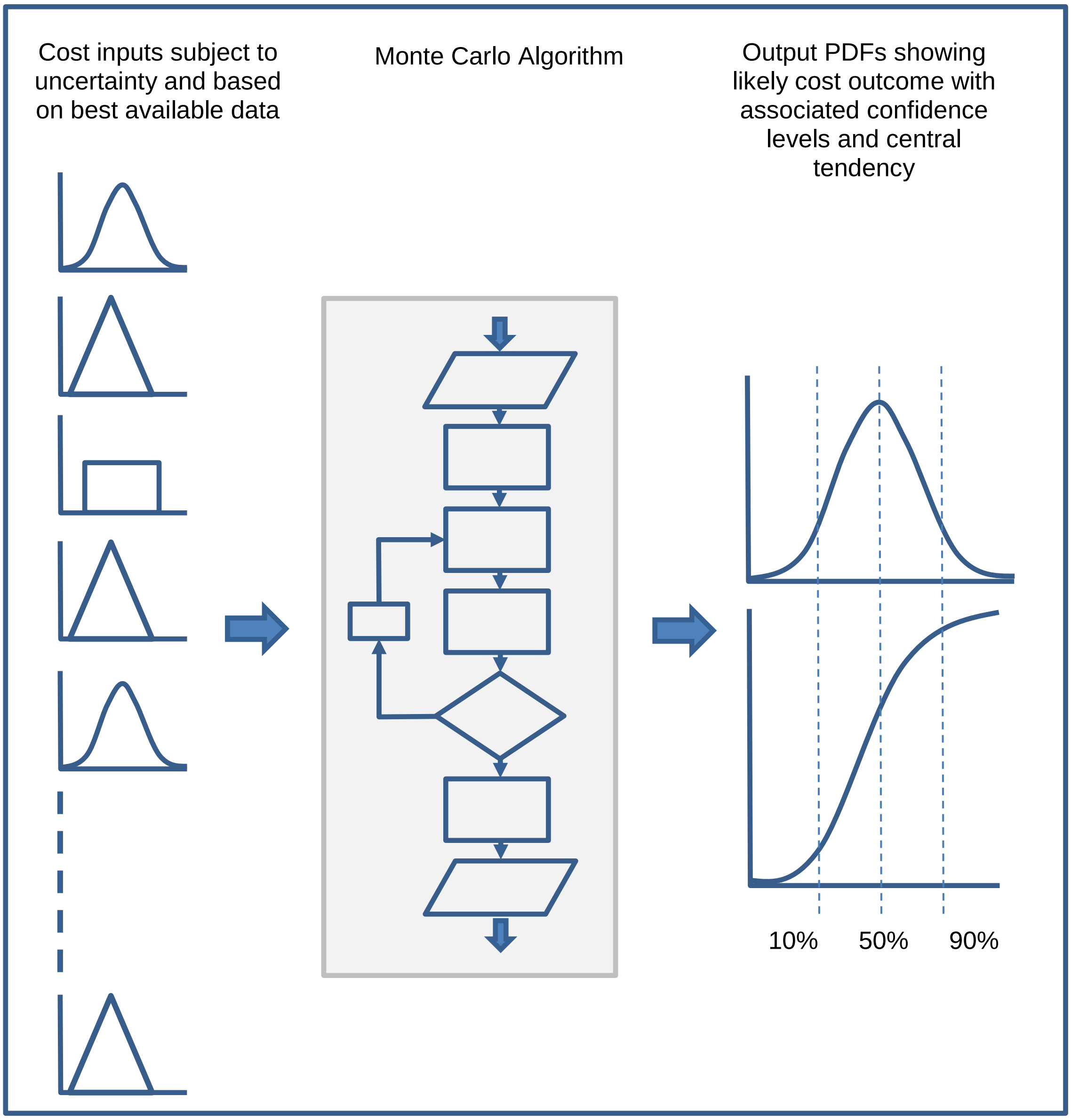


Figure 8.8.2. Overall Monte Carlo Simulation for Cost Uncertainty Analysis

8.9 Software for Risk Analysis Using the Monte Carlo Approach

It is evident from Section 8.8 that the Monte Carlo method demands a computational implementation. This has led to the development of numerous algorithms, either bespoke and so tailored to a specific application (for example Cunningham et al., 2011) or 'Commercial Off The Shelf' (COTS) software packages that can be applied generically for schedule and cost risk analysis. A review of risk management support tools (Dikmen et al., 2004) considered a range of COTS packages available in 2004, 11 of which were based upon Monte Carlo simulation. An illustrative summary of findings is reproduced within Appendix F, having been adapted and updated by the researcher.

As may be appreciated, owing to the dynamic nature of both software and commercial markets, a number of the products that were current in 2004 have since been developed into new software tools and are now traded under different organisational brands.

Whilst Appendix F does not claim to be an exhaustive survey, it demonstrates that creation and application of risk analysis software has been, and continues to be, the focus of considerable commercial competition involving the development of a range of support tools. Furthermore, it is evident that certain brands have consolidated their positions as market leaders. These include Palisade, Oracle, Deltek, Risk Decisions and riskHive. This reasoning has led the researcher to consider the application of three leading software packages for cost risk analysis, namely @Risk (Palisade), Crystal Ball (Oracle) and Arrisca (riskHive). One package, Arrisca, will receive particular focus and will be used for the purpose of demonstration. The approach is further described within Section 8.10.

8.10 Tools for Cost Risk Analysis Using the Monte Carlo Approach

Within the context of cost risk analysis, the Monte Carlo approach described above translates to the following:

- The input to a cost model of a collection of uncertain cost estimates. Typically, these are 3PEs (Min, ML and Max) having a triangular probability distribution. They may also be a combination of 3PEs and deterministic values (based upon fixed quotations) and so having rectangular probability distributions. Other distributions for input variables may be used if there is clear basis for that distribution.
- The performance of Monte Carlo simulations on the input estimates within the cost model.
- The presentation of a probability distribution for cost showing output values and the likelihood of realising those values. This is typically expressed as a probability density function (for example a 'normal' distribution) or a cumulative density function (the corresponding 'S-curve'). The likelihood of a cost value falling within a given range is indicated on the distribution and expressed in terms of confidence levels (typically 10%, 50% and 90%).

As discussed within Section 8.9, software tools based on the Monte Carlo approach are available for cost risk analysis. The basic process when using software tools is to:

- Build the cost model using a software spreadsheet that describes an uncertain situation.
- Run a Monte Carlo simulation on the model using the functionality of the cost risk software.
- Analyse and present the results.

For the purpose of illustration, this text considers the software packages shown within Figure 8.10.1. These are COTs packages used by analysts and project managers to conduct risk assessment, assurance and adjustment. The tools act as 'add-ins' for Microsoft (MS) Excel, meaning that they provide software that adds functionality and features to the Excel host models.

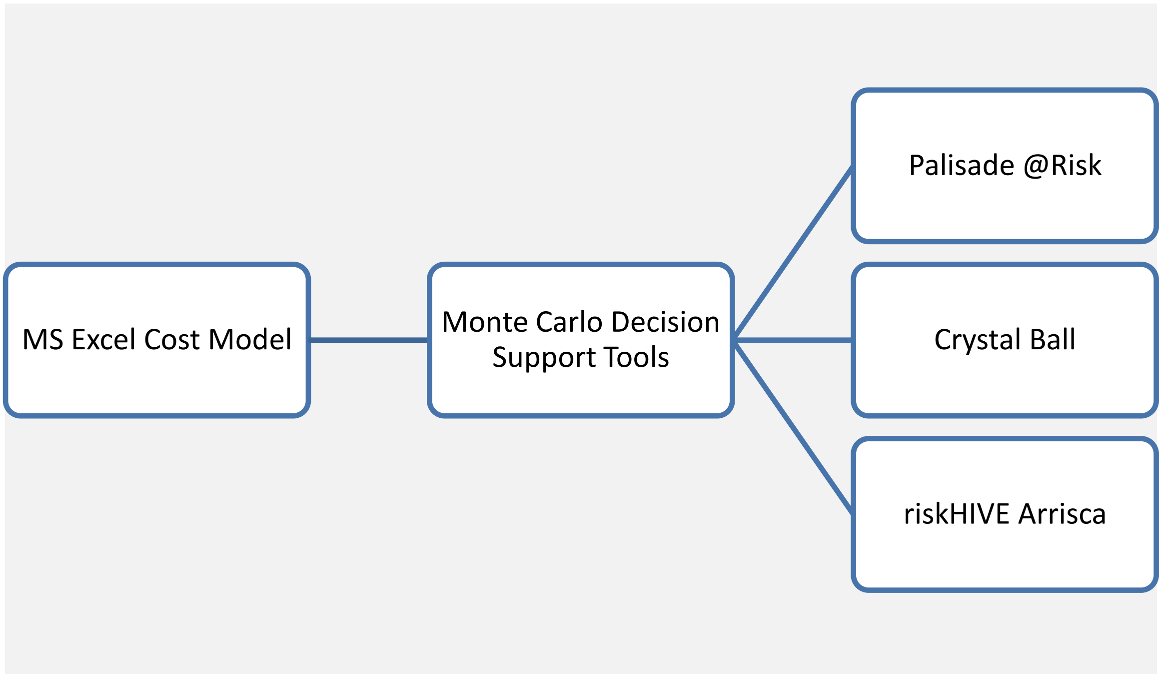


Figure 8.10.1. Cost Risk Analysis Software Based on Monte Carlo [54]

This approach has been adopted because it is apparent from literature reviews that these packages have been consistently applied as market leaders across a wide range of fields (see below). Furthermore, each has been applied to defence

[54] Offered by the researcher based upon professional experience and literature review.

programmes and so has relevance to the subject matter of this thesis. The following descriptions introduce each of the packages.

8.10.1 Palisade @RISK

Palisade is demonstrably an international company and market leader within the field of risk analysis software products (Palisade, 2017b). The company founder (Sam McLafferty) privately developed his own Monte Carlo simulator before founding Palisade in 1984 and releasing the first @RISK software in 1987. The contemporary tools offer a suite of programs that integrate with MS Excel and MS Project for cost and project risk analysis to support programme decision making.

As noted within Section 8.8, the Palisade website offers a useful source of reference that demonstrates application across a wide range of industries (Palisade, 2017a). The website references are organised into the following categories: Academia, Agriculture, Construction, Engineering, Energy, Utilities, Environment, Finance, Banking, Government, Defence, Healthcare, Pharmaceuticals, Insurance, Manufacturing, Project Management, Six Sigma, Transportation and Others.

8.10.2 Crystal Ball

Oracle Crystal Ball is a suite of applications based upon MS Excel. The Oracle website (Oracle, 2017a) makes the claim that “Crystal Ball is the leading spreadsheet-based application for predictive modeling, forecasting, simulation, and optimization”. Application across 22 industries is claimed including: Academia, Engineering, Environmental, Finance, Healthcare and Government sectors.

Crystal Ball was applied by Brown (2009) to investigate the construction cost predictions for naval vessels derived by NAVSEA 05C, the Cost Engineering and Industrial Analysis division of NAVSEA[55]. Within the work, it is explained that data was collected from analysis of the cost model for the CG(X) ship[56]. This was an extensive model, encompassing all aspects of fleet cost, including inflation and

[55] NAVSEA (Naval Sea Systems Command), is the largest of the U.S. Navy's (USN) system commands with the mission to design, build, deliver and maintain ships and systems on time and on cost for the USN.
[56] CG(X) was the designation used for the USN Next Generation Cruiser, a multi-mission ship with emphasis on air defence and ballistic missile defence (BMD).

profit, in an Excel workbook having 63 worksheets. The cost data used in the NAVSEA model was derived from SME offering 3PEs of Min, ML and Max costs. It is further explained that Crystal Ball was chosen for the analysis because it was the software used by NAVSEA 05C at that time.

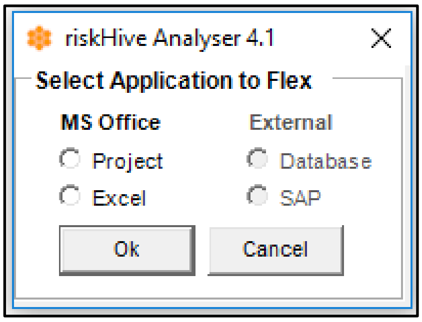
The significance of this type of cost evaluation can be appreciated from the Commander's message regarding the mission of NAVSEA, i.e. "to design, build, deliver and maintain ships and systems on time and on cost for the United States Navy" (NAVSEA, 2017). Furthermore, the importance of this type of evaluation was dramatically demonstrated when, in 2010, the US Congressional Research Service (CRS) reported that the Navy's FY2011 budget proposed cancelling the CG(X) programme as unaffordable and, instead, building an improved version of the Arleigh Burke class Aegis destroyer (CRS, 2010), (O'Rourke, 2013).

8.10.3 The riskHive Arrisca Analyser [57]

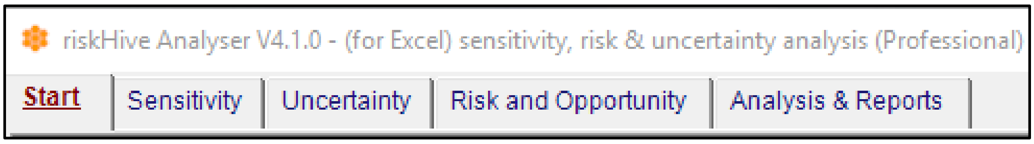
The riskHive 'Arrisca Risk Analyser' (often referred to simply as 'Arrisca') is a tool for the stochastic analysis of cost and schedule models that are built using host applications, including MS Excel spreadsheets and MS Project plans. The capabilities facilitate the performance of cost and schedule risk analysis. When conducting cost risk analysis, the software features allow sensitivity analysis to be performance upon the cost model inputs in order to identify the dominant (key) inputs that drive the output values.

Uncertainties can be imported in the form of 3PEs, then analysis undertaken using the built-in Monte Carlo simulation tools. Once analysis has been performed, the results can be displayed as graphical probability distributions together with summary narratives stating the confidence levels associated with particular outputs. The Arrisca user interface for this functionality is shown within Figure 8.10.3.1, Figure 8.10.3.2 and Figure 8.10.3.3 [58].

[57] Subject to Copyright 2017 riskHive Software Solutions Ltd. The Arrisca Risk Analyser is used by the researcher with the permission of Ian Baker, riskHive Software Solutions Ltd.
[58] These figures have been compiled by the researcher using screen-shots taken during analysis using Arrisca.

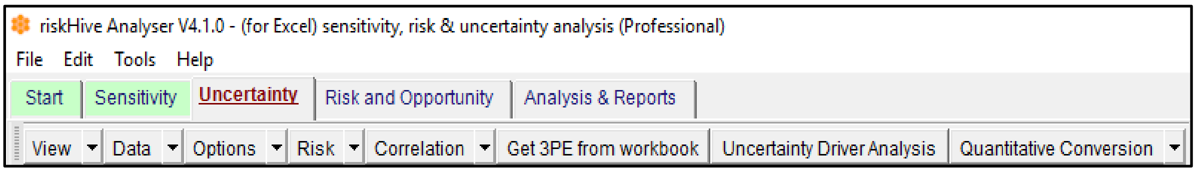


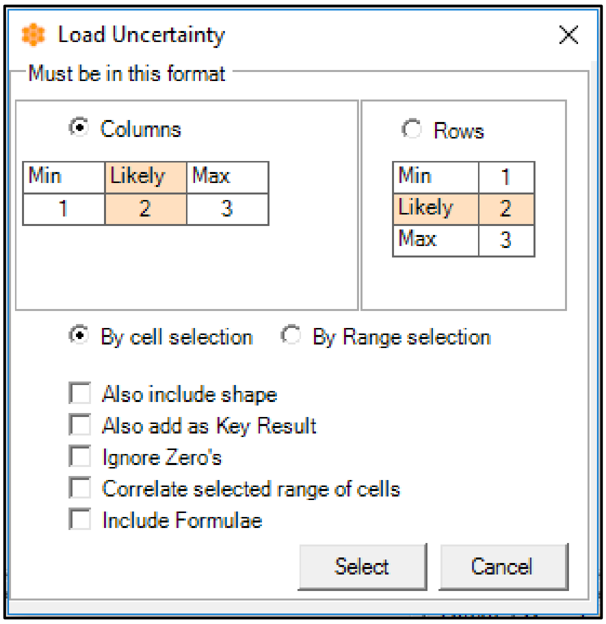
The Risk Analyser supports risk assessment and adjustment using cost and schedule models. Effects of key drivers can be assessed via sensitivity analysis. Monte Carlo simulation can be used for uncertainty analysis. Results can be displayed in graphical form and as summary statements.



Source: based upon screen-shots from riskHive Software Solutions

Figure 8.10.3.1. Arrisca User Interface for Risk Analysis



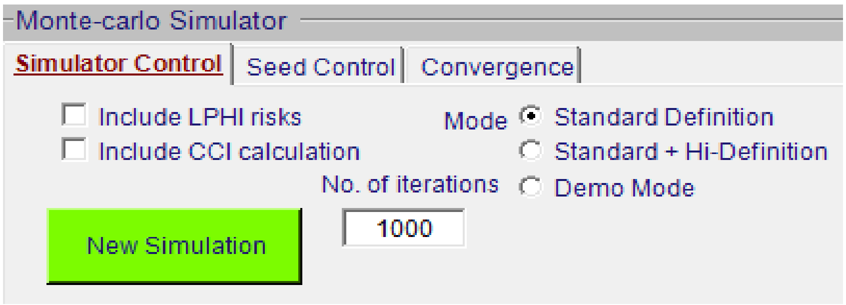


Uncertainties can be imported from the cost model in the form of 3-Point Estimates (3PE) involving Minimum, Most Likely and Maximum values.

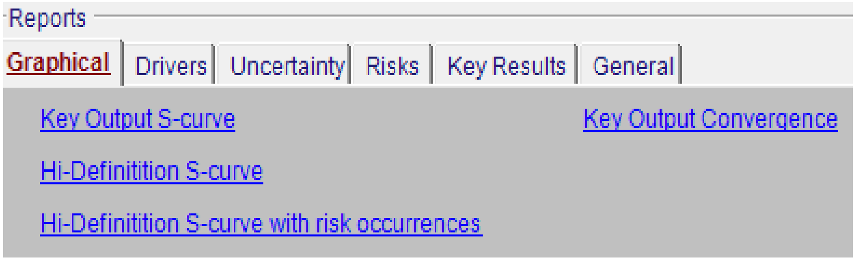
Source: based upon screen-shots from riskHive Software Solutions

Figure 8.10.3.2. Arrisca User Interface for Uncertainty Analysis

Monte Carlo Simulation can be performed and controlled via the dedicated Graphical User Interface



Results of the uncertainty analysis can be exported to MS Excel in the form of charts, the underlying data for those charts and summary narratives



Source: based upon screen-shots from riskHive

Figure 8.10.3.3. Arrisca Interface for Monte Carlo Analysis and Report

8.11 A Systematic Treatment of A&A Cost Uncertainty

The preceding sections have broadly discussed the commercial context of defence procurement and have described the essential characteristics of cost engineering, including the nature of cost uncertainty and the application of uncertainty analysis software. It is the assertion of the researcher that these principles can be directed towards the As&As implemented by commercial shipyards during the Upgrade and Update of RFA vessels. To this end, this section describes a systematic methodology that can be generically applied to the costs associated with individual As&As and work packages of As&As forming part of the work scope during a maintenance period.

The proposed modelling methodology for the treatment of A&A cost uncertainty involves the following steps:

8.11.1 Step 1. Define the Cost Modelling Scenario

The objective of the cost estimation should be clearly defined in terms of the engineering work under scrutiny, the scope of the cost estimate and the estimation technique to be applied. The descriptions of estimation techniques given within Section 8.6 support this activity. A clear understanding of the modelling scenario is needed in order to derive a valid set of requirements that must be addressed throughout the modelling methodology in order to satisfy the end user.

8.11.2 Step 2. Collect Cost Data

Once the work scope has been identified, the next step is to identify the costs associated with that work scope. Costs are typically derived from analogy to previous projects of a comparable nature, or they may be obtained directly from capability suppliers. In the context of As&As, cost estimation would benefit where the same As&As have previously been implemented to other ships, particularly within the same ship class. As discussed within Section 8.7, the uncertainty associated with cost data is generally high during the early stages of a project when full technical detail and programme impact are not yet known. It follows that the uncertainty associated with cost data is low when costs are based upon actual data from comparable projects or when costs have been obtained as fixed-price quotations from shipyard suppliers.

8.11.3 Step 3. Build a Cost Model

The consideration of A&A costs throughout the DCB process has been discussed within Section 8.3. In this context, a cost model is a computation of those costs associated with the investigation of an A&A proposal and, if supported, its subsequent design development. Contemporary practice typically involves a cost model being developed using MS Excel, with the cost variables being subject to numerical computation to represent the costing scenario. The nature of the cost engineering associated with a cost model is discussed throughout Section 8.4 and Appendix D.

8.11.4 Step 4. Apply Probability Principles to the Cost Model

When dealing with cost variables having uncertainty ranges at the input of a cost model, it follows that the output cannot be a single deterministic value. In other words, where the input is subject to uncertainty, the output must also be subject to uncertainty. In such cases, statistical analysis is performed upon the cost model whereby probability techniques are used to evaluate the confidence with which a cost output will fall within a given range. The principles are discussed throughout Section 8.8 and are also the focus of Step 5 below. In order to facilitate a probability analysis, the cost inputs are each assigned a probability distribution based upon either (1) knowledge of the probability distribution for the cost data or (2) assumptions made towards the probability distribution for the data based upon best available information. A commonly encountered practice involves the use of triangular distributions for 3PEs, as discussed within Section 8.6.

8.11.5 Step 5. Perform Cost Risk Analysis Using the Monte Carlo Approach

Having constructed a cost model in Step 3 and assigned probability distributions to the input variables at Step 4, the next step is to perform the probabilistic analysis. The principles for applying Monte Carlo analysis are discussed within Section 8.8. The use of software add-in tools for an MS Excel cost model are discussed throughout Section 8.9 and Section 8.10.

8.11.6 Step 6. Interpret the Results

The concept of the ‘intelligent customer’ was discussed within Section 8.5 whereby the client is required to understand the cost estimate in order to judge if costs are Appropriate, Attributable to the contract and Reasonable (AAR). When performing a Monte Carlo Analysis, the results are generated from the simulations in the form of a probability distribution showing the confidence levels associated with obtaining a particular result. Typically, confidence levels of 10%, 50% and 90% are given. The principle is demonstrated within Figure 8.8.2 and discussed within Section 8.10.

Ultimately, the decision-maker must decide upon a particular cost option depending upon the costing strategy in operation, having been informed by the results of the cost engineering activities and analysis.

8.11.7 Step 7. Document the Basis of Estimate (BoE)

This discussion indicates that the cost engineer must apply judgement where ambiguity exists for data. Indeed, this ambiguity is the root cause of the cost uncertainty. Where assumptions, adjustments and data manipulation take place, all must be documented as part of the 'Basis of Estimate' (BoE). In this regard, it is the experience of the researcher that the BoE commonly includes a ‘Master Data Assumptions List’ (MDAL). This facilitates the Quality Assurance of any model by offering a record of the source, assumptions and decisions for data and methodology within the model (UK Government, 2016).

It follows that, in the widest sense, delivery of the BoE should involve the comprehensive documentation of all aspects of the cost estimate. This would typically include the following (GAO, 2009):

- Traceability for the source of cost data.
- Detail and explanation for calculations and results.
- Justification for choice of estimating method.

A comprehensive BoE provides robust justification for the conclusions of the cost modelling.

8.11.8 Step 8. Validate the Results and Update the Cost Model

Within the context of cost engineering, Verification and Validation are activities used together for checking that a cost model meets user requirements and satisfies the intended purpose.

The Project Management Body of Knowledge (PMBOK) states the following definitions (PMI, 2013):

- **Verification.** The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition.
- **Validation.** The assurance that a product, service, or system meets the needs of the customer and those of other identified stakeholders.

From these definitions it may be appreciated that, perversely, a cost model may pass a verification check but fail a validation check. This could occur if the model had been developed to address requirements that in themselves failed to fully address the needs of the end user. This clearly demonstrates the need to fully understand the scope of work defined within the modelling scenario identified in Step 1 (Section 8.11.1).

Best practice towards the development and validation of high quality cost estimates is discussed in detail by the US Government Accountability Office within its 'Cost Estimating and Assessment Guide' (GAO, 2009). Focus is directed towards systematically ensuring that an estimate has the following characteristics:

- **Documented.** The requirements for documenting a Basis of Estimate have been discussed within Step 7 (Section 8.11.7).
- **Comprehensive.** The cost model should reflect the full scope of activities and materials identified in the project Work Breakdown Structure (WBS). The associated 'Cost Breakdown Structure' should provide assurance that all cost elements have been included whilst none have been double-counted.
- **Accurate.** The rationale and computation within the cost model should be verified to check that modelling requirements have been satisfied and that no errors occur. Estimates should reflect the cost outcome most likely to be encountered since costs that are either highly optimistic or highly conservative do not offer a realistic basis for decision making. In addition, assurance towards the accuracy of the cost estimate could be obtained by comparison to an Independent Cost Estimate (ICE) performed by a third party. Where data becomes available for actual costs incurred, the model should be updated to reflect those actual costs.
- **Credible.** The credibility of a cost model relates to the soundness of its derived cost estimate and is, therefore, concerned with identifying and understanding modelling limitations and assumptions. The impact of these can be examined by performing a sensitivity analysis whereby the significant modelling assumptions are varied, and the cost outcome recalculated. Further assurance could be obtained by comparing the estimate to industry 'cost norms' or benchmarks for activities of a comparable nature.

8.12 Demonstration of Methodology – Heat Exchanger Header Costing

8.12.1 Step 1. Define the Cost Modelling Scenario

The scenario considers the cost data for the material selection exercise discussed within Chapter 7. One of the design alternatives for the exercise involved the use of titanium for components within a sea water heat exchanger. The cost engineering objective is to derive a cost estimate for a major component, i.e. the sea water header.

A 3PE technique will be applied to statistically derive the confidence that the component cost will range between the most optimistic minimum (Min) and the worst-case maximum (Max). For reasons of commercial and programme sensitivity, the suppliers have not been named and full technical details for the component are not offered.

8.12.2 Step 2. Collect Cost Data

Suppliers were approached to provide cost estimates for the component. These provided the inputs for the heat exchanger cost model.

8.12.3 Step 3. Build a Cost Model

Supplier responses are shown within Table 8.12.3.1. This models the material costs directly associated with the component manufacture, test and delivery.

Table 8.12.3.1. Supplier Cost Estimates for Heat Exchanger Component

Heat Exchanger Component	**Supplier**		
Cost Element (£)	**A**	**B**	**C**
Casting	21,819	26,575	Not applicable
Forging	Not applicable	Not applicable	31,600
Fabrication	1,900	Included in casting	Included in forging
Machining	1,235	1,235	1,235
Non-Destructive Test (NDT)	2,400	2,400	2,400
Pressure Test	895	895	895
Mechanical Test	80	80	80
Delivery	76	509	1,007
Total (£)	**28,405**	**31,694**	**37,217**

Working on the basis that a specific supplier will not be down-selected at the early concept stage (selection is part of a lengthy tendering process), it is evident that the cost of the component is uncertain but will fall somewhere between £28,405 and £37,217. It can be seen that the total cost estimates from each supplier have been constructed from a number of elements. These are the engineering processes involved in manufacture, testing and supply of the component. Each of these costs elements, unless offered as a firm quotation, will have its own associated uncertainty. Furthermore, it should be appreciated that this component forms only part of the overall system, meaning that the cost of this component forms only part of the overall cost. In other words, the cost for this component will form just one input of a larger cost model that must consider the uncertainties for the entire heat exchanger.

8.12.4 Step 4. Apply Probability Principles to the Cost Model

It was explained within Section 8.7 that cost uncertainty is the inability to be definite with regards to cost data, meaning that uncertainty exists where data is subject to shortfalls, unquantified errors or lack of understanding towards the system under scrutiny. For the purpose of this costing exercise, it is consistent with the professional experience of the researcher that uncertainty can be accommodated using a 3PE technique. This involves stating the supplied data in terms of the Min, ML and Max anticipated costs. This is illustrated within Table 8.12.4.1.

Table 8.12.4.1. Derived 3-Point Estimates for Heat Exchanger Component

SW Header	**3 – Point Estimate**			**Assumed distribution**
Cost Element	**Min (£)**	**ML (£)**	**Max (£)**	
Production	23,719	26,575	31,600	Triangular
Machining	1,235	1,235	1,235	Rectangular
NDT	2,400	2,400	2,400	Rectangular
Pressure Test	895	895	895	Rectangular
Mechanical Test	80	80	80	Rectangular
Delivery	76	509	1,007	Triangular
Totals (£)	**28,405**	**31,694**	**37,217**	
Assumptions	1. Product cost defined as Casting + Forging + Fabrication 2. Rectangular distribution is assigned where estimates are uniform. 3. Costs for Production and Delivery are taken as 3-Point Estimates with assumed triangular distribution.			

The probability distribution for each cost element has been assumed by the researcher in the absence of any defining information. For the purpose of this demonstration, these are pragmatic assumptions based upon experience. Triangular distribution is assumed to 3PEs and rectangular distribution is assumed where costs are uniform. Even so, the researcher acknowledges that in practice, justification for the distributions should be made on the basis of discussion with experienced cost engineering colleagues and wider investigation if necessary[59].

8.12.5 Step 5. Perform Cost Risk Analysis Using the Monte Carlo Approach

Using the functionality described within Section 8.10.3, an Arrisca uncertainty analysis has been applied to the Heat Exchanger 3PE. The results of three Monte Carlo simulations are demonstrated within Figure 8.12.5.1, Figure 8.12.5.2 and Figure 8.12.5.3. These have been generated by the riskHive Arrisca software and edited by the researcher. The results have been summarised within Table 8.12.5.1 and Table 8.12.6.1.

As shown within Table 8.12.5.1, different simulations have been performed in order to demonstrate the effects of changing the number of iterations. It can be seen that the simulations have been run firstly with 500 iterations, then 1000 iterations then 5000 iterations. The effects of random number generation (during the Monte Carlo simulation) are most evident when fewer iterations have been performed. This is shown by the erratic tendency of the curve within Figure 8.12.5.1. As the number of iterations increases, this tendency diminishes such that a relatively smooth curve is shown for 5000 iterations within Figure 8.12.5.3. Furthermore, a clear trend towards a triangular probability distribution has emerged.

Table 8.12.5.1. Comparison of Simulations for Heat Exchanger Costs

500 Iterations, 2 mins			
80% of all outcomes (The Confidence Interval) were between	30,304	and	34,754
The Confidence Interval has a range of	4,450		
1000 Iterations, 4 mins			
80% of all outcomes (The Confidence Interval) were between	30,365	and	34,877
The Confidence Interval has a range of	4,512		
5000 Iterations, 20 mins			
80% of all outcomes (The Confidence Interval) were between	30,379	and	34,833
The Confidence Interval has a range of	4,454		

59 It may be noted that, whilst not considered necessary for this demonstration, a sensitivity analysis could be performed using the Arrisca software to investigate the effect of changing the type of assumed distribution.

As shown within Table 8.12.5.1, the time taken to complete each simulation increases as the number of iterations increases. For this demonstration, the relatively simple cost model took minutes or tens-of-minutes to complete up to 5000 iterations using a personal computer with specification that could be considered as 'standard' within contemporary markets. It can be appreciated that, using the same computer, a complex cost model performing 10^4 iterations or 10^6 iterations, could take hours or even days to complete.

It follows that the number of iterations should be commensurate with the degree of complexity of the model and the level of convergence required for the end result. In this instance, the results are sufficiently consistent to suggest that a pragmatic approach, for the purposes of demonstration and deriving an expediently quick result, would be to use a simulation consisting of between 1000 and 5000 iterations. Indeed, it is the experience of the researcher that between 1000 and 10,000 iterations are commonly performed when compiling estimates of this nature.

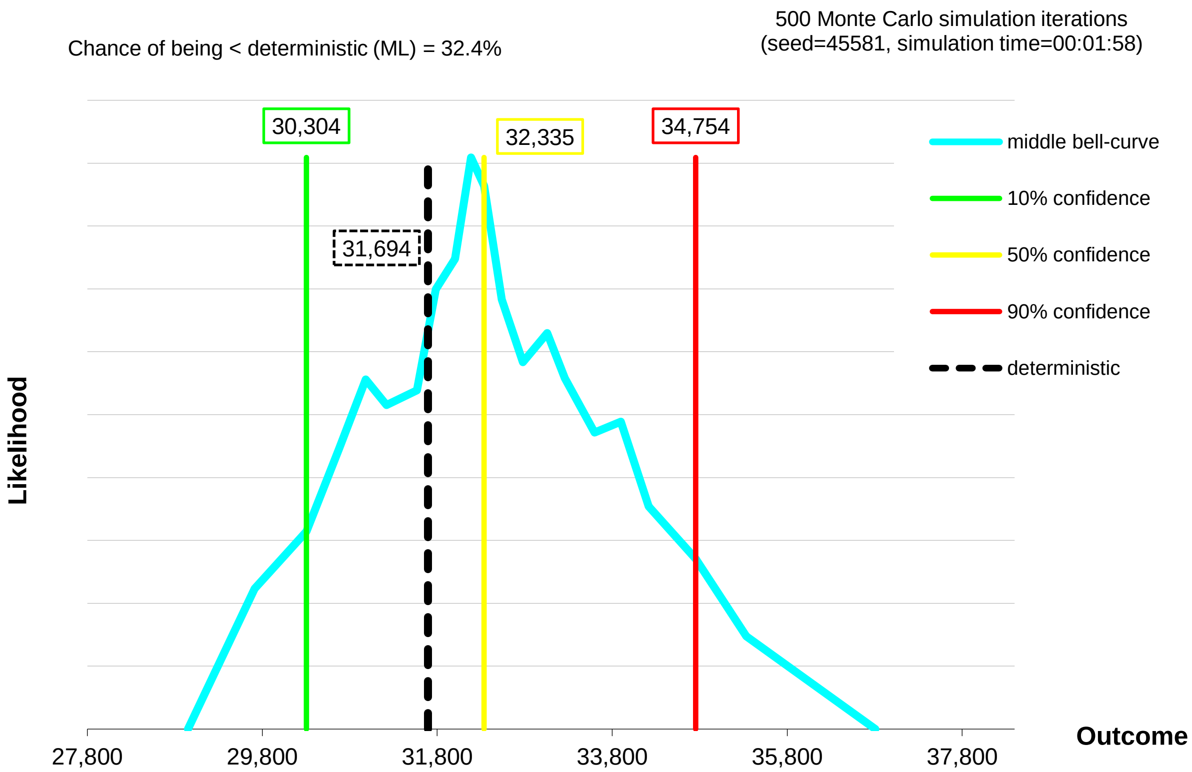


Figure 8.12.5.1. Arrisca Simulation for Component 3PE (500 Iterations)

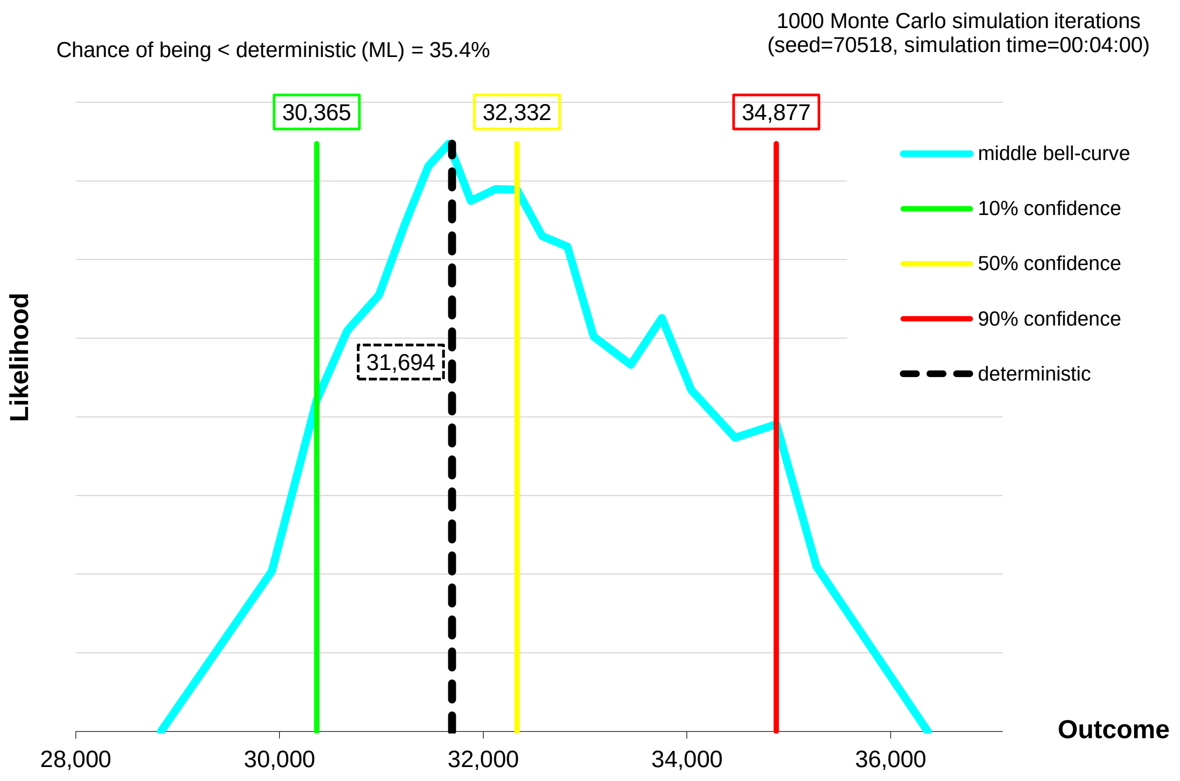


Figure 8.12.5.2. Arrisca Simulation for Component 3PE (1000 Iterations)

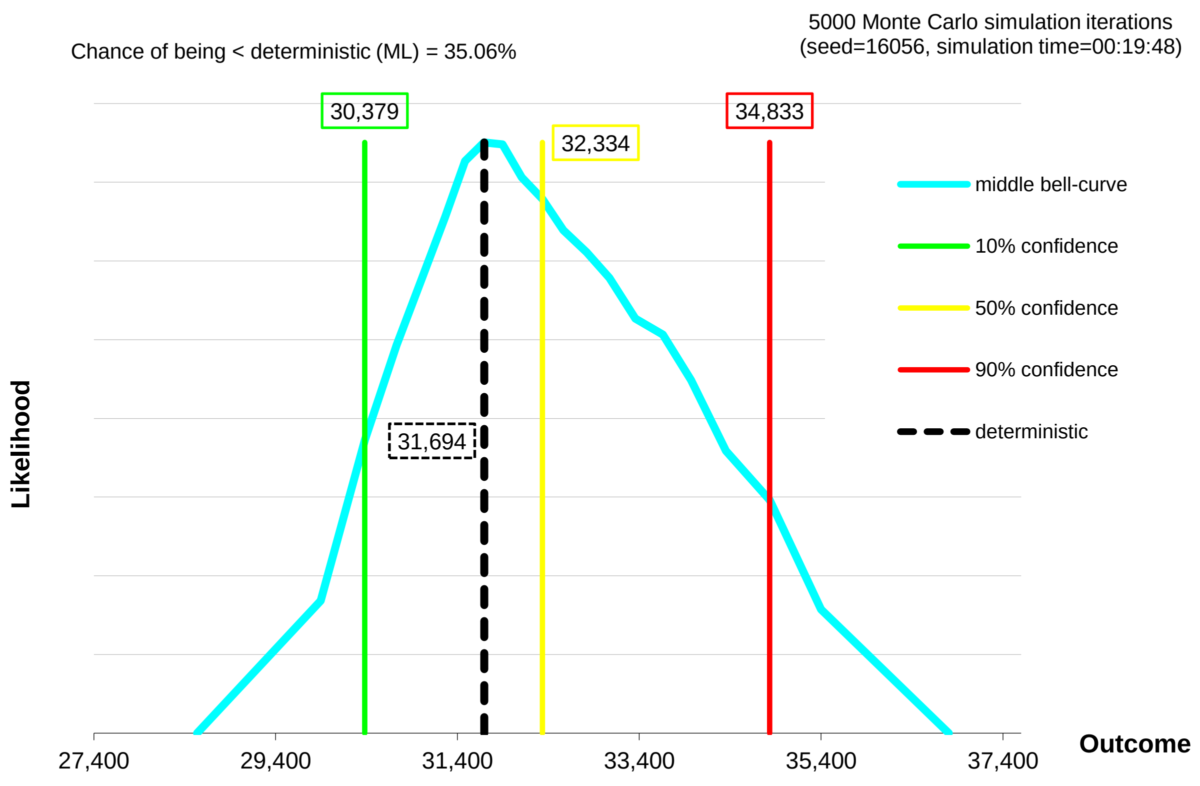


Figure 8.12.5.3. Arrisca Simulation for Component 3PE (5000 Iterations)

8.12.6 Step 6. Interpret the Results

When using riskHive Arrisca, results of the Monte Carlo simulation are generated and conveniently offered to the user for analysis and documentation. The outcome of the simulation (5000 iterations) is shown within Figure 8.12.5.3. Based upon the corresponding Arrisca report, the interpretation is given within Table 8.12.6.1 and discussed below.

Table 8.12.6.1. Final Analysis of Simulation for Heat Exchanger Costs

The deterministic (single-point from model) outcome	£31,694		
Based on a data set generated from 5000 Monte Carlo simulation iterations (seed=16056, simulation time=00:19:48)			
Chance of being < deterministic (ML) = 35.06%			
Chance of being > deterministic = 64.94%			
The average (mean) outcome is	£32,475		
The maximum outcome is	£36,804		
The minimum outcome is	£28,535		
80% of all outcomes (The Confidence Interval) were between	£30,379	and	£34,833
The Confidence Interval has a range of	£4,454		
There is a 90% chance that the outcome will be less than	£34,833		
There is a 50% chance that the outcome will be less than	£32,334		
There is a 10% chance that the outcome will be less than	£30,379		
Skew (measure of distribution symmetry)	0.224	Note: equals '0' for a normal distribution	
Kurtosis (measure of distribution tails due to outliers)	0.158	Note: equals '3' for a normal distribution	

It is evident that the analyst can interpret the results to inform the cost decision in a way that is appropriate to the preferred costing strategy. For example, it is predicted from Table 8.12.6.1 that if a ML cost of £31,694 is accepted, then there is a 65% chance (64.94%) that this cost will be exceeded. The conservative approach would be to seek funding in the region of £35,000 since there is 90% confidence that the cost will be less than £34,833. Furthermore, it appears to be unrealistically optimistic to form a decision based upon the lowest cost estimate since there is only a 10% chance that the cost will be less than £30,379. Even so, it may be the case that the decision-maker wishes to accept the lower cost estimate on the basis that management funding reserves could be made available to accommodate cost overruns due to uncertainty. The concept of 'Reserve Analysis' is discussed within Section 8.6.

8.12.7 Step 7. Document the Basis of Estimate (BoE)

The BoE can be stated as follows:

- **Purpose.** The estimate has been compiled for the purpose of demonstration and is based upon an actual material selection exercise. Full details for the context are offered within Chapter 7.
- **Traceability for the source of cost data.** Component suppliers were approached to provide cost estimates for the sea water header. Supplier responses are documented within Table 8.12.3.1.
- **Detail and explanation for calculations and results.** A simple summation cost model has been developed, as shown within Table 8.12.4.1. Modelling assumptions have been documented within the table.
- **Justification for choice of estimating method.** A 3PE technique has been applied and a cost uncertainty analysis performed using a Monte Carlo simulation. This technique is appropriate since the supplied cost data demonstrated an uncertainty range. This, in turn, strongly suggested the need for probabilistic cost estimation. As a result, the 3PE technique has allowed the likelihood (confidence) of a range of cost outcomes to be assessed.

8.12.8 Step 8. Validate the Results and Update the Cost Model

The results are considered valid since the modelling approach demonstrates the following:

- **Documented.** The BoE has been documented.
- **Comprehensive.** The cost elements within the model reflect the WBS for the manufacture, test and delivery of the component, excluding material scrap and re-work. All cost elements have been considered. None have been double-counted.
- **Accurate.** It has been verified that modelling requirements have been satisfied and that model calculations have been checked for errors. The estimate is neither too optimistic nor too conservative since a ML cost is

bounded between Min and Max likely outcomes. Therefore, realistic decision making can be made by assessing the confidence associated with each outcome. Costs within the model are based upon those actually incurred and the cost outcome is consistent with the actual cost accepted for the component.

- **Credible.** The cost model is limited to a simple summation approach with no allowance made for material scrap or re-work. These elements must therefore form part of the risk funding provision. In the absence of data defining any other PDF, the distributions for cost elements at the model input are assumed to be either triangular or rectangular. The model results have proven consistent with the actual cost incurred for the component. The modelling approach is thus considered credible.

8.13 Demonstration of Methodology – A&A Work Package Costing

Section 8.12 demonstrated all stages of the costing methodology with respect to a heat exchanger component being costed as part of a single A&A. As a supplement, this section demonstrates how the same reasoning can be applied to estimate the cost for a work package consisting of a number of As&As. Table 8.13.1 shows the A&A work package. The following cost modelling scenario applies:

- The scope of work is based upon the researcher's experience of an actual A&A work package implemented to an RFA vessel. Each A&A is referred to by title only. Full technical descriptions for the As&As are not considered necessary for the purpose of this cost demonstration.
- For the purpose of this demonstration, the estimates for each A&A are expressed only in terms of the hours required for skilled labour. For reasons of commercial sensitivity, the labour rates are not shown, the full labour breakdown is not shown and the materials breakdown is not shown.
- This demonstration has focus upon the uncertainty analysis performed within steps 4, 5 and 6 of the costing methodology. The ML costs are based upon those encountered for the actual A&A work package. 3PEs have been generated by the researcher using uncertainties appropriate for obtaining budget authorisation (i.e. a Class 3 estimate) as defined within Appendix E. The Min (-15%) and Max (+20%) uncertainty limits are taken

as the central values for the ranges given for the Class 3 estimate. Use of the higher value for the worst case (Max) scenario helps prevent unreasonable bias towards the most optimistic (Min) scenario. The approach is discussed within Section 8.7.

Monte Carlo analysis was performed using the Arrisca simulator over 10,000 iterations. Within Figure 8.13.1, the results are shown to have a good approximation to a normal PDF. Figure 8.13.2 shows the corresponding cumulative distribution. Interpretation of the results is offered within Table 8.13.2.

The results simulate that if the estimate is based upon the ML total of 56,728 hours (skilled labour), then there is a high likelihood (77.5%) that this will be exceeded. The conservative approach would be to seek funding approval in the region of 59,000 hours since there is 90% confidence that the cost will be less than 59,238. Furthermore, it appears to be unrealistically optimistic to form a decision based upon the lowest cost estimate since there is only a 10% chance that the hourly total will be less than 56,087.

Table 8.13.1. Labour Hour 3-Point Estimates for A&A Work Package

A&A TITLE	Min (minus 15%)	ML (hrs)	Max (plus 20%)
INSTALL UPDATED RO PLANT	2,295	2,700	3,240
REPLACE GAS TIGHT DOORS AT CO2 BOUNDARIES	128	150	180
UPDATE PNEUMATIC CONTROL SYSTEM	213	250	300
INSTALL ADDITIONAL FUEL STATION REEL FOR SHORE POWER	425	500	600
INSTALL RAS HYDRAULIC ROOM AFFF SYSTEM	127	150	179
UPDATE FUEL VALVE COOLING SYSTEM	153	180	216
INSTALL ADDITIONAL CO2 DRENCH WARNING BEACONS	26	30	36
UPDATE PRIMING SYSTEM FOR FIRE PUMPS	578	680	816
CONVERT SEPARATION TANK	1,700	2,000	2,400
UPGRADE SHIP I.T. NETWORK	68	80	96
REDESIGN GALLEY	2,125	2,500	3,000
UPGRADE DOMESTIC REFRIGERATION COMPARTMENTS	468	550	660
SURVEY BALLAST WATER SYSTEM	340	400	480
MOORING EQUIPMENT TESTING AND MODIFICATION	383	450	540

MARPOL CONVERSION OF WING TANKS TO WATER BALLAST	5,270	6,200	7,440
MODIFICATIONS TO RASCO ACCESS	77	90	108
REPLACE LIFEBOATS WITH UPDATES	3,825	4,500	5,400
FIT ACCESS ARRANGEMENTS TO NUC LIGHTS ON MAINMAST	213	250	300
FIT BALLISTIC SHIELDS AT GPMG & MINIGUN POSITIONS	1,360	1,600	1,920
REPLACE 05 DECK MINIGUN MAGAZINE LOCKERS	85	100	120
UPDATE CARGO FUEL PIPEWORK & VALVES	6,630	7,800	9,360
INSTALL MCAS PATROLMAN ALARM	7	8	10
REPLACE FIRE DETECTION SYSTEM	61	72	86
PROVIDE CRASH STOP FOR RADIO ROOM VENTILATION	20	24	29
UPDATE ELECTRICAL FITTINGS WITHIN GAS ENVELOPE	340	400	480
REPLACE MMS OILY BILGE PUMP	400	470	564
REMOVE AUTOKLEAN FILTERS	136	160	192
REPLACE STEERING GEAR WITH UPDATES	2,805	3,300	3,960
INSTALL FIRE MAIN ISOLATING VALVES	102	120	144
REPLACE RASCO CONSOLE	102	120	144
REPLACE CARGO OWS	2,550	3,000	3,600
FIT REMOTE ACTUATION TO DIESO CARGO VALVE D20	9	10	12
FIT INCINERATOR	5,950	7,000	8,400
INSTALL CO2 SYSTEM UPGRADES	247	290	348
UPDATE MAIN ENGINE JACKET WATER PUMPS	1,360	1,600	1,920
REPLACE BOILERS WITH UPDATED VARIANTS	7,480	8,800	10,560
INSTALL INTERNAL COMMS POSITION FOR No 2 FRPP	31	36	43
UPDATE GPI	43	50	60
UPDATE HCO RADAR TRANSCEIVER	7	8	10
IMPLEMENT ELECTRONIC CHARTING UPGRADE	85	100	120
	48,218	**56,728**	**68,073**

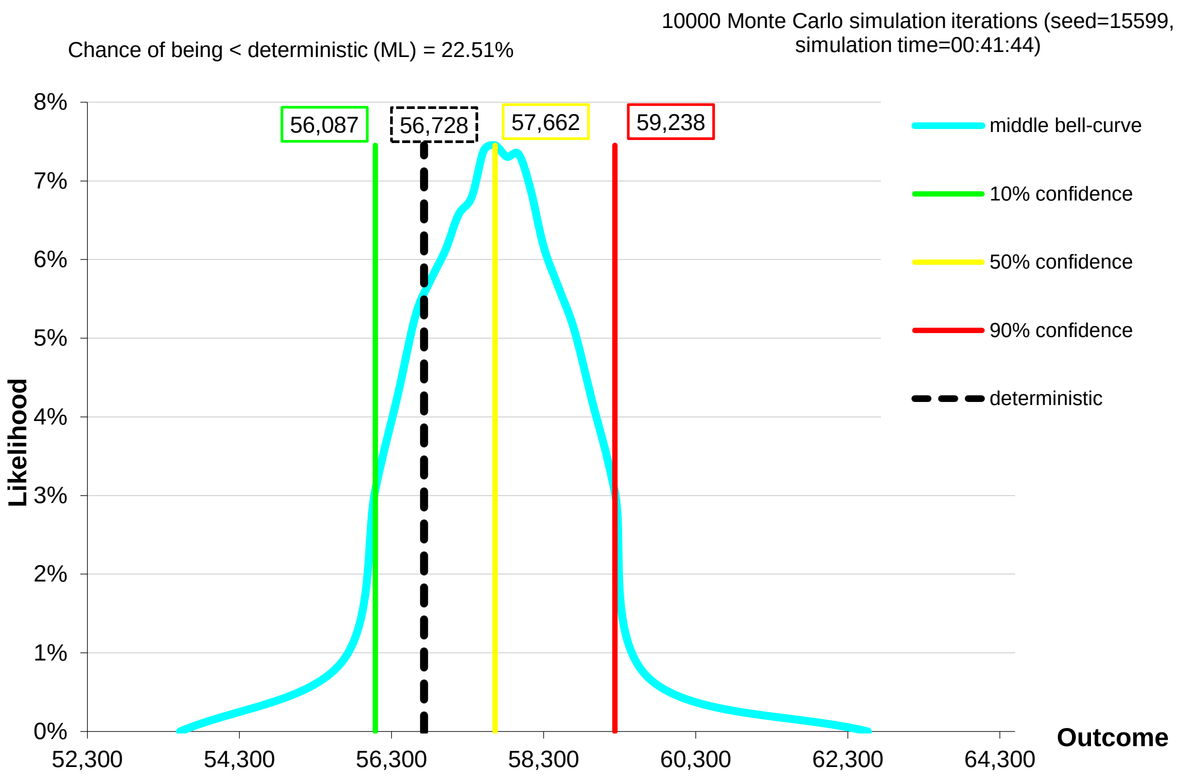


Figure 8.13.1. Arrisca PDF for A&A Work Package Labour Hours

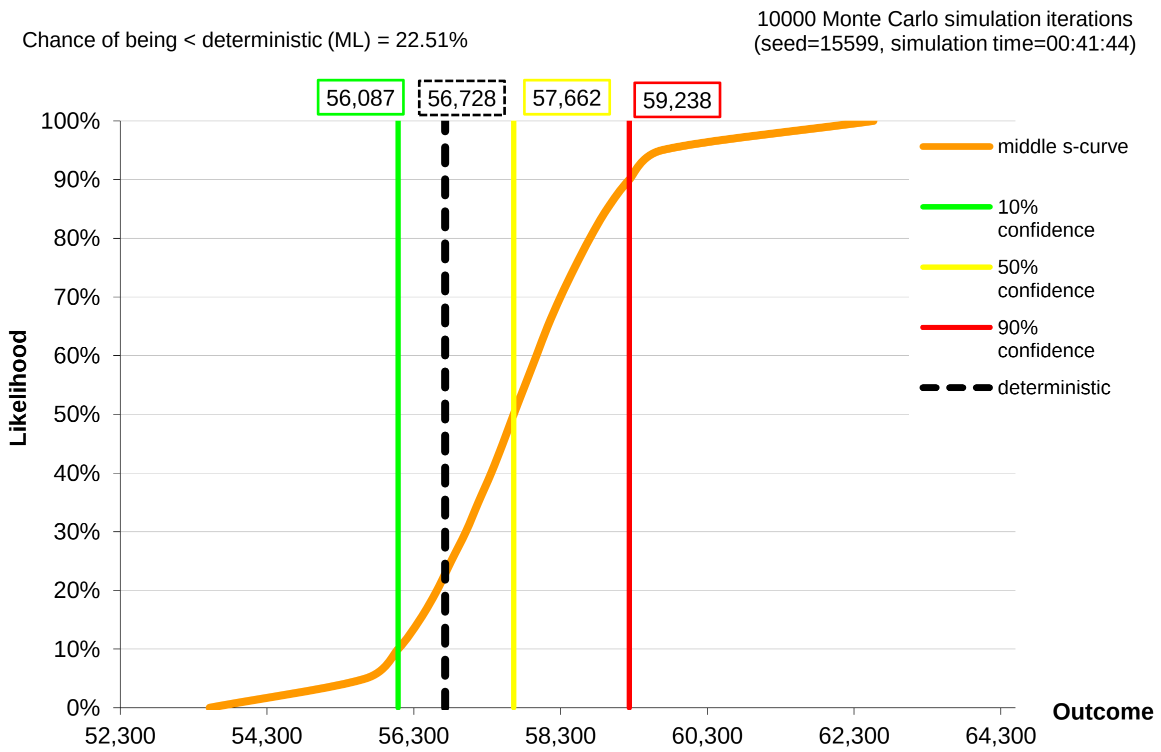


Figure 8.13.2. Arrisca CDF for A&A Work Package Labour Hours

Table 8.13.2. Analysis of Simulation for A&A Work Package Labour

The deterministic (single-point from model) outcome	56,728 hrs		
Based on a data set generated from 10,000 Monte Carlo simulation iterations (seed=15599, simulation time=00:41:44)			
Chance of being < deterministic (ML) = 22.51%			
Chance of being > deterministic (ML) = 77.49%			
The average (mean) outcome is	57,660 hrs		
The maximum outcome is	62,564 hrs		
The minimum outcome is	53,519 hrs		
80% of all outcomes (The Confidence Interval) were between	56,087 hrs	and	59,238 hrs
The Confidence Interval has a range of	3,151 hrs		
There is a 90% chance that the outcome will be less than	59,238 hrs		
There is a 50% chance that the outcome will be less than	57,662 hrs		
There is a 10% chance that the outcome will be less than	56,087 hrs		
Skew (measure of distribution symmetry)	2.833	Note: equals '0' for a normal distribution	
Kurtosis (measure of distribution tails due to outliers)	0.402	Note: equals '3' for a normal distribution	

The credibility of the demonstration lies within the application of uncertainty analysis to a key cost driver (labour hours) in a way encountered for A&A work packages, using data from an actual A&A work package for an RFA vessel.

8.14 Conclusion

This Chapter has offered a review of the cost engineering context and approach generically applicable to the procurement of defence engineering capability for the UK MoD. Since that defence capability is fundamentally publicly funded, and because of the wide range, large scale and high costs of defence programmes, the themes of 'value for money' and 'a fair and reasonable price' run throughout the discussions. Measures to gain assurance towards these themes are especially necessary where procurement is made on the basis of non-competitive tendering with single source suppliers. Regardless of whether a contract is sought by competitive or non-competitive means, the MoD must act as an intelligent customer to determine that the price is AAR.

This chapter has addressed the need, highlighted at the end of Chapter 7, to establish a credible basis-of-estimate when ‘cost’ is used as a decision making criterion. Accordingly, the chapter has offered a description of the cost engineering principles that could be used to support financial decision making applied to As&As for RFA vessels. Whilst an exhaustive treatment of ‘costing’ is considered beyond the scope of this text, the chapter is self-contained to the extent that the principles of cost engineering have been provided to a level sufficient to allow a pragmatic and practical consideration of the costs associated with As&As.

It has been explained that, in the context of As&As, cost estimates are most robust when based upon fixed shipyard quotations or based upon comparable As&As previously implemented to other ships, particularly within the same ship class. However, such data may not be available in practical situations. In this case, the uncertainty associated with cost data is generally high during the early stages of a project when full technical detail and programme impact are not yet known. For this reason, a discussion of the Monte Carlo method has been offered as a probabilistic means of simulating likely cost outcomes when cost data is uncertain. Contemporary software tools have been described with one in particular, riskHive Arrisca, being used to demonstrate the analysis functionality as an MS Excel add-in.

Building upon discussion of defence procurement, cost engineering and uncertainty analysis, a systematic methodology has been presented that can be generically applied to estimate the costs associated with individual As&As and work packages of As&As. The method is aimed at providing robust estimates on the basis that they are documented, comprehensive, accurate and credible. The chapter culminates with a demonstration of the methodology to offer assurance towards its applicability. The demonstration uses actual data for a material selection exercise and an A&A work package. The demonstration uses the functionality of Arrisca as an established software application for the analysis of cost uncertainty.

Chapter 9: Discussion

9.1 Integration of Research

The studies conducted in all chapters are synthesised according to Figure 9.1.1.

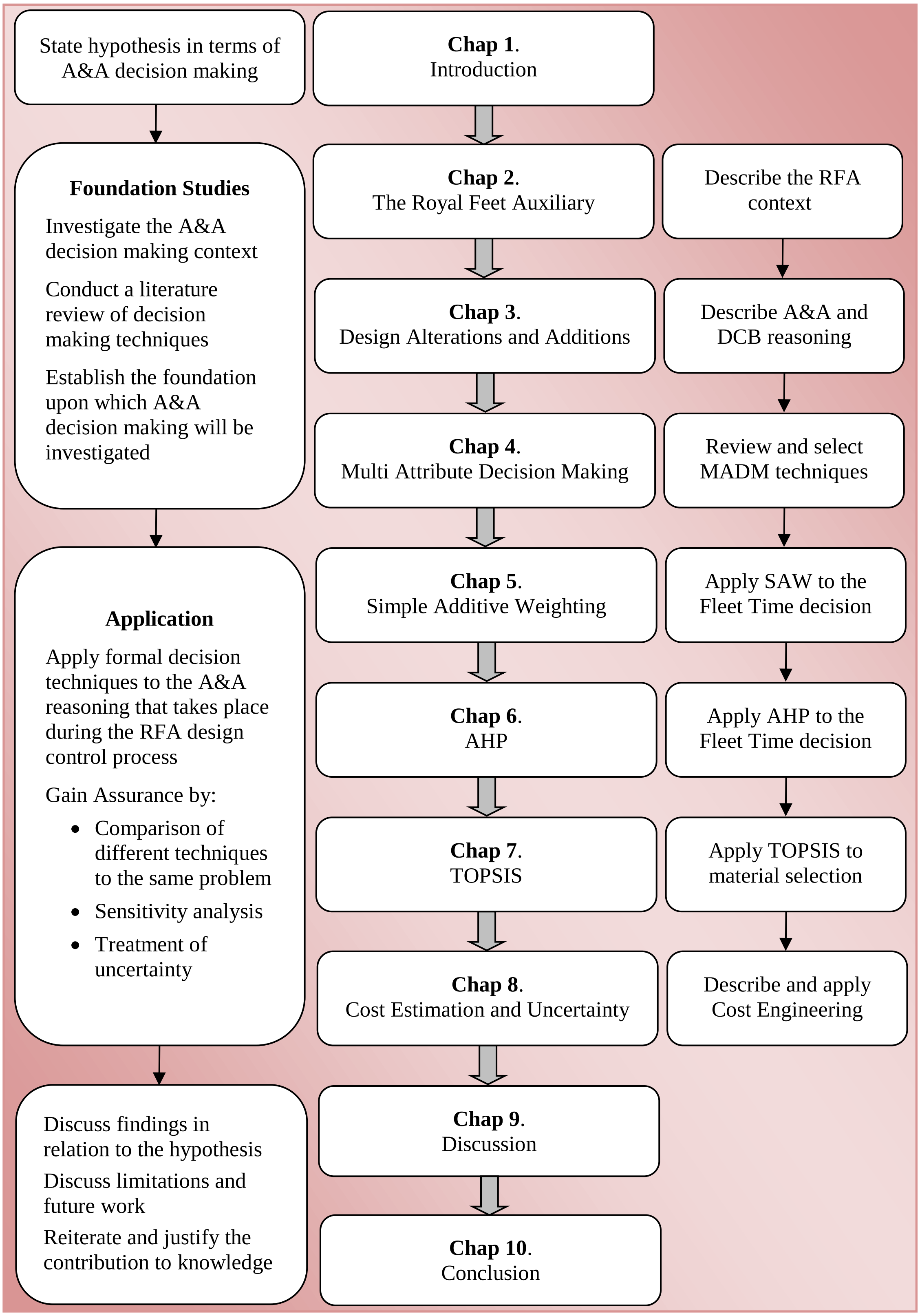


Figure 9.1.1. Synthesis of Research

This has been developed from statement, at the outset of these studies, of the research objectives and structure. The full details of interpretation, methods and structure of studies have been offered within individual chapters. The key findings for the overall body of work are now discussed and integrated. The fully justified and referenced arguments supporting this discussion are detailed within individual chapters.

The thesis has focused upon the decision making problems associated with the treatment of design changes (As&As) for RFA vessels during their service life. Accordingly, Chapters 1 to 4 have provided the methodical foundation of understanding towards the context and nature of A&A reasoning. Subsequent chapters have built upon this foundation by applying formal decision techniques. Literature reviews have formed part of this foundation. These have investigated and described what is already known about the RFA, the nature of As&As applied to the RFA and the formal techniques that could be used as decision support tools for As&As.

It has been identified that radical changes occurred between 2007 and 2017 to the shape of the RFA flotilla. During this period, pending the introduction of replacement ships, elderly vessels were kept in service after decades of operation by extensive and expensive work packages. The As&As forming part of these work packages can be understood in terms of the need to Upgrade and Update elderly ships to maintain and enhance their capability.

During the review of multi criteria decision approaches, it was seen that their value towards As&As is realised when conclusions are systematically derived towards a problem having several solution options, each of which is evaluated against key criteria.

Chapters 5 and 6 demonstrated the application of two different decision techniques (SAW and AHP) to the implementation of As&As during Fleet Time. Application of different techniques to the same problem enabled comparison of their relative merits for that application. The investigation yielded results having similar trends, offering credibility to this approach, as discussed further within Section 9.2.4.

It was seen that the AHP is fundamentally reliant upon a pairwise comparison technique to quantify what otherwise might be subjective opinions based upon the intuition and the reason of experienced experts. In so doing, a numerical scale is applied which maps a set of linguistic expressions ('equally great', 'moderately greater', 'strongly greater', etc) against a set of numeral values representing the significance of the expressions.

A problem arises in situations when it is difficult to quantify the linguistic expressions with certainty. The mapping between linguistic terms and discrete numerals may be regarded as too simple an approach to take when the boundary between discrete expressions is not discretely clear. For this reason, although not the focus of this thesis, in some applications the AHP has been combined with 'fuzzy' techniques that deal with imprecise or uncertain information. This, together with its highly structured approach, indicates that the AHP can offer a comprehensive and systematic treatment of an A&A decision problem. Whilst positive aspects associated with the AHP have become apparent during the research, it has also become apparent that the AHP imposes a high cognitive burden. Hence, it could be envisaged that a discussion between a group of practical engineers of the AHP techniques, involving reciprocal matrices, eigenvalue computation and consistency ratios, would not be a pragmatic or intuitive discussion.

Ultimately, the aim is to select a technique that is appropriate to the decision problem. With this in mind, based upon the findings of the study, it is the view of the researcher that, whilst its use should not be discounted for other A&A decisions, the AHP does not offer a proportional approach for the selection of As&As for Fleet Time implementation.

By contrast, it was demonstrated that the SAW technique did offer a convenient and intuitive approach. Indeed, the literature review supported this view and indicated a wide acceptance of the technique. Therefore, there is evidence to suggest that for the A&A application under test, and for wider A&A decision making, the SAW technique offers a particularly suitable approach that could be quickly adopted and applied by a range of decision stakeholders.

The literature review of MADM indicated that TOPSIS is particularly established as a method notable for its systematic computational approach. Chapter 7 applied TOPSIS to an actual heat exchanger material selection exercise conducted previously using a different decision technique. The outcomes of the TOPSIS exercise and the actual exercise indicated consistent trends in terms of material preference. This offers assurance towards the suitability of the technique in this application. This suitability was reinforced by a sensitivity analysis whereby the effect of changing criteria weightings was observed upon the decision outcome. This clearly indicated that the decision outcome will be influenced in the direction of the criteria weighting. It was demonstrated how this influence could be consciously made to reflect the preferences of the decision maker.

The sensitivity analysis demonstrated that the decision outcome could be biased towards ‘procurement cost’ by preferably weighting the cost attributes. This highlighted the need for robust cost estimation and led to discussion in Chapter 8 of Cost Engineering within the wider context of defence procurement. Chapter 8 explained how the MoD, when acting to procure defence capability, can act as an intelligent customer to establish a credible basis-of-estimate for As&As and so determine that the price is Appropriate, Attributable to the contract and Reasonable (AAR). Particular emphasis was placed upon the probabilistic treatment of cost uncertainty using software tools based upon Monte Carlo simulation. Chapter 8 does not claim any new development in the field of cost engineering but does establish a systematic and pragmatic methodology to gain assurance towards A&A costs on the basis that they are documented, comprehensive, accurate and credible. Integrated within that methodology is the treatment of A&A cost uncertainty using the riskHive Arrisca analyser. Application of the methodology is demonstrated using actual A&A cost data.

9.2 Validation of Research

The assertion is made by the researcher that the thesis offers valid research on the basis that it is documented, comprehensive, accurate and credible. In doing so, the researcher has elected to adopt the approach used within Chapter 8 (Section 8.11.8) to examine the validity of the cost engineering modelling. Since it offers a systematic and convenient checklist, the approach has been adapted and directed towards the overall thesis, as discussed below.

9.2.1 Documented

The studies are documented throughout the chapters. The structure of the research is offered together with the objectives, delimitation, methods, interpretation and conclusions. The arguments are traceable to their source reference material.

9.2.2 Comprehensive

The research is comprehensive in the sense that the objectives are identified, investigated and concluded, all within a scope of work that has been defined and completed. Arguments have been presented within individual chapters as discrete work packages that offer structure, detail, footnotes and references sufficient for the reader to follow and form an opinion. Whilst the focus and delimitation of the studies have been stated, the research has considered a range of A&A scenarios and a range of MADM techniques. Throughout the thesis, the studies have built upon a foundation comprising literature reviews and discussion of wider context. The studies conducted throughout individual chapters have been synthesised within the findings of the complete thesis.

9.2.3 Accurate

The techniques used throughout individual chapters have been reviewed throughout the research programme as part of the iteration between researcher and academic supervisor(s). The formal decision techniques follow established methodologies, as discussed and referenced throughout the thesis. The arguments structured around A&A reasoning and RFA in-service design control are based upon documented MoD business process and engagement with MoD SQEP.

9.2.4 Credible

The techniques and methodologies applied to the A&A decision making, including the treatment of A&A cost, have all been based upon well-established principles. Indeed, as referenced within individual chapters, the literature reviews indicate that all of the techniques have wide and proven application and consistently feature in the work of authors on the subjects of MADM and Cost Engineering. The test cases used to investigate and demonstrate the techniques are based upon A&A examples drawn from actual records across 6 ship classes, covering 9 of the 13 ships in RFA service between 2008 and 2012. Therefore, credibility can be claimed on the basis that the studies have applied accepted techniques to As&As that are representative of those found in practice.

Furthermore, the results of studies have been checked for consistency across different tests using the same data inputs. This was done when two different methods, SAW (Chapter 5) and AHP (Chapter 6), were applied to the same A&A problem, that of selecting As&As suitable for FT implementation. The outcomes demonstrated consistent trends, thereby offering assurance towards the credibility of the methodologies and results. Even so, it is acknowledged by the researcher that, in the event of disagreement between methods, additional measures will be needed to determine the reliable outcome, as discussed within Section 6.5.

When conducting the material selection exercise using TOPSIS (Chapter 7), the outcomes of the ‘thesis exercise’ and the ‘actual exercise’ indicated consistent trends in terms of material preference. Again, this offers assurance towards the technique and results. In addition, the impact of criteria weighting towards material preference was examined by performing a sensitivity analysis. This provided understanding of the effects of criteria weighting and highlighted ‘cost’ as a key driver for the decision outcome.

The credibility of the costing studies, subsequently performed within Chapter 8, lies within the application of uncertainty analysis based upon established (Monte Carlo) techniques using software packages having acceptance within the market place. Furthermore, the cost analysis for As&As used actual cost data for materials (in the case of the material selection exercise) and actual data for labour hours (in the case of the A&A work package exercise).

The role of Subject Matter Experts (SME) towards the studies has been highlighted in specific instances, such as the identification of Risk Factors during the SAW exercise (Chapter 5). Their role is discussed more fully within Appendix B. Other aspects of the studies have received review and contributions from SME, as discussed within the thesis Acknowledgements.

Finally, the overall content of the thesis reflects the experience of the researcher as a professional marine engineer working in the fields of design assurance and cost engineering between 2007 and 2017.

9.3 Contribution of Research to Knowledge

This study has proposed and demonstrated the application of techniques that, in the experience of the researcher, have not previously been applied to A&A decision making as an integral part of the A&A decision making process. This stated, there is no suggestion by the researcher that the approach currently adopted towards As&As for RFA ships lacks rigor. On the contrary, this study has investigated and explained the design control process as an established and effective means of delivering A&A decisions. The contribution offered by the researcher is to examine the current decision practice, review other decision techniques, and identify how those techniques could be applied to offer further benefits in terms of systematic reasoning and decision analysis.

This approach was applied to the investigation of implementing As&As during Fleet Time, whereupon, following discussions with SME, the constraints toward implementation were systematically identified and categorised into Risk Factors by the researcher. Whilst the consideration of constraints and risk was doubtless performed previously, it was not, to the best knowledge of the researcher, performed systematically in the way discussed during the SAW studies of Chapter 5. For this reason, the researcher has produced an academic paper (under consideration by the RFA at the time of writing) that reports the findings of those studies.

In a wider sense, this study will contribute to the awareness of the reader due to the investigation and explanation of the RFA, the nature of As&As, the MADM techniques and the principles of Cost Engineering.

9.4 Limitations of Research and Future work

Based upon the reasoning offered within Chapter 4, three established techniques, SAW, AHP and TOPSIS, were selected for application to A&A decision making. This defined the scope of investigation. Therefore, the study of other techniques involving, for example, 'fuzzy' or hybrid approaches, has not been undertaken within this research, but could form the focus of future research.

The psychology and behavioural studies associated with decision making has not fallen within the scope of this study. It may be the case that A&A decisions are subject to the influence of optimism, overconfidence and cognitive bias.

The research has necessarily been focussed on a bounded scope of work and has investigated the application of formal decision techniques to the topics of Fleet Time implementation of As&As and the selection of engineering materials. However, there are other decisions associated with A&A reasoning, as highlighted during discussion of the DCB process. Therefore, additional studies could usefully be directed towards the development of a comprehensive framework of decision support tools applicable to the wider DCB process. The wider range of DCB decisions was discussed within Chapter 4 and includes:

- Decisions to support or reject an A&A proposal.
- Decisions to categorise an A&A as Major or Minor.
- Decisions to assign Priority for an A&A.
- Decisions associated with the development of design options for an A&A.
- Decisions towards the fit opportunity of an A&A, including consideration of implementation during FT.

Additional studies could include compiling an audit of decisions previously made to identify trends and 'decision norms' for A&A proposals. At first glance this seems impossible if the assertion is conceded that As&As are independently associated with the vast range of systems across a flotilla of different ships. However, to challenge this assertion, the opposite stance could hypothesise, for example, that all As&As applied to RFA ships have fundamental commonality, in the sense that they all relate to the following design intents:

- Satisfy requirements for ship safety.
- Manage systems obsolescence.
- Provide assurance towards ship capability.

Using the records of decisions made for previous As&As, it may be possible to efficiently group them into these, or other, categories of design intent.

The approach of examining previous records could also be undertaken to inform future A&A cost estimates. The aim would be to reduce cost uncertainty by analysis of actual cost data for previous As&As, individually and as part of larger work packages. This would enable future A&A costs to be estimated by analogy to previous As&As of a comparable nature.

Chapter 10: Conclusion

As stated within the thesis objectives (Chapter 1), this research examines the hypothesis that formal decision making techniques can be applied to As&As for RFA ships.

In response, the arguments and conclusions for the studies undertaken have been offered within individual chapters, then synthesised within the thesis Discussion (Chapter 9). Based upon the evidence offered throughout, it is asserted by the researcher that this thesis constitutes a valid study that offers a contribution to knowledge in terms of the application of formal decision techniques to the design changes (As&As), and their associated costing, that take place for RFA ships during their service life.

This is not to claim that new MADM techniques have been developed or that Cost Engineering concepts have been extended. Indeed, the literature reviews conducted throughout the studies indicate that these disciplines have been extensively studied – seemingly to the point of saturation. Instead, the original contribution offered by the research lies in the systematic application of decision making techniques to A&A reasoning, for RFA ships, in a way that, to the best knowledge of the researcher, has not previously been implemented as an integral part of the A&A process.

Furthermore, a niche has been identified involving the implementation of As&As during Fleet Time. This has been the focus of particular investigation (Chapters 5 and 6), resulting in the systematic identification and categorisation of the Risk Factors constraining A&A implementation during Fleet Time. Accordingly, a paper has been produced to report the findings. At the time of writing, this had been offered to the RFA Design Authority for consideration.

The fact that focus has been placed upon niche aspects of A&A decisions indicates that the study has delimitation in terms of the scope of work addressed. In this respect, the studies have not attempted to exhaustively investigate all aspects of A&A decision making. Nor have they attempted to critically examine the vast range of formal decision techniques. Fuzzy and hybrid decision techniques, for example, have been consciously omitted from the studies in order to bound the investigation within a defined and pragmatic range of Multi Attribute

Decision Making. Furthermore, whilst the effects of cognitive bias were considered during the costing investigations (Chapters 7 and 8), the psychology associated with decision making has not been studied in relation to As&As.

In this respect, the thesis offers an illustrative, rather than a definitive, study. Hence, it is the view of the researcher that the thesis offers a credible baseline by illustrating how formal decision techniques can be applied to A&A reasoning. Those aspects not included within the thesis scope provide the impetus for further investigations.

Key themes running throughout the research are that A&A decisions should be systematically derived by Subject Matter Experts using informed judgement, and that a proportional and pragmatic approach is needed due to the schedule and cost constraints of ship programmes. These themes have been addressed, since decision making approaches have been demonstrated that are based upon formal techniques established across a vast range of fields. Furthermore, the application of a bounded scope of decision techniques has illustrated a proportional approach, involving convenient and intuitive methodologies, particularly in the case of the Simple Additive Weighting technique.

Therefore, the study has offered a pragmatic means to implement objective and credible A&A decisions. The value of this approach lies in the avoidance of design decisions based upon intuition and involving cognitive bias.

In presenting this approach, it is asserted by the author that the research has satisfied its objectives by supporting the hypothesis and offering a contribution to A&A knowledge for RFA ships, subject to the declared delimitations.

References

AACE. (2005). *Recommended Practice No. 18R-9, Cost Estimate Classification System – As Applied in Engineering, Procurement and Construction for the Process Industries* [ONLINE] Available at: https://web.aacei.org/docs/default-source/toc/toc_18r-97.pdf [Accessed 01 May 2018].

AACE. (2017). *What Are Cost Engineering & Total Cost Management?* [ONLINE] Available at: http://web.aacei.org/about-aace/what-is-cost-engineering. [Accessed 16 September 2017].

AcostE. (2017). *Provoc – Glossary of Common Project Control Terms*. [ONLINE] Available at: http://www.acoste.org.uk/uploads/terminology.pdf. [Accessed 16 September 2017].

A&P. (2017). *A&P Group Welcomes RFA Tidespring to UK*. [ONLINE] Available at: http://www.ap-group.co.uk/2017/04/03/ap-group-welcomes-rfa-tidespring-to-uk/. [Accessed 21 September 2017].

Afshari.A., Mojahed.M. & Yusuff.R.M. (2010). Simple additive weighting approach to personnel selection problem, *International journal of innovation management and technology*, 1(5), pp 511-515.

alternativeTo. (2018). *Alternative to @Risk*. [ONLINE] Available at: https://alternativeto.net/software/-risk/. [Accessed 26 May 2018].

Anderson, D. R., Sweeney, D. J. & Williams, T. A. (2003). *An Introduction to Management Science: Quantitative Approaches to Decision Making*, tenth edition, Melissa Accuna, pp. 718. ISBN: 0-324-14563-2.

Andrews A. & Pawling R. (2006). Concept Studies for A Joint Support Ship, paper presented to *World Maritime Technology Conference*, London, 2006.

Aruldoss, M., Lakshimi, T. M. & Prasanna, V.P. (2013). "A Survey on Multi Criteria Decision Making Methods and Its Applications", *American Journal of Information Systems* 1, No.1 pp 31-43.

Azar, F. (2000). Multiattribute Decision making: Use of Three Scoring Methods to Compare the Performance of Imaging Techniques for Breast Cancer Detection, *Technical Report No. MS-CIS-00-10*, Department of Computer and Information Science, University of Pennsylvania.

Belton, V. & Gear, T. (1983). On a Short-Coming of Saaty's Method of Analytic Hierarchies, *Omega, The International Journal of Management Science*, Vol 11, Issue 3, pp 228-230.

Benayoun, R., Roy, B. & Sussman, N. (1966). *Manual de Reference du Programme Electre*, Note de Synthese et Formation, No. 25, Direction Scientifque SEMA, Paris, France.

Berrittella, M.; Certa, A.; Enea, M. & Zito, P. (2007). *An Analytic Hierarchy Process for the Evaluation of Transport Policies to Reduce Climate Change Impacts*. [ONLINE] Available from the Social Science Research Network (SSRN) Electronic Paper Collection at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=962379. [Accessed 17 December 2017].

Blunn, G.W. & Jones E.B.G. (1984). The Immobilisation of Copper by Marine Fouling Microorganisms *INCRA Project No. 332A*, International Copper Association.

BMT Defence Services. (2017). *BMT AEGIR® Logistic Support Vessels*. [ONLINE] Available at: http://www.bmtdsl.co.uk/bmt-design-portfolio/auxiliaries/bmt-aegir-logistic-support-vessels/. [Accessed 29 August 2017].

BMT Group. (2017). *Defence Platform Design and Support*. [ONLINE] Available at: http://www.bmt.org/markets/defence/defence-platform-design-and-support/. [Accessed 8 August 2017].

Bottani, E. & Rizzi, A. (2006). A Fuzzy TOPSIS Methodology to Support Outsourcing of Logistics Services, *Supply Chain Management: An International Journal*, Vol.11, No.4, pp. 294 – 308.

Bridgman, P.W. (1922). *Dimensionless Analysis*, Yale University Press, New Haven, CT, USA.

Brown, C.L. (2009). Improved Methodology for Developing Cost Uncertainty Models for Naval Vessels, *Excerpt from the Proceedings of the 6th Annual Acquisition Research Symposium of the Naval Postgraduate School, Monterey, California*, Volume II: Defense Acquisition in Transition.

Cammell Laird Shipyard. (2017). *RFA FORT VICTORIA COMPLETES MAJOR REFIT*. [ONLINE] Available at: https://www.clbh.co.uk/defence-services/military-projects/rfa-fort-victoria. [Accessed 21 September 2017].

CDA. (2016). *Copper Alloys in Seawater: Avoidance of Corrosion: Publication No 225*. [ONLINE] Available at: https://www.copper.org/applications/marine/cuni/pdf/pub-225-copper-alloys-in-seawater-avoidance-of-corrosion.pdf. [Accessed 17 December 2017].

Cheng, E.W.L. (2002). Analytic Hierarchy Process (AHP): A Defective Tool when used improperly, *Measuring Business Excellence*, Vol. 6, No. 4, pp. 33 – 37.

CRS. (2010). *Navy CG(X) Cruiser Program: Background for Congress*, Congressional Research Service, Report RL34179.

Cunningham A., Wang W., Zio E., Wall A., Allanson D. & Wang J. (2011). Application of delay-time analysis via Monte Carlo simulation *Journal of Marine Engineering And Technology*, 10, pp 57-72.

Currie, D. (2011). *Review of Single Source Pricing Regulations: An Independent Report into the Single Source Pricing Regulations Used by the Ministry of Defence, Led by Lord Currie of Marylebone*, [ONLINE] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/35913/review_single_source_pricing_regs.pdf [Accessed 05 April 2018].

Defence Aerospace. (2004). *Qinetiq Announces Acquisition of HVR Consulting Services Limited*. [ONLINE] Available at: http://www.defense-aerospace.com/articles-view/release/3/43877/qinetiq-buys-hvr-consulting-(aug.-11).html. [Accessed 15 September 2017].

DE&S. (2015). Maintenance Management in Surface Ships, *BR 1313*, Issue 6, Chap 8, Ministry of Defence.

Deltek. (2017). *Deltek Acumen Risk*. [ONLINE] Available at: https://www.deltek.com/~/media/product%20sheets/acumen/acumen-risk-ps.ashx. [Accessed 15 September 2017].

Deng, H., Yeh, C.H. & Willis, R. (2000). Inter-company comparison using modified TOPSIS with objective weights, *Computers & Operations Research*, Vol.27, 963-973.

Deswal, M & Garg, S.K. (2015). Application of TOPSIS: A Multiple Criteria Decision Making Approach in Supplier Selection, *International Journal of Advanced Technology in Engineering Science*, Vol. No.3, Issue 11, pp 303-307.

Dienemann, P.F. (1966). *Estimating Cost Uncertainty Using Monte Carlo Techniques*. [ONLINE] Available at: https://www.rand.org/pubs/research_memoranda/RM4854.html [Accessed 22 November 2017].

Dikmen, Irem & Birgonul, M & Erdem, A. (2004). A critical review of risk management support tools, *Association of Researchers in Construction Management.* 1. Pp 1145-54.

Dow, D. (2004). Does the discipline of project controls really add value? *The Journal of the Association of Cost Engineers – The Cost Engineer*, 42(6), pp17-23.

DSA-DMR. (2016). *MoD Shipping Regulations for Safety and Environmental Protection*. [ONLINE] Available at: https://www.gov.uk/government/publications/mod-shipping-regulations-for-safety-and-environmental-protection. [Accessed 26 May 2018].

EUR-Lex. (2017). *Regulation (EU) No 530/2012 of the European Parliament and of the Council of 13 June 2012 on the accelerated phasing-in of double-hull or equivalent design requirements for single-hull oil tankers*. [ONLINE] Available at: http://eur-lex.europa.eu/eli/reg/2012/530/oj. [Accessed 5 September 2017].

Exxon Mobile. (2017). *Risk Management and Emergency Preparedness, Spill Prevention and Response*. [ONLINE] Available at: http://corporate.exxonmobil.com/en/environment/emergency-preparedness/spill-prevention-and-response/valdez-oil-spill?parentId=ef7252d1-7929-4f5c-9fa2-05404bde2a0f. [Accessed 21 August 2017].

Falvey R., La Chimia A., Morrissey O., Zgovu E. (2008). *'Competition Policy and Public Procurement in Developing Countries'*, CREDIT Research Paper No. 08/07, Centre for Research in Economic Development and International Trade, University of Nottingham. [ONLINE] Available at: https://www.nottingham.ac.uk/credit/documents/papers/08-07.pdf [Accessed 21 September 2017].

Frontline. (2018). *Frontline Solvers V2018 Product Overview*. [ONLINE] Available at: https://www.solver.com/products-overview. [Accessed 26 May 2018].

GAO. (2009). *GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs*. [ONLINE] Available at: http://www.gao.gov/products/GAO-09-3SP. [Accessed 22 November 2017].

Garvey P. (2000). *Probability Methods for Cost Uncertainty Analysis-A Systems Engineering Perspective*, Marcel Dekker, Inc. New York.

Government Online. (2017). *Commercially Supported Shipping Future In-Service Support*. [ONLINE] Available at: http://www.government-online.net/commercially-supported-shipping-future-in-service-support/. [Accessed 21 September 2017].

Hall, A.D. (1989). *Metasystems Methodology: A New Synthesis and Unification*, Oxford: Pergamon Press.

Hitch, C. J. (1955). 'An Appreciation of Systems Analysis'. Santa Monica, CA: RAND Corporation. Also available at: https://www.rand.org/pubs/papers/P699.html

HSE. (2017). *ALARP "at a glance"*. [ONLINE] Available at: http://www.hse.gov.uk/risk/theory/alarpglance.htm. [Accessed 18 December 2017].

Hwang, C.L., & MASUD, A.S.M. (1979). *Multi Objective Decision Making: Methods and Applications*, in collaboration with PAIDY, S.R., & Yoon, K., Berlin/Heidelberg/New York: Springer-Verlag.

Hwang, C. L., Lai, Y.J. & Liu, T.Y. (1993). A New Approach for Multiple Objective Decision Making, *Computers and Operational Research* 20: 889-899.

Hwang C. L. & Yoon K. (1981). *Multiple Attribute Decision Making: Methods and Applications*. Berlin/Heidelberg/New York: Springer-Verlag.

ICEAA. (2017). *Cost Estimating Body of Knowledge (CEBoK®)*. [ONLINE] Available at: http://www.iceaaonline.com/cebok/. [Accessed 17 September 2017].

IMO. (2017a). *Construction Requirements for Oil Tankers – Double Hulls*. [ONLINE] Available at: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/OilPollution/Pages/constructionrequirements.aspx. [Accessed 2 August 2017].

IMO. (2017b). *Marine Environment / Pollution Prevention / Oil Pollution / Background*. [ONLINE] Available at: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/OilPollution/Pages/Background.aspx#1. [Accessed 22 August 2017].

IMO. (2017c). *International Convention for the Prevention of Pollution from Ships (MARPOL)*. [ONLINE] Available at: http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx. [Accessed 22 August 2017].

INFORMS. (2018). *Operations Research & Analytics*. [ONLINE] Available at: https://www.informs.org/Explore/Operations-Research-Analytics [Accessed 5 April 2018].

Jee, D. & Kang, K. (2000). A Method for Optimal Material Selection aided with Decision Making Theory, *Materials and Design*", Vol. 21, pp. 199-206.

Kaur, P. & Kumar, S. (2013). An Intuitionistic Fuzzy Simple Additive Weighting (IFSAW) Method for Selection of Vendor, *Journal of Business and Management*, Volume 15, Issue 2, pp 78-81.

Kimber, A. (2006a). Future Ship Concepts for Repair and Maintenance at Sea, paper presented to *World Maritime Technology Conference*, London, 2006. Viewed August 2017.

Kimber, A. & Vic, A. M. (2006b). Future naval tankers – bridging the environmental gap – the cost effective solution, paper presented to *World Maritime Technology Conference*, London, 2006. Viewed August 2017.

Kirk, W.W. & Tuthil, A.H. (1991). Copper-nickel and heat exchanger systems, *Application of Copper-Nickel Alloys in Marine Systems Seminar*, South Korea

Liu N. & Maes K. (2009). The European Union's role in the prevention of vessel-source pollution and its internal influence, *The Journal of Maritime Law* 15(5), pp.411-422

Lootsma, F.A. (1990). The French and The American School in Multi-Criteria Decision Analysis, *Recherche Operationnele / Operations Research*, Vol 24, No.3, pp. 263-285.

Lucey T. (2002). *Costing*, 6th ed., Continuum, London

McNamara D.J. (2013). *Development of Models Using Monte Carlo Simulation to analyse the Efficiency of the Operation of Marine Systems*. PhD Thesis, Liverpool John Moores University, UK.

McNamara D., Cunningham A., Riahi R., Jenkinson I. & Wang J. (2017). Application of Monte Carlo techniques with delay-time analysis to assess maintenance and inspection policies for marine systems, *Proceedings Of The Institution Of Mechanical Engineers Part E-Journal Of Process Mechanical Engineering*, 231 pp 89-106

Martin C. (2016a). The Attributes and Roles of Naval Forces. In: *The UK as a Medium Maritime Power in the 21st Century,* Palgrave Macmillan, London

Martin C. (2016b). Logistics: The Arbiter of Opportunity. In: *The UK as a Medium Maritime Power in the 21st Century,* Palgrave Macmillan, London

Metropolis, N. & Ulam. S. (1949). The Monte Carlo method, *Journal of the American Statistical Association*, Vol 44 (247), pp. 335-341.

Miller, D.W. & Starr, M.K. (1969). *Executive Decisions and Operations Research*, Prentice-Hall Inc., Englewood Cliffs, NJ, USA.

MoD. (2011). *Recycling of OAKLEAF A111 Royal Fleet Auxiliary Tanker*. [ONLINE] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/27674/RFA_Oakleaf_A111_Recycling.pdf. [Accessed 13 August 2017].

MoD. (2012a). *Recycling of Ex-RFA Bayleaf, Fleet Replenishment Tanker, Disposal Services Authority*. [ONLINE] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/368722/20141029-Ex_RFA_Bayleaf_re-design.pdf. [Accessed 3 August 2017].

MoD. (2012b). *MoD to order four new RFA tankers*. [ONLINE] Available at: https://www.gov.uk/government/news/mod-to-order-four-new-rfa-tankers. [Accessed 22 August 2017].

MoD. (2013). *Recycling of Ex-RFA Fort George, Auxiliary Oiler Replenishment (Single Hull Tanker)*. [ONLINE] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/286351/DSA_ExRFA_Fort_George.pdf. [Accessed 4 April 2018]

MoD. (2015a). *SDSR 2015 Defence Fact Sheets*. [ONLINE] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/492800/20150118-SDSR_Factsheets_1_to_17_ver_13.pdf. [Accessed 18 August 2017].

MoD. (2015b). *RFA Argus and RFA Diligence out of service dates and planned replacements for both vessels, Freedom of Information Response, 2015-10463*. [ONLINE] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/484506/2015-10463_FOI_Request.pdf. [Accessed 12 August 2017].

MoD. (2016). *Disposal Services Authority (DSA) seeks expressions of interest for the sale of the former RFA Diligence; a forward repair ship of the RFA.*. [ONLINE] Available at: https://www.gov.uk/government/publications/notice-of-sale-former-rfa-diligence-a-forward-repair-ship. [Accessed 12 August 2017].

National Archives. (2014). *The Single Source Contract Regulations 2014*. [ONLINE] Available at: http://www.legislation.gov.uk/uksi/2014/3337/contents/made. [Accessed 28 September 2017].

NATO. (2017). *Defence Expenditure of NATO Countries (2010-2017)*. [ONLINE] Available at: http://www.nato.int/cps/en/natohq/news_145409.htm. [Accessed 13 August 2017].

NAVSEA. (2017). *Commander's Message*. [ONLINE] Available at: http://www.navsea.navy.mil/Who-We-Are/CMDR-Intent/. [Accessed 10 September 2017].

Nicklin, G.J.E., Lt (RN). (2008). Living with the Threat of Microbiologically Influenced Corrosion in Submarine Sea Water Systems: The Royal Navy Perspective, *9th International Naval Engineering Conference and Exhibition (INEC 2008)*, Hamburg.

O'Rourke, R. (2013). *Navy CG(X) Cruiser Program: Background, Oversight Issues, and Options for Congress, CRS Report for Congress, October 27, 2008 - RL34179*, BiblioGov, USA.

Oracle. (2017a). *Oracle Crystal Ball Overview*. [ONLINE] Available at: http://www.oracle.com/us/products/applications/crystalball/overview/index.html. [Accessed 10 September 2017].

Oracle. (2017b). *Oracle's Primavera Risk Analysis*. [ONLINE] Available at: https://www.oracle.com/applications/primavera/products/risk-analysis.html. [Accessed 15 September 2017].

Ostwald P.F. & McLaren T.S. (2004). *Cost Analysis and Estimating for Engineering and Management*, Pearson/Prentice Hall.

Palisade. (2017a). *White Papers*. [ONLINE] Available at: http://www.palisade.com/articles/whitepapers.asp. [Accessed 10 September 2017].

Palisade. (2017b). *About Palisade, Risk and Decision Analysis Solutions since 1984*. [ONLINE] Available at: http://www.palisade.com/about/about.asp. [Accessed 10 September 2017].

PMI (Project Management Institute). (2013). *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)*, Fifth Edition, Project Management Institute Inc.

Powell, C.A. & Michels, H.T. (2000). Copper-nickel for seawater corrosion resistance and antifouling - a state of the art review, *NACE International Annual Conference and Exhibition 2000*, Paper Number 00627, Orlando, Florida.

Risk Decisions. (2017). *home of Predict!*. [ONLINE] Available at: http://www.riskdecisions.com/. [Accessed 15 September 2017].

riskHive. (2017). *Products and Services*. [ONLINE] Available at: http://riskhive.com/. [Accessed 15 September 2017].

Roszkowska, E. (2013). Rank Ordering Criteria Weighting Methods – a Comparative Overview, Optimum. *Studia Ekonomiczne*, Issue 5(65), pp 14-33.

Royal Navy. (2003). *BR 8593 (17), Alterations and Additions (A&A) Procedures For Surface Ships And Submarines*. Enquiries - Whitehall London SW1A 2HB: Ministry of Defence.

Royal Navy. (2011). *BR 875 - Regulations for Royal Fleet Auxiliaries, Volume 3, Chapter 1, Para 0116 – Status of RFAs*. Enquiries - Whitehall London SW1A 2HB: Ministry of Defence.

Royal Navy. (2013). *Trials begin on state-of-the-art demonstrator for next generation ships*. [ONLINE] Available at: http://www.royalnavy.mod.uk/news-and-latest-activity/news/2013/may/31/130531-next-generation-demonstrator. [Accessed 30 August 2017].

Royal Navy. (2015). *Royal Fleet Auxiliary bids farewell to RFA Orangeleaf*. [ONLINE] Available at: http://www.royalnavy.mod.uk/news-and-latest-activity/news/2015/september/29/150929-orangeleaf-retires-from-rfa-service. [Accessed 3 August 2017].

Royal Navy. (2017a). *Royal Fleet Auxiliary*. [ONLINE] Available at: http://www.royalnavy.mod.uk/our-organisation/the-fighting-arms/royal-fleet-auxiliary#future-ships. [Accessed 3 August 2017].

Royal Navy. (2017b). *End of an era as RFA Gold Rover reaches end of service*. [ONLINE] Available at: http://www.royalnavy.mod.uk/news-and-latest-activity/news/2017/february/22/170222-rfa-gold-rover-end-of-an-era. [Accessed 3 August 2017].

Saaty, T.L. (1977). A Scaling Method for Priorities in Hierarchical Structures, *Journal of Mathematical Psychology*, 15, 234-281.

Saaty T.L. (1980). *The Analytic Hierarchy Process*, McGraw-Hill, New York, USA.

Saaty T.L. (1994). Fundamentals of Decision Making and Priority Theory with the AHP, RWS Publications, Pittsburgh, PA, USA.

Saaty T.L. (2008). Decision Making with the Analytic Hierarchy Process, *International Journal of Services Sciences*, Vol. 1, No. 1, pp 83-98.

Saaty T. L.& Vargas L. G. (2012). *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*, second edition, ISBN 0884-8289, International Series in Operations Research & Management Science, volume 175, Springer, New York, USA.

Schleich, W. & Steinkamp; K. (2003). Biofouling Resistance of Cupronickel: Basics and Experience, *Stainless Steel World Conference Nov 2003*; Maastricht.

SCRAM. (2017). *Schedule Compliance Risk Assessment Methodology*. [ONLINE] Available at: https://sites.google.com/site/scramsitenew/. [Accessed 15 September 2017].

Starr, M.K. (1972). *Production Management*, Prentice-Hall Inc., Englewood Cliffs, NJ, USA.

Stillwell W. G., Seaver D. A. & Edwards W. (1981). A Comparison of Weight Approximation Techniques in Multiattribute Utility Decision Making, *Organizational Behaviour and Human Performance*, 28, pp 62-77.

Triantaphyllou, E. & Mann, S.H. (1989). An Examination of the Effectiveness of Multi-Dimensional Decision-Making Methods: A Decision-Making Paradox, *Decision Support Systems,* Vol 5, Issue 3, pp.303-312

Triantaphyllou, E., Kovalerchuk, B., Mann, Jr., L., & Knapp, J. (1997). Determining the Most Important Criteria in Maintenance Decision Making, *Quality in Maintenance Engineering*, Vol. 3, No. 1, pp. 16-28.

Triantaphyllou, E. (2000). *Multi-Criteria Decision Making Methods: A Comparative Study*, Applied Optimization Series, Vol. 44, Kluwer Academic Publishers.

Tsaur, S.H., Chang, T.Y. & Yen, C.H. (2002). The evaluation of airline service quality by fuzzy MCDM, *Tourism Management*, Vol.23, 107-15.

UK Government. (2012). *Acquisition System Guidance (formerly the AOF)*. [ONLINE] Available at: https://www.gov.uk/guidance/acquisition-operating-framework. [Accessed 17 September 2017].

UK Government. (2013). *The EU Defence and Security Public Contracts Regulations (DSPCR) 2011*. [ONLINE] Available at:

https://www.gov.uk/government/publications/the-european-union-defence-and-security-public-contracts-regulations-dspcr-2011. [Accessed 29 September 2017].

UK Government. (2014). *Defence Reform Act 2014*. [ONLINE] Available at: https://www.gov.uk/government/collections/defence-reform-act-2014. [Accessed 28 September 2017].

UK Government. (2015). *Public procurement policy*. [ONLINE] Available at: https://www.gov.uk/guidance/public-sector-procurement-policy. [Accessed 29 September 2017].

UK Government. (2016). *Assumptions Log Template.* [ONLINE] Available at: https://www.gov.uk/government/publications/assumptions-log-template [Accessed 29 September 2017]

UK Government. (2017a). *Public Expenditure Statistical Analyses 2017*. [ONLINE] Available at: https://www.gov.uk/government/statistics/public-expenditure-statistical-analyses-2017. [Accessed 13 August 2017].

UK Government. (2017b). *Procurement at MoD*. [ONLINE] Available at: https://www.gov.uk/government/organisations/ministry-of-defence/about/procurement. [Accessed 24 September 2017].

UK Government. (2017c). *Commercially Supported Shipping (CSS) Future In-Service Support (FISS) - Through Life Support Requirement*. [ONLINE] Available at: https://www.contractsfinder.service.gov.uk/Notice/bb67a204-c2e1-4f0b-b5d9-44016130c9ed?p=@RPT0=NjJNT08=UFQxUlR. [Accessed 21 September 2017].

UK Parliament. (2016). *Defence Equipment: Decommissioning: Written question - 24277*. [ONLINE] Available at: http://www.parliament.uk/business/publications/written-questions-answers-statements/written-question/Commons/2016-01-26/24277/. [Accessed 7 August 2017].

UNCTAD, United Nations Conference on Trade and Development. (2012). *Competition policy and public procurement*. [ONLINE] Available at: http://unctad.org/meetings/en/SessionalDocuments/ciclpd14_en.pdf. [Accessed 30 September 2017].

Ung ST, Williams V, Chen HS, et al. (2006). Human Error Assessment and Management in Port Operations using Fuzzy AHP, *Marine Technology Society Journal* 40 (1): 73-86 SPR.

Vanguard Software Corporation. (2017). *Vanguard Software*. [ONLINE] Available at: http://www.vanguardsw.com/. [Accessed 15 September 2017].

Wang, T.C. & Chang, T.H. (2007). Application of TOPSIS in Evaluating Initial Training Aircraft under a Fuzzy Environment, *Expert Systems with Applications*, Vol. 33, pp. 870-880.

Washington Technology. (2006). *Deltek buys Welcom*. [ONLINE] Available at: https://washingtontechnology.com/articles/2006/03/21/deltek-buys-welcom.aspx. [Accessed 15 September 2017].

Wikipedia. (2018). *Comparison of risk analysis Microsoft Excel add-ins*. [ONLINE] Available at: https://en.wikipedia.org/wiki/Comparison_of_risk_analysis_Microsoft_Excel_add-ins. [Accessed 26 May 2018].

Yang, J., Wang, J., Xu, D. L., Kieran, O. & Ruxton, T. (2001). Formal Decision Making Tools and Their Application to Maritime Safety Assessment, *Journal of UK Safety and Reliability Society*, Vol. 21, No. 2, pp. 42-64. ISSN: 0961-7353.

Yoon, K. (1987). A Reconciliation Among Discrete Compromise Situation, *Journal of Operational Research Society*, Vol. 38. pp. 277-286.

Yoon, K. (1989). The Propagation of Errors in Multiple-Attribute Decision Analysis: a Practical Approach, *Journal of Operational Research Society*, Vol. 40. pp. 681-686.

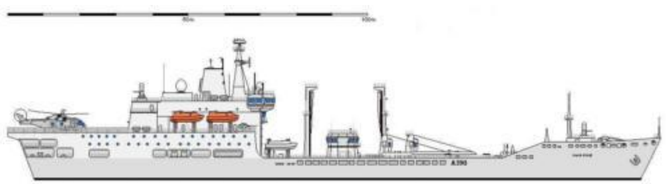
Yoon, K. & Hwang, C.L. (1995). *Multi-Attribute Decision Making: An Introduction*, Sage University Paper Series on Quantitative Applications in the Social Sciences, 07-104, Thousand Oaks, CA: Sage.

Zeleny, M. (1982). *Multiple Criteria Decision Making*. New York: McGraw-Hill

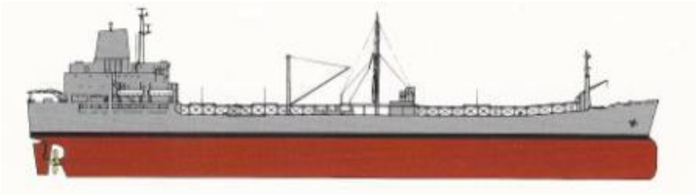
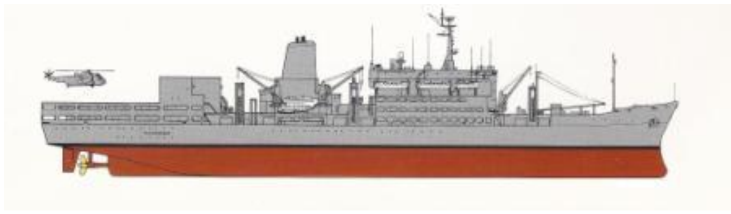
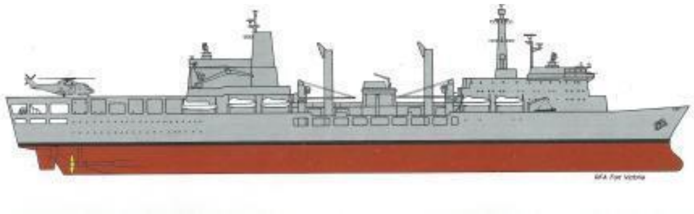
Appendices

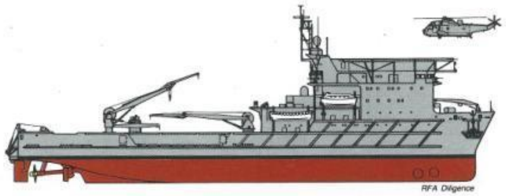
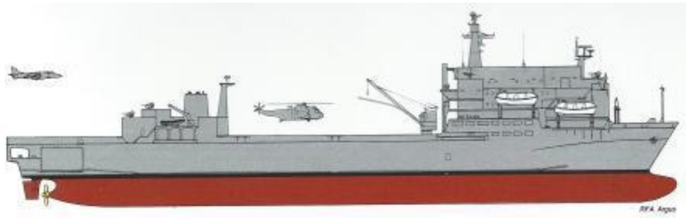
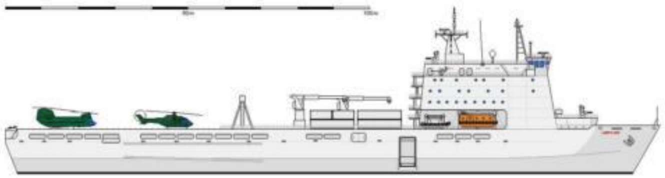
Appendix A

Vessels of the RFA between 2007 and 2017 [60]

Class	Generic Type	Ships	Image [61]	Displacement (tonnes)	Remarks
Wave-class AO	Tanker	Wave Knight (A389) Wave Ruler (A390)		31,500	Fast Fleet Tankers launched in 2000 and 2001. Crewed by RFA with provision for additional RN personnel for helicopter and weapons systems operations. Built to replace three Ol Class tankers launched in 1964 / 1965 and taken out of service by 2000.
Rover-class AOL	Tanker	Gold Rover (A271) Black Rover (A273)		16,160	Small Fleet Tankers launched in 1973 and built to replenish fuel, oil, aviation fuel, lubricants, fresh water and a limited amount of dry cargo and refrigerated stores. Fitted with a single spot flight deck without a hangar. Single Hull Tanker to be replaced by MARS tankers from 2017. RFA Black Rover taken out of service 2016. Gold Rover out of service in 2017.

[60] Details were current in Aug 2017 before the Tide Class tankers were commissioned into RFA service.
[61] Images have been sourced and reproduced with permission from the RFA Historical Society, http://historicalrfa.org/.

Leaf-class AOT	Tanker	Brambleleaf (A81) Bayleaf (A109) Orangeleaf (A110) Oakleaf (A111)		37,874	Ships launched 1975 to 1981 as merchant vessels. Taken into RFA service and renamed between 1980 and 1985 to replenish diesel fuel, aviation fuel and limited capacity of refrigerated and general naval stores. Single Hull Tanker to be replaced by MARS tankers from 2017. RFA Oakleaf taken out of service 2007 and dismantled 2011. Brambleleaf out of service 2007 and dismantled 2009. Bayleaf out of service in 2011 and dismantled 2012. Orangeleaf out of service in 2015 and dismantled 2016.
Fort Rosalie-class AFSH	Fleet Solid Support Ship	Fort Rosalie (A385) Fort Austin (A386)		23,384	Launched 1976 and 1978. Accepted into service 1978 and 1979. Replenishes food, stores and ammunition. Flight deck and hangar enables VERTREP and helicopter operations.
Fort Victoria-class AOR	Auxiliary Oiler Replenishment Vessel	Fort Victoria (A387) Fort George (A388)		33,675	Launched 1990 and 1991. Auxiliary Oiler Replenishment (AOR) ships capable of replenishing dry stores and fuel. Flight deck and hangar enables helicopter maintenance. RFA Fort George taken out of service in 2011 and dismantled in 2013.

FRS	Forward Repair Ship	Diligence (A132)		10,853	Launched in 1980. Designed as a commercial offshore maintenance and Diving Support Vessel but purchased by MoD in 1983 and converted to Forward Repair Ship with workshops for hull and machinery repairs. Also facilities for supplying electricity, water, fuel, air, steam, cranes and stores to other ships and submarines. Has sullage reception facilities. Ship removed from service in 2016. DSA arranging sale.
PCRS	Primary Casualty Receiving Ship	Argus (A135)		28,081	Initially designed as a Ro-Ro container ship and launched in 1980. Purchased and converted by MoD. Current role is Primary Casualty Receiving Facility (PCRF). Secondary role is to provide specialist aviation training facilities.
Bay-class LSD(A)	Landing Ship Dock	Largs Bay (L3006) Lyme Bay (L3007) Mounts Bay (L3008) Cardigan Bay (L3009)		16,160	Launched 2003 to 2005. Amphibious landing ships for sea lift of vehicles and embarked troops. Landing craft carried within well dock. Equipped with heavy cranes. RFA Largs Bay removed from service as part of the SDSR (2010) and commissioned in Royal Australian Navy as HMAS Choules in 2011.

Appendix B

Basis for the Research Judgements and Preferences

When determining preference for criteria weighting and evaluation of options within formal decision making techniques, unless otherwise stated, the approach taken is based upon the following.

Judgement has been informed by the professional experience of the researcher as a marine engineer working in support of the RFA between 2008 and 2012. Judgement has also been informed by subsequent experience within the fields of Cost Engineering (2012 to 2014) and design assurance for marine systems (2014 to 2017).

However, judgement has not been based solely on the experience and opinion of the researcher.

Rather, viewpoints have been sought from a range of Subject Matter Experts (SME). These are groups and individuals who, by virtue of their experience, qualifications and responsibilities, can be regarded as Suitably Qualified and Experienced Personnel (SQEP)[62]. SME includes senior ship engineers with STCW[63] qualifications, chartered engineers within the MoD Design Authority and shipyard engineers with a mix of formal qualifications and field experience exceeding 3 years.

Within the forum for Design Control Boards (DCBs), the A&A examples offered within this thesis, for the purposes of illustration and test cases, have all previously been the focus of informed collective discussion and decision making by SQEP. The DCB concept involves assembling the Naval customer (represented by NCHQ), the RFA Design Authority, the MoD waterfront project managers (i.e. those detached to the shipyard), the shipyard engineers (i.e. the suppliers) and any other required SME. The objective is to efficiently make the most effective judgements and decisions possible towards A&A proposals.

[62] The terms 'SME' and 'SQEP' are used interchangeably throughout the thesis.
[63] The International Convention on Standards of Training, Certification and Watch-keeping for Seafarers (or STCW), 1978, sets qualification standards for masters, officers and watch personnel on seagoing merchant ships.

Hence, as far as possible, this thesis has utilised the judgements and decisions previously directed towards the A&A examples.

Where new judgement or opinion has been needed to support the methodologies developed within the thesis, an attempt has been made by the researcher to seek additional discussions with the RFA and wider MoD engineering community. This has been met with limited success since responses to requests for feedback have not been representative of the full range of DCB SQEP. The likely reasons are that:

- At the time of writing, the researcher was working on projects outside of the RFA and so no longer engaged with the DCB process on a full-time basis;
- Consequently, responses to survey requests by SQEP stakeholders have necessarily been subject to other programme priorities.

Because this potentially imposes a limitation to the validity of results, an alternative, pragmatic, approach has been adopted by the researcher where SQEP discussions have not occurred. This involves judging preference and priority for A&A aspects based upon:

- The importance of the ship functional capability to which the A&A relates (with some functions being more important than others) together with:
- A category of A&A urgency (e.g. mandatory, significant or desirable).

This approach is based upon formally documented procedures for RN and RFA vessels (Royal Navy, 2003). Full details have not been reproduced within the thesis to protect sensitive information.

It is evident, therefore, that informed judgements have been made that are based upon:

- The professional experience of the researcher;
- Collective discussion between subject experts;
- Referral to formally documented procedures.

In addition, judgements have been made with quantitative basis throughout the Cost Engineering studies where actual cost data has been available.

Appendix C

Steps of the AHP Process (Saaty, 1980)

Step 1	State the decision problem.
Step 2	Put the problem in broad context – embed it if necessary in a larger system including other actors, their objectives and outcomes.
Step 3	Identify the criteria that influence the behaviour of the problem.
Step 4	Structure a hierarchy of the criteria, sub criteria, properties of alternatives and the alternatives themselves.
Step 5	In a many-party problem, the levels may relate to the environment, actors, actor objectives, actor policies and outcomes, from which one derives the composite outcome (state of the world).
Step 6	To remove ambiguity, carefully define every element within the hierarchy.
Step 7	Prioritise the primary criteria with respect to their impact on the overall objective called the focus.
Step 8	State the question for pairwise comparison clearly above each matrix. Pay attention to the orientation of each question, e.g., costs go down, benefits go up.
Step 9	Prioritise the sub criteria with respect to their criteria.
Step 10	Enter pairwise comparison judgements and force their reciprocals.
Step 11	Calculate priorities by adding the elements of each column and dividing each entry by the total of the column. Average over the rows of the resulting matrix and you have the priority vector.
Step 12	In the case of scenarios calibrate their state variables on a scale of -8 to 8 as to how they differ from the present as zero.
Step 13	Compose the weights in the hierarchy to obtain composite priorities and also the composite values of the state variables which collectively define the composite outcome.
Step 14	In the case of choosing among alternatives, select the highest priority alternative.
Step 15	In the case of resource allocation, cost out alternatives, compute benefit to cost ratio and allocate accordingly, either fully or proportionately. In a cost prioritisation problem allocate resources proportionately to the priorities.

Appendix D

Elements of a Price Estimate

D.1 The Price Build

The key components that make up a price estimate are shown within Figure D.1.1. It is evident that the selling price must take account of all the costs incurred during the provision of the product or service and must also include the profit.

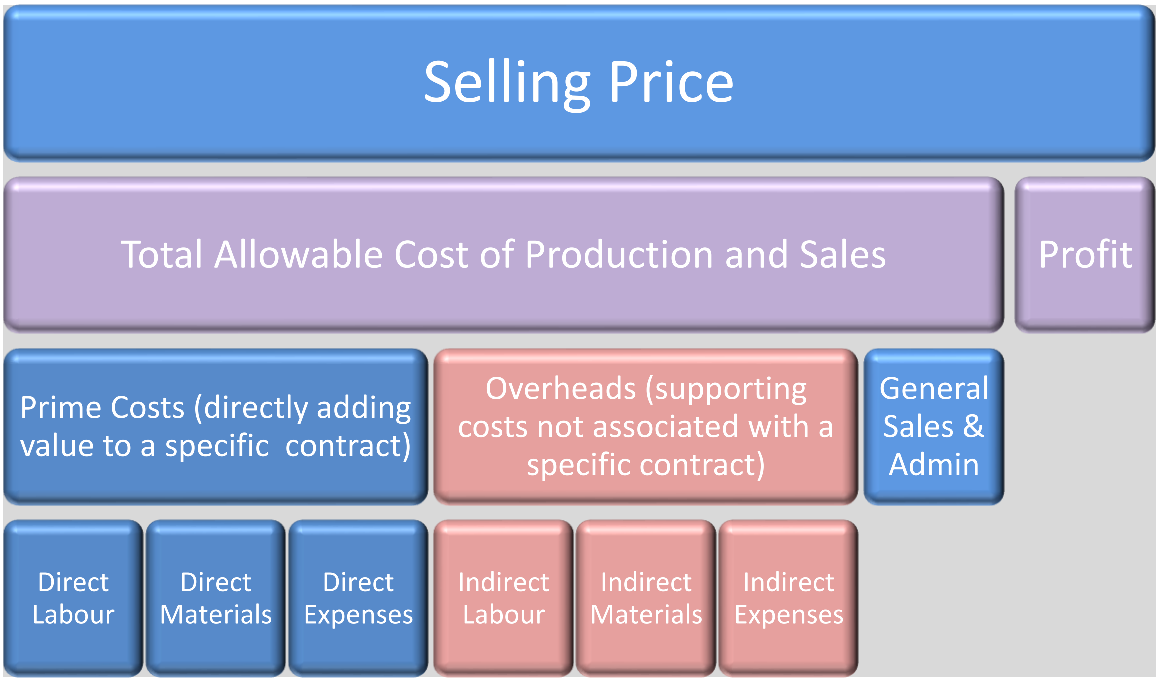


Figure D.1.1. Elements of a Selling Price Estimate [64]

Figure D.1.1 has been adapted and offered by the researcher, based upon training and professional experience as a Cost Engineer between 2012 and 2014, with the MoD Cost Assurance and Analysis Service (CAAS). Related Cost Engineering principles are fully described within the MoD Cost Engineering Directed Development (CEDD) training material and the library of CAAS business processes. Although these are for internal use and have not been published, the core underlying principles are described in detail within the standard texts given above (Ostwald & McLaren, 2004), (ICEAA, 2017), together with other text books related to the subject. Indeed, the referenced ICEAA Cost Engineering Body of

[64] Offered by the researcher based upon own cost engineering training and professional experience between 2012 and 2014.

Knowledge (CEBOK) is considered to be an industry standard and forms the basis of formal ICEAA professional experience and qualification.

The key principles are discussed as follows:

D.2 Selling Price

The principles underlying pricing of defence contracts may be illustrated with reference to the Single Source Contract Regulations (National Archives, 2014), as discussed within Section 8.1.

The price payable is determined in accordance with Eqn. (D.1).

$$P_S = (CPR \times AC) + AC \qquad \text{Eqn. (D.1)}$$

where:	(unit of measurement)
P_S = Selling Price	(£)
CPR = Contract Profit Rate	(%)
AC = Allowable Costs	(£)

For a competitive tender, a supplier will set the profit rate according to the pricing strategy adopted within the marketplace. This might involve, for example, the application of industry-standard profit margins (based upon sector analysis) or the top-down allocation of favourable pricing aimed at winning contracts from competitors. However, for single source contracts the CPR is subject to a profit formula, as defined within the SSCR, 2014. In this case, the aim is to replicate competitive market forces by measures that include applying a cost risk adjustment to the baseline profit rate and applying an incentive adjustment with respect to the performance provisions within the contract (i.e. increased performance attracts increased profit).

According to the DRA (UK Government. 2014), 'Allowable Costs' within a Qualifying Defence Contract (QDC), are those costs that demonstrate compliance with the so-called “AAR test”, i.e.:

- The cost is Appropriate.
- The cost is Attributable to the contract.
- The cost is Reasonable in the circumstances.

These attributes run throughout the following discussions of cost-types.

D.3 Prime Costs

These are the costs that can be directly associated with the provision of a particular product, be it a contract, work package or service. Whilst the specific composition of prime cost may vary between contracts, the main elements include the following:

- **Direct Labour Costs**. The total cost of employees engaged in design, production and installation for a contract, including all directly related subcontracted services and expenses.
- **Direct Material Costs**. The cost of purchased raw materials and components that directly add value to the finished product. Direct costs may include adjustment allowances that take account of factors such as learning, scrap rates and re-work.
- **Direct Expenses.** Expenses directly associated with a particular contract typically include travel, subsistence, bespoke insurance and license charges, equipment hire costs, professional and legal fees.

D.4 Overheads

Indirect costs cannot be associated with a specific contract for products or services. Rather, these are the costs associated with the support functions, without which the contract could not be fulfilled. Indirect costs are normally collected together as separate overhead accounts and include elements such as business infrastructure, buildings, facilities, maintenance, utilities and other general expenses. Insofar as overheads are essential to the product delivery (whilst not directly delivering the product), their cost must be recovered within the selling price. Whilst overheads can be recovered in a number of ways (Lucy, 2002, pp.88-122), it is common within labour-intensive industries for them to be absorbed within the charging rates applied for direct labour. This is discussed further below.

D.5 Recovery (Charging) Rates

The charging rates applied for products or services provide the means of recovering the costs incurred. The fundamental concepts of cost recovery are discussed within this section and are based upon an approach offered by Ostwald & McLaren (2004).

A charging rate for the recovery of overhead cost is given by Eqn. (D.2).

$$R_{OH} = \frac{C_{OH}}{H_{DL}}$$ Eqn. (D.2)

where: (unit of measurement)

R_{OH} = Overhead Recovery Rate (£/hr)

C_{OH} = Total Cost of Overhead (£)

H_{DL} = Direct Labour Hours (hr)

The total number of direct labour hours (H_{DL}) is being used as the absorption base for the total overhead expenditure. This means that, for each direct labour hour, a charge will be applied that will be used to pay for the cost of overheads. The use of direct labour hours as the basis for overhead recovery is appropriate within the context of a labour-intensive business such as ship-building. Other absorption bases may be used depending upon the nature of the product. For example, 'machine-hours' would be appropriate for a mechanised plant where business costs are largely associated with highly automated processes. In that case, overheads would be apportioned on the basis of 'cost per machine-hour' rather than 'cost per (direct) labour-hour'.

A charging rate for the recovery of direct labour cost is given by Eqn. (D.3).

$$R_{DL} = \frac{C_{DL}}{H_{DL}}$$ Eqn. (D.3)

where: (unit of measurement)

R_{DL} = Direct Labour Rate (£/hr)

C_{DL} = Total Cost of Direct Labour (£)

Again, the total number of direct labour hours is being used as the recovery base. When determining the appropriate direct labour rate, it is necessary for a business to accurately quantify the total cost (usually annual) of direct labour associated with the product. Cost components would be identified from company accounting records and would include salaries, insurance and pension contributions.

The total number of direct labour hours for the same period would then be derived from the summation of available productive hours across all staff directly engaged. This would include factors such as overtime-worked but would not include factors such as public holidays. Furthermore, it would be recognised that available labour hours cannot realistically achieve 100% effective utilisation, since a proportion of each working day is occupied with activity not directly productive, such as mandatory training activities and team meetings.

Eqns. (D.2) and (D.3) demonstrate how various costs can be recovered by applying charging rates appropriate to their particular nature - overheads in the case of Eqn. (D.2) and direct labour in the case of Eqn. (D.3). An alternative approach is demonstrated by Eqn. (D.4) whereby the costs of both overheads and direct labour are combined within a single recovery rate, with the direct labour hours being used as the absorption base.

$$\mathrm{CR} = \mathrm{R_{OH}} + \mathrm{R_{DL}} = \frac{\mathrm{C_{OH}} + \mathrm{C_{DL}}}{\mathrm{H_{DL}}} \qquad \text{Eqn. (D.4)}$$

where: (unit of measurement)

CR = Charging Rate (£/hr)

Appendix E

Cost Estimate Classification Matrix for Process Industries (AACE, 2005) [65]

	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges
Class 5	0% to 2%	Concept Screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget Authorisation or Control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid / tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

[65] Reprinted with the permission of AACE International, 1265 Suncrest Towne Centre Dr., Morgantown, WV 26505 USA. Phone 304-296-8444. Internet: http://web.aacei.org, e-mail: info@aacei.org.

Appendix F

Commercial Monte Carlo Based Risk Analysis Software [66]

Product Name (2004)	**Product Vendor** (2004)	**Product Application** (updated by researcher in 2018)	**Product Update and Reference** (updated by researcher in 2018)
@Risk	Palisade	Project cost/schedule risk estimation.	Numerous examples of application found (Palisade, 2017b).
Decision Pro	Vanguard Software	Setting up a project model for scenario building.	Now called Vanguard Studio (Vanguard Software Corporation, 2017).
Crystal Ball	Decisioneering	Probabilistic modelling of project variables, estimation of cost and time.	Now trading under the Oracle brand. Numerous examples of application found (Oracle, 2017a).
iDecide	Decisive Tools	Construction of project models, risk assessment.	iDecide downloads still offered on some third-party websites. Updated information for Decisive Tools not found.
Monte Carlo	Primavera	Integrates with project schedules and cost estimates to model risks and analyze cost and schedule impacts of mitigating them.	(Oracle, 2017b)
Predict Risk Analyser	Risk Decisions	Modelling project variables with probability distributions, integrated with various planning.	(Risk Decisions, 2017)
Risk+	Project Gear	Cost and schedule risk analysis tool that integrates with host model(s). Claims to reduce time and complexity by assigning uncertainty across groups of activities rather than individual inputs.	Now trading as Deltek Acumen (Deltek, 2017).
Open Plan Professional Futura	Welcom Software Technology Adlington Associates	Now Trades as Deltec Open Plan as a tool for Project Risk Management, Earned Value Management (EVM) and Cost Management.	Welcom Software Technology, WST, was a small company acquired by Deltec in 2006. (Washington Technology, 2006).

[66] Information that was current in 2004 and presented by Dikmen et al. (2004) has been extracted, adapted and updated by the researcher in 2018. The information offers a survey of products that demonstrates trends in terms of the wide ranging, and changing market for, Monte Carlo based risk analysis software. The survey does not claim to be exhaustive.

SCRAM	SCRAM Software	Collaborative effort between Australian Department of Defence, RedBay Consulting in Australia, and Software Metrics Inc. in USA. Root Cause Analysis of Schedule Slippage model (or RCASS) for major impact on schedule. Monte Carlo analysis for probability of achieving a given delivery date.	Contemporary evidence found for SCRAM – the Schedule Compliance Risk Assessment Methodology (SCRAM, 2017).
REMIS	HVR Consulting Services	Structured support for all risk management phases, integrated with other support tools (e.g. @Risk), construction of WBS, risk register, mitigation plans.	HVR acquired by QinetiQ in 2004. (Defence Aerospace, 2004).
Ris3 RisGen	Line International	Risk identification, construction of risk registers, modelling project variables and preparing mitigation plans.	Ris3 RisGen still referenced on some third-party websites but appears to be outdated. Updated information not found.
Products Added by Researcher in 2018			
Arrisca Risk Analyser	riskHive Software Solutions	riskHive offers a range of products for risk management, monitoring, analysis and control. Uses a common interface to connect with MS Excel and MS Project. Inputs for risks, opportunities, uncertainty and correlation. Built-in Monte Carlo Simulation and Analysis tools. Outputs results to MS Office applications.	(riskHive, 2017)
Analytic Solver (including Risk Solver)	Frontline Systems, Inc.	Frontline's evolutionary range of solvers includes tools for optimisation, simulation and data mining. The Risk Solver uses Monte Carlo simulation in MS Excel for risk analysis.	(Frontline, 2018)
Other Related Product Comparisons			
Comparison of Risk Analysis Microsoft Excel Add-Ins (Wikipedia, 2018). Crowdsourced Software Recommendations - Alternative to @RISK (alternativeTo, 2018)			