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Addressing the Coast Guard Fleet Mix Problem From a Value-Centric Perspective

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Marine Technology
Submission date: June 2017
Supervisor: Bjørn Egil Asbjørnslett, IMT
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Preface

This thesis is a part of my Master of Science degree in Marine Technology with specialization in Marine Systems Design at the department of Marine Technology at the Norwegian University of Science and Technology (NTNU). The work has been written during the spring semester of 2017, and the workload corresponds to 30 ECTS.

During one of my specialization courses in my fourth year, the word "value" was introduced as a way of measuring system success. In commercial maritime segments, the word "value" is often related to a system's ability to make profit over its lifetime, by assessing which design actions that can be made in order for the system to be engaged in profitable contracts. What started to fascinate me was how the word "value" could be used to assess the profitability of non-commercial maritime systems which often provide non-monetary value through their accomplished tasks. With my Master's thesis I saw the opportunity to address the coast guard fleet mix problem, a topic which has received little attention here at NTNU.

Although many challenges related to the coast guard fleet mix problem are not accounted for in this thesis, the aim of this thesis is to provide a basis to understand why the coast guard fleet mix problem is particularly complex, and how it might be assessed. Through a case study, the problem will be considered using a value-centric decision methodology, with focus on how stakeholder value can be captured during an early design phase in order to scope value-profitable coast guard fleet structures.

Trondheim, 2017-06-15

Marius Oddmund Buland

Acknowledgment

I would like to thank several people for their help and guidance throughout the process of writing this thesis. First, I would like to thank my main supervisor Professor Bjørn Egil Asbjørnslett for guiding me towards relevant literature, for discussing how to start addressing the coast guard fleet mix problem, and for giving me constructive feedback during my work throughout this semester. I would also like to thank my co-supervisor Phd. Candidate and Research Assistant Sigurd Solheim Pettersen for interesting discussions on value-centric decision methodologies, and for helping me with modeling issues in the computer software MATLAB. Further, I would like to thank my fellow student Morten Andreas Strøm for many interesting discussions considering the application of different decision-methodologies focusing on capturing stakeholder value. He is writing an interesting Master's thesis aiming to develop frameworks able to support life cycle management of uncertainty, in order to handle exogenous uncertainty. He does so by using Markov Decision Processes and Approximate Dynamic Programming to identify value robust design-strategy configurations.

Further, I would like to thank Commander Oddgeir Nordbotten, Staff Officer at SST Plan and Captain Sigurd Smith, Commanding Officer at SST Plan for giving me the opportunity to write my Master's thesis in collaboration with the Norwegian Naval Staff, and for having me at Haakonsvern Naval Base to discuss potential topics.

I would like to thank the Norwegian Coast Guard staff located at Sortland Naval base, especially Lieutenant Commander Charles Blålid, Head of section for operations at the Norwegian Coast Guard, for having me to discuss many of the challenges that has to be accounted for when considering the coast guard fleet mix problem.

Lastly, I would like to thank my girlfriend Kristin for her support and kindness during my work with this thesis.

Thank you,
Marius Oddmund Buland

Summary

The decision to acquire a fleet of coast guard vessels is typically irreversible and of longterm impact. Once vessels are bought and built, they typically remain within the fleet for a few decades. This emphasizes the importance of acquiring vessels that can remain valuable to involved stakeholders throughout their life-cycle. However, determining the optimal coast guard fleet structure is difficult due to its complexity. The coast guard fleet mix problem is particularly complex since the problem involves determining which vessel capabilities that are needed, as well as how the fleet is to be utilized. In contrast to commercial maritime fleets, where accomplished missions often yields monetary profit, a coast guard's accomplished tasks are often represented as non-monetary values. Recommending a sufficient fleet structure might therefore be somewhat diffuse as it is difficult to measure the return of these types of investments.

Over the past years, system success has been closely related to requirements and/or cost related characteristics, especially within defense acquisition programs. Due to the presence of endogenous and exogenous uncertainties, decision-makers have often tried to maximize system capability as a consequence to high marginal costs. This has often resulted in highly complex system solutions at very high cost levels which somehow ends up short in delivering their full potential. This is due to a requirement-centered mindset, and the literature suggests that decision-makers should consider value-centric design and decision methodologies.

Using the Responsive Systems Comparison method, an illustrative case study is presented focusing on assessing the coast guard fleet mix problem from a value-centric perspective. The model incorporates a set of vessel designs which are evaluated using a multi-attribute utility aggregation model. To capture future uncertainty, a set of epoch variables are established to represent potential future operating contexts. The results from the case study show that the main benefit of using the Responsive Systems Comparison method is that it allows decision-makers to include different stakeholder objectives and attribute preferences when evaluating different coast guard fleet solutions. This enables dialog and knowledge building towards finding fleet solutions that will continue to deliver value to involved stakeholders over the fleet's life-cycle. However, due to the selected multi-attribute utility aggregation model and lack of realistic data, making a recommendation of sufficient fleet structure is difficult, as the model is not able to consider operational attributes.

To improve the case study, further work on the problem should aim to collect data that can be used to represent more realistic epochs. What is particularly interesting for further consideration is how combining fleet size and mix models and simulation models with the Responsive Systems Comparison method might increase the tradespace exploration process, as it aligns the perspectives on value-centric decision making with well documented optimization algorithms. Introducing these models with the Responsive Systems Comparison method might help to describe how capable different fleet structures, presented in a tradespace, might be in responding to different contextual situations. This will hopefully enhance decision-makers' and involved stakeholders' understanding of how many vessels that are actually needed, and which vessel capabilities to include in the vessel designs by scoping cost-utility tradeoffs. Other attributes, design variables and epoch variables considered important for the coast guard fleet mix problem should be investigated.

Sammendrag

Når beslutningen om å gå til anskaffelse av en kystvaktflåte er tatt, vil denne avgjørelsen som regel være irreversibel og få langvarige konsekvenser. Etter at fartøyene som skal utgjøre strukturen er kjøpt og bygd, vil disse gjerne forbli i flåten gjennom flere tiår. Dette understreker viktigheten av å anskaffe skip som skaper verdi for involverte interessenter gjennom skipets og flåtens levetid. På grunn av høy kompleksitet er en optimal flåtestruktur for en kystvakt vanskelig å avgjøre. Flåtestrukturproblemet for en kystvakt er spesielt komplekst, da dette innebærer å avgjøre hvilke kapabiliteter det er behov for på fartøysnivå, samt hvordan flåten skal operere. Innenfor kommersielle flåtestrukturproblemer måles strukturens verdi gjerne i flåtens evne til å generere profitt. Dette er i kontrast til en kystvakt, som gjennom sitt virke utgjør en verdi som ikke like lett kan måles i profitt. Det å skulle anbefale en tilstrekkelig kystvaktstruktur vil derfor være vanskelig, da verdien av investeringen ikke like lett lar seg måle.

Gjennom de siste årene har kvaliteten på et system vært basert på rigide krav og/eller kostnadsrelaterte karakteristikker. Dette gjelder særlig innenfor militære anskaffelsesprosjekter. På grunn av både endogene og eksogene usikkerhetsfaktorer, samt høye marginalkostnader, har beslutningstakere typisk ønsket å maksimere systemkapabiliteten til systemet. Dette har ofte resultert i svært komplekse systemer med tilhørende høye kostnadsnivåer. Likevel har systemene ofte ikke levd opp til forventningene, noe som stiller spørsmål ved hvor gode investeringene har vært. Dette kan ses som et resultat av et tankesett med fokus på rigide krav, fremfor en mer verdisentrert tilnærming som forsøker å evaluere et større spenn av mulige løsninger.

Ved bruk av Responsive Systems Comparison-metoden har det blitt gjennomført et casestudie med fokus på å adressere flåtestrukturproblemet for en kystvakt gjennom en verdisentrert tilnærming. Modellen inkorporerer et sett av ulike fartøysdesign som evalueres ved bruk av en nytteverdifunksjon. For å ta hensyn til fremtidig usikkerhet har et sett av epokevariabler blitt etablert for å representere potensielle fremtidige operasjonskontekster. Resultatet fra casestudiet illustrerer en av fordelene ved bruken av Responsive Systems Comparison-metoden. Metoden tillater beslutningstakere å inkludere behovene og ønskene til flere interessenter. Dette muliggjør dialog og en felles forståelse for hvordan behovene til ulike interessenter påvirker løsningsrommet. Dette kan bidra til å finne løsninger som kan sørge for at tankene om hvilke oppgaver en kystvaktflåte bør kunne utføre i fremtiden også blir ivaretatt. På grunn av den valgte nytteverdifunksjonen og mangel på realistiske data, er det likevel vanskelig å gi konkrete anbefalinger for nødvendig

flåtestruktur for en kystvakt. Dette fordi nytteverdifunksjonen ikke tar hensyn til operasjonelle aspekter ved en kystvaktflåte.

Dersom flåtestrukturproblemet for en kystvakt skal adresseres videre bør realistiske data være på plass for å kunne generere mer virkelighetsnære epoker. Det vil være spesielt interessant å forsøke og kombinere klassisk flåtestrukturoptimering, samt simulering, med Responsive Systems Comparison-metoden. Dette kan potensielt øke forståelsen for hvilke faktorer som utgjør en bedre flåtestruktur. I tillegg bør andre relevante attributter, designvariabler og epokevariabler undersøkes nærmere.

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Chapter 1

Introduction

1.1 Background

The coast guard fleet mix problem is particularly complex. The problem involves determining which vessel capabilities that are needed, and how the fleet is to be utilized, addressing the issue of determining how many vessels that are actually needed. In contrast to commercial maritime fleets, where accomplished missions yields monetary profit, determining the optimal coast guard fleet mix is difficult, as accomplished tasks often represents non-monetary values. Recommending a sufficient fleet structure might therefor be somewhat diffuse as it is difficult to measure the return on these types of investments.

The decision to acquire a fleet of coast guard vessels is typically irreversible and of longterm impact. Once vessels are bought and built, they typically remain within the fleet for a few decades. This emphasizes the importance of acquiring vessels that can sustain valuable to involved stakeholders throughout their life-cycle. This addresses the need for methodologies that are suitable for assessing value-profitable coast guard fleet structures, by focusing on how to capture involved stakeholders' value perceptions in relation to which aspects that constitute the better coast guard fleet when the future operating context is uncertain.

This thesis is written in collaboration with the Norwegian Naval Staff, SST Plan, addressing the coast guard fleet mix problem. Due to tight budget restrictions, and uncertainty related to future operating contexts for the Norwegian Coast Guard, SST Plan wants new insight from an academic point of view considering methodologies for decision-making that can be used to assess the coast guard fleet mix problem.

1.2 Objectives

The overall objective of this thesis is to discuss and to get a better understanding of certain challenges faced when designing coast guard fleet structures, and how a value-centric design approach might help to support decision-making within this topic. In order to answer this, the following objectives are to be met in this Master's thesis:

1. Perform a literature study scoping what others have done within the field of assessing maritime fleet compositions with especially focus on coast guard- and naval fleet compositions. The candidate shall also derive relevant literature considering value-centric decision methodologies.
2. Derive the role and tasks of the Norwegian Coast Guard as an introduction to the coast guard fleet mix problem, before presenting some of the challenges faced when considering the coast guard fleet mix problem on a generic basis.
3. Briefly describe the challenges related to decision-making with multiple objectives, and how uncertainty affects the decision-making process.
4. Describe and compare different methodologies relevant for the coast guard fleet mix problem, and from this discuss why especially value-centric decision methodologies might help to support decisions in relation to this topic.
5. Present a generic and illustrative case study where a value-centric decision methodology is demonstrated for the coast guard fleet mix problem.
6. Discuss and conclude on the method applicability to assess the coast guard fleet mix problem based on results from the case study. From this, recommend further work on the topic.

1.3 Limitations

The main limitation in this thesis is related to the availability of relevant data for the case study, and to get insight into how strategic decisions are made in relation to the coast guard fleet mix problem. This thesis has been written in collaboration with the Norwegian Naval Staff. The challenges discussed during the case study are similar to some of the challenges faced by the Norwegian Coast Guard. However, it is important to emphasize that the performance attributes and design variables selected in the case study, neither represent actual values from the Norwegian Coast Guard, nor the Norwegian

Coast Guard's preferences in terms of which capabilities and number of vessels they value during different operational contexts. The author of this thesis created all performance attributes, weights and stakeholder preference levels to facilitate research purposes of how a value-centric decision methodology can be used to enhance the grounds for decision-making when assessing the coast guard fleet mix problem.

As this thesis is to be written as open source material, it will neither consider military aspects and capabilities that a coast guard might posses, nor financial and political aspects concerning decision-making strategies of major naval acquisitions.

Finding open source material considering coast guard- and naval fleet mix problems has been difficult. Many of the reviewed papers described the coast guard fleet mix problem in relation to the U.S Coast Guard, potentially narrowing the view of the problem. However, many of the challenges discussed in these papers are considered relevant on a general basis.

1.4 Structure of the Report

The structure of this report is laid out in the following way:

- Chapter 2 presents literature considered relevant for addressing the coast guard fleet mix problem from a value-centric perspective. The literature review starts by reviewing papers addressing the coast guard- and naval fleet mix problems. Further, literature considering commercial fleet renewal and fleet size and mix problems is considered. Last, state of the art research focusing on value-centric decision methodologies, naval ship design and traditional ship design is reviewed.

- Chapter 3 presents the Norwegian Coast Guard illustrating their fleet structure, role and tasks. A brief description of some of the challenges faced by the Norwegian Coast Guard is presented in order to visualize the coast guard fleet mix problem from a realistic perspective. This chapter ends with a general description of why the coast guard fleet mix problem is particularly complex. From this point on, the thesis is viewed from an academic and generic perspective. This means that assumptions and statements made during upcoming chapters are based on the thoughts of the author.

- Chapter 4 presents different decision-making methodologies based on the methodologies that were frequently mentioned in the reviewed literature. Benefits and drawbacks of the different methodologies is discussed in relation to how they can be used to address the coast guard fleet mix problem. A special focus on value-centric decision methodologies is given, describing why these methodologies might enhance the ground for decision support.

- Chapter 5 outlines the nine step version of Responsive Systems Comparison method which will be used for the case study.
- Chapter 6 gives a generic case study addressing the coast guard fleet mix problem using the Responsive Systems Comparison method by focusing on capturing stakeholder value.
- Chapter 7 presents the results from the case study, focusing on visualizing the benefits of tradespace exploration when assessing different coast guard fleet structures.
- Chapter 8 provides a discussion of the case study and corresponding results. A critical assessment of the case study will be given by discussing strategies on how the case study can be improved.
- Chapter 9 gives a final conclusion and recommendations for further work.

Chapter 2

Literature Review

The goal of the literature review is to scope what others have done within the field of evaluating maritime fleet compositions. Understanding the advantages and disadvantages of the methodologies used in previous research, will help to select the methodology best suited for answering the objectives of this thesis. Since details and strategies concerning coast guard and naval acquisitions are often classified, it has been difficult to collect extensive literature from recent time.

Radovilsky and Wagner (2014) presented the effects of an implemented optimization model, the "Boat Allocation Tool" (Wagner & Radovilsky, 2012) within the U.S Coast Guard. In Wagner and Radovilsky (2012), an initial deterministic boat allocation model was presented with the aim of finding the optimal allocation of the U.S Coast Guard's entire fleet of vessels and boats among the Coast Guard's stations nationwide. In the model, a value-at-risk inequality constraint was implemented to analyze the effects of demand uncertainty at each coast guard station. This was done in order to minimize mismatches between the stations' demand of specific mission hours, and the supply of boat hours. The implementation of the model led to a significant reduction in the number of stations with either shortages or excess of boat capacity, while at the same time minimizing the operating costs (Radovilsky & Wagner, 2014).

Farmer (1992) presented an elastic mixed-integer programming model for quarterly scheduling of the U.S Coast Guard's cutter class vessels. The benefit of the model was that it could assist the district schedulers at each Coast Guard district with quick development of feasible cutter schedules. The model implementation showed that each Coast Guard district did not miss required patrol statuses for the upcoming planning horizon. Tomko (1991) presented a method for quantifying the U.S Coast Guard's mission requirements and platform suitability. This was done in order to solve the U.S Coast Guard's force structure problem concerning reallocation of existing platforms, and the acquiring of new platforms. A linear integer optimization model was presented in order to allocate platforms to each Coast Guard district. The model sought to assure that the right platform based on mission context was allocated to the right station while assuring that each stations' resource demand was maintained. Bhargava (1991) on the other hand examined the challenges considering the decision support systems for fleet mix planning in the U.S Coast Guard. Bhargava (1991) discussed in detail how long-term planning horizons, uncertainty concerning future mission objectives, and demand for a fleet's services, make the coast guard fleet mix planning problem particularly complex. Through this thesis, Bhargava (1991) highlights the contending question related to whether the objective of the fleet mix planning problem should be to minimize the overall cost subjected to a set of performance constraints, or if the objective should be to maximize the fleet performance subjected to a set of budgetary constraints.

Crary, Nozick, and Whitaker (2002) conducted a study on naval fleet composition. The study illustrated how quantitative methods in conjunction with expert opinions can provide insight in how to size the U.S destroyer fleet. Through the analytical hierarchy process (AHP), expert opinion was gathered in order to estimate the effectiveness of a given fleet of ships through multiple stages of a war scenario. Based on the experts' opinions, distributions were obtained to evaluate which fleet compositions that had the highest probability of winning a war scenario through the implementation of a mixed integer model.

Within commercial maritime fleet size and mix- and fleet renewal problems, extensive work has been done. Multiple papers focus on handling uncertainty in terms of making good decisions. The objective is often to maximize profit or minimize the operational cost within different shipping aspects under various market context. Pantuso, Fagerholt, and Hvattum (2014) conducted a review on the available literature concerning maritime fleet renewal and fleet size and mix problems. They concluded that future research within the topic should especially focus on the renewal of fleets to better account for uncertain market behaviors and the fact that there is a large number of alternative ways for shipping companies to renew their fleet. Pantuso, Fagerholt, and Wallace (2016) addressed the fleet renewal problem with particular focus on the uncertainty aspect of acquiring new vessels. This paper presented a stochastic programming model for the fleet renewal problem. The aim of this research was to assess whether or not better decisions can be achieved by the use of stochastic programming rather than deterministic programming. The results showed that the stochastic model performed noticeably better than deterministic models using average data. This because the stochastic model could include random events with uncertain parameters. Pantuso, Fagerholt, and Wallace (2015) presented a solution scheme for a class of multistage stochastic programs in which a hierarchy of decisions emerges. This was further tested for a case addressing the maritime fleet renewal problem. The solution scheme was based on decomposition of the problem by creating a master problem treating aggregated level decisions, and many sub problems treating detailed level decisions in terms of addressing beneficial investments. They also concluded that stochastic models can give decision-makers better insight of which decision strategy to take. Halvorsen-Weare, Fagerholt, Nonås, and Asbjørnslett (2012) investigated the problem of determining the optimal fleet composition of offshore supply vessels, and their corresponding weekly voyages and schedules in order to service a given number of offshore installations from one common onshore depot. The objective of this supply vessel planning problem was to minimize the costs, while at the same time maintain reliable supply services. The suggested solution showed increased savings. However, the model presented reached its limits, and may not be beneficial to solve larger problems than presented in the study.

Kana, Shields, and Singer (2016) explored the challenges that arise in decision-making within naval design due to a complex and large decision-space landscape, and how difficulties in naval decision-making have led to various technical issues, cost overruns and schedule delays. One particular point highlighted in this study is the difficulty of measuring the return on an investment made within a navy enterprise, and that more novel approaches within decision-making must be addressed. This because there are often neither standard definitions, nor measurements that define, or let alone calculate the return on such investments. Kana et al. (2016) pointed out that the system performance expected for future operating contexts are difficult to foresee, since stakeholders' perceptions may change over time, and that naval systems are often acquired for a 20-30 year perspective. Two models from the social science literature was used through a case example, the U.S Navy Littoral Combat Ship (LCS) program, to describe why engineers struggle to understand complex decision scenarios under uncertainty.

Due to the difficulty of measuring the return on non-commercial investments, design focus might shift towards finding solutions that can be installed and operated cheaply, as reviewed by Rittel and Webber (1973). They discussed why finding scientific bases for confronting problems of social policy is bound to fail due to the nature of these problems. They emphasized how science at that point had developed to deal with "tame" problems, whereas social policy problems could not be thoroughly described as they were considered as "wicked problems". A "tame" problem could be solved by applying the "correct" algorithm finding the optimal solutions. For "wicked" problems though, the "correct" algorithm does not exist because of external and internal pressure with respect to how value preferences may vary within a society. It is therefore difficult to talk of the "optimal" solution when dealing with "wicked problems". From this, Rittel and Webber (1973) pointed out that solving "wicked" problems require decision-makers to address the problem from various perspectives, communicating how the problem might respond to various attempts.

A. Brown and Salcedo (2003) presented a multiple-objective genetic optimization methodology applied to naval ship design, aiming to derive design solutions providing high mission effectiveness. The methodology searched for non-dominated solutions for a given set of constraints, where a non-dominated solution represents a feasible solution from which no other feasible solutions exists. The objective attributes considered were mission effectiveness and cost. Through cost effectiveness plots, feasible non-dominated design concepts were displayed on a Pareto frontier from which customers can select design concepts that seem to fulfill their requirements.

Whitcomb (1998) discussed how the integration of multiple subsystems into naval ship design, while simultaneously meeting cost and effectiveness measures, makes the naval ship design problem particularly complex. This because alternative ship designs can not be built and tested in order to aid in collecting actual operation effectiveness and cost information. This is due to the cost and time involved in ship design, and that naval designs are often one of a kind. Whitcomb (1998) pointed out the need for decision support tools that can aid decision-makers in which capabilities that are needed, and how they affect the naval ship design process. The paper outlined several alternative design philosophy implementations like weighted sum, analytical hierarchy process (AHP) and multi-attribute utility theory (MAUT) for design decision-making using quantitative examples. Whitcomb (1998) concluded that using these methods might help decision-makers to quantify and characterize objectives and attributes for the design process, before any design alternatives are synthesized avoiding decision-makers being locked to specific design actions.

A. M. Ross, O'Neill, Hastings, and Rhodes (2010) discussed how the term "value" has been ever more important in order to derive design, by aligning perspectives and methods form Value-Driven Design frameworks. A series of value-centric design methodologies, including analytical hierarchy process (AHP), net present value (NPV) and multi-attribute utility theory (MAUT) were compared based on benefits and drawback. A. M. Ross, O'Neill, et al. (2010) pointed out that no method is fully complete in capturing the definition of value, and that in order to capture and quantify the ”value” of systems, decision-makers must align the quantification approach with the expected meaning of the word ”value”. By doing so, decision-makers can enhance their understanding of which aspects of a design problem that create stakeholder value.

Collopy and Hollingsworth (2009) discussed how Value-Driven Design changes the way decision-makers deal with extensive attributes. Extensive attributes were in this context described as attributes of the system or product being designed, or attributes of its components, where the system attribute is a function of component attributes. Collopy and Hollingsworth (2009) emphasized how there in Value-Driven Design frameworks are no requirements applied to extensive attributes, neither at the system level, nor the component level. Instead, engineering teams have an objective function, that converts the teams' sets of attributes into a score. The design task for the engineering team is to create design solutions that yields the highest value score while meeting requirements on the non-extensive attributes.

O. C. Brown and Eremenko (2009) pointed out how a requirement-centered mindset has led to increased system complexity and cost overruns, especially within aerospace and defense acquisitions. A value-centric mindset within complex engineering might aid decision-makers away from rigid requirements by rather assessing a variety of system solutions by scoping stakeholder preferences (O. C. Brown & Eremenko, 2009).

A recent study on naval fleet compositions focusing on capturing stakeholder value was conducted by Vascik et al. (2016). They introduced a method to conduct portfolio designs for affordability through Epoch-Era analysis by including aspects from modern portfolio theory with tradespace visualization, using a carrier strike group design case example. The research presented in this study was an extension of previous work conducted by researchers at the Systems Engineering Advancement Research Initiative (SEAri) at the Massachusetts Institute of Technology, on system affordability. The study illustrated how an initial attractive design solution might become less attractive over time due to time-varying exogenous uncertainties, influencing the value contribution of constituent systems over a portfolio's life cycle. By evaluating multiple potential carrier strike group portfolios across different epochs using system of systems attribute aggregation, discussed by Chattopadhyay et al. (2009), Vascik et al. (2016) illustrated how their approach might support decision-makers to identify robust long-term design and acquisition strategies by involving multiple stakeholder level perceptions.

Schaffner et al. (2014) introduced a method for early conceptual development of major defense systems and demonstrated the method's application to a case study of a hypothetical naval ship acquisition. His work was based on the study conducted by Schofield (2010), who investigated how to enhance affordability and operability through a coast guard cutter project case study. Through the Reponsive Systems Comparison Method (RSC), Schaffner et al. (2014) derived and evaluated multiple design alternatives in order to derive "affordable" and "valuable" naval defense solutions. Schaffner et al. (2014) concluded that the RSC method might be an approach which provides stakeholders with a deeper perspective on the affordability of systems while still in the conceptual design phase before any major commitment of resources has occurred. Stakeholders will then be able to better understand how a system will behave across various environments, as well as the trades at play between design variables and resulting expenses.

The approach presented by Gaspar et al. (2012) and Schaffner et al. (2014) has been used in several research projects at SEARi, mostly on non-maritime applications. A. M. Ross, Hastings, Warmkessel, and Diller (2004) presented a conceptual design methodology, the Multi-Attribute Tradespace Exploration methodology, which incorporates multi-attribute utility theory (as presented by (Keeney & Raiffa, 1993)) and tradespace exploration do derive value-profitable system solutions in engineering. McManus and Hastings (2006) provided a framework to aid in the understanding of uncertainties and how different techniques could be used to exploit uncertainty in complex system design. Rhodes and Ross (2010) introduced a five aspect framework for engineering of complex systems. Here, complexity is decomposed into the structural, behavioral, contextual, temporal and perceptual aspects.

A. M. Ross and Rhodes (2008a) introduced the epoch-era analysis to handle future uncertainty by representing future operating contexts as static epochs. Their conclusion was that by combining these epochs into dynamic eras, system performance could be better assessed in terms of how stakeholder needs are met through time. A. M. Ross, McManus, and Long (2008) and A. M. Ross, McManus, Rhodes, Hastings, and Long (2009) introduced the Responsive Systems Comparison Method incorporating tradespace- and epoch-era analysis focusing on stakeholders' values within system design. By always accounting for stakeholders' value through a system's life cycle, A. M. Ross, McManus, et al. (2009) emphasized how decisions at an early design stage can be better assessed.

Within the traditional ship design domain the focus has been on the structural and behavioral aspects as seen in design approaches such as the system based ship design of Levander (2012) or the set-based design by Singer, Doerry, and Buckley (2009). However, Gaspar et al. (2012) discussed how to tackle future uncertainty within ship design by also accounting for the contextual aspect, the perceptual aspect and the changes in these through the temporal aspect. Through tradespace- and epoch-era analysis, Gaspar et al. (2012) explored the behavioral, contextual and perceptual aspects of multiple design alternatives. The focus was on determining the best design that will provide continued value for stakeholders. Pettersen and Asbjornslett (2016b) investigated the problem of designing resilience into a fleet for maritime emergency response operations. By combining tradespace analysis and design structure matrices against potential system failure modes, the performance of fleets with respect to emergency response operations was evaluated. Erikstad and Rehn (2015) presented a state of the art example of methods for handling design stage uncertainty related to marine systems design. They concluded that deterministic methods do not properly evaluate the performance of ocean engineering systems in uncertain operating contexts, and that stochastic models are one way of assessing uncertainty.

Chapter 3

The Norwegian Coast Guard

3.1 Role and Tasks

The Norwegian Coast Guard is one out of four main departments within the Norwegian Navy, and the Norwegian Navy constitutes one out of five defense branches within the Norwegian Armed Forces. This means that the Norwegian Coast Guard is a standing maritime force (The Norwegian Armed Forces, 2017b). The Norwegian Coast Guard is one of Norway's most important law enforcement agencies at sea. The department performs important value missions on behalf of the Norwegian Government, assuring that Norway's sovereignty and rightful claims are maintained (The Norwegian Gouverment, 2014). The Coast Guard Act which specifies what the Norwegian Coast Guard should do and can do, gives the Norwegian Coast Guard authority to intervene on behalf of a number of state agencies under their professional management (Lovdata, 1997; SAP 97 (C) Del I A, 2014).

The Norwegian Coast Guard's tasks have traditionally been divided into naval and civil tasks (SAP 97 (C) Del I A, 2014; The Norwegian Armed Forces, 2017a). During peace time, the Norwegian Coast Guard's main priority is to monitor and control the fishery activities taking place in waters under Norwegian fisheries jurisdiction, and to assist in search and rescue operations (SAP 97 (C) Del I A, 2014; The Norwegian Gouverment, 2014). Monitoring the fishery activity includes assuring that regulations set by The Norwegian Coastal Administration are followed, where the Coast Guard Act defines which corrective measures the Norwegian Coast Guard can undertake when potential illegal activities are discovered (SAP 97 (C) Del I A, 2014; The Norwegian Coastal Administration, 2017) Roughly 70 percent of the Norwegian Coast Guard's resources are used to monitor the fishery activity subjected to the fishery jurisdiction (The Norwegian Gouverment, 2014).

The sea areas covered in the jurisdiction are Norway's territorial waters, the Norwegian exclusive economic zone, the fishery zone around Jan Mayen and the fisheries protection zone around Svalbard SAP 97 (C) Del I A (2014); The Norwegian Gouverment (2014). These areas are illustrated in figure 3.1. The total area subjected to the Norwegian fishery jurisdiction is 2.140.000 square kilometers, including the international waters and the adjacent areas. The maritime activity within these areas spread from Skagerak in the south to the High North outside Svalbard (SAP 97 (C) Del I A, 2014).

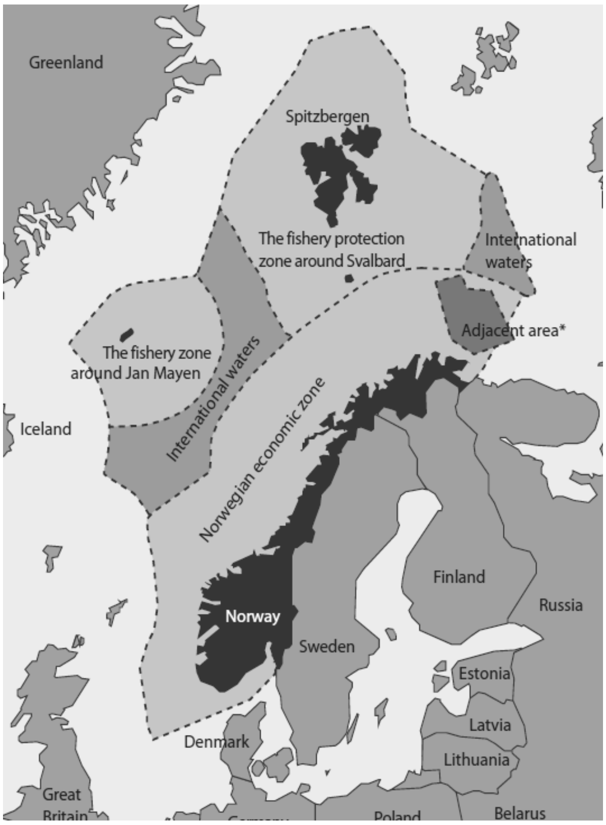

Figure 3.1: The dashed lines illustrate the large geographical area that the Norwegian Coast Guard patrol (Steinshamn, 2010).

The challenges faced along the Norwegian coast and sea areas are compound and complex. Increased commercial maritime traffic, in addition to the various fisheries, pose a risk of potential unforeseen events. In addition to their priority tasks, the Norwegian Coast Guard possesses capabilities that enables them to assist in a various set of tasks like (SAP 97 (C) Del I A, 2014; The Norwegian Armed Forces, 2017a; The Norwegian Gouverment, 2014):

- Oil recovery operations
- Tugging operations and

- Fire fighting operations
- Ice breaking
- Medical assistance and transportation
- Mechanical assistance
- Navigational assistance
- Diving assistance
- Participation in preparedness exercises
- Participation in scientific research sorties
- Military crises

3.2 Fleet Structure and Vessels

The fleet structure of the Norwegian Coast Guard consists of fourteen patrol vessels. Some are owned by the Norwegian Armed Forces, and some are owned by commercial ship yards, where the Norwegian Armed Forces lease these vessels. The vessels are designed with especially focus on good seakeeping capabilities in order to operate in the rough sea states experienced within mentioned geographical areas, and the vessels has a typical ”offshore vessel look” . An illustration of the Norwegian Coast Guard’s fleet structure is given in figure 3.2. The structure is divided into an inner- and outer coast guard structure. The Inner Coast Guard consists of six patrol vessels. Five of the vessels belong to the ”Nornen Class” and one to the ”Reine Class” which is a modified version of the ”Nornen Class” vessels. These vessels are primarily built for nearby coastal operations. The ”Nornen Class” vessels are in addition equipped with one small high speed patrol boat. This boat can operate away from the mother ship for up to two days, increasing the action range of the vessel. In table 3.1 a more detailed description of these vessels are provided.

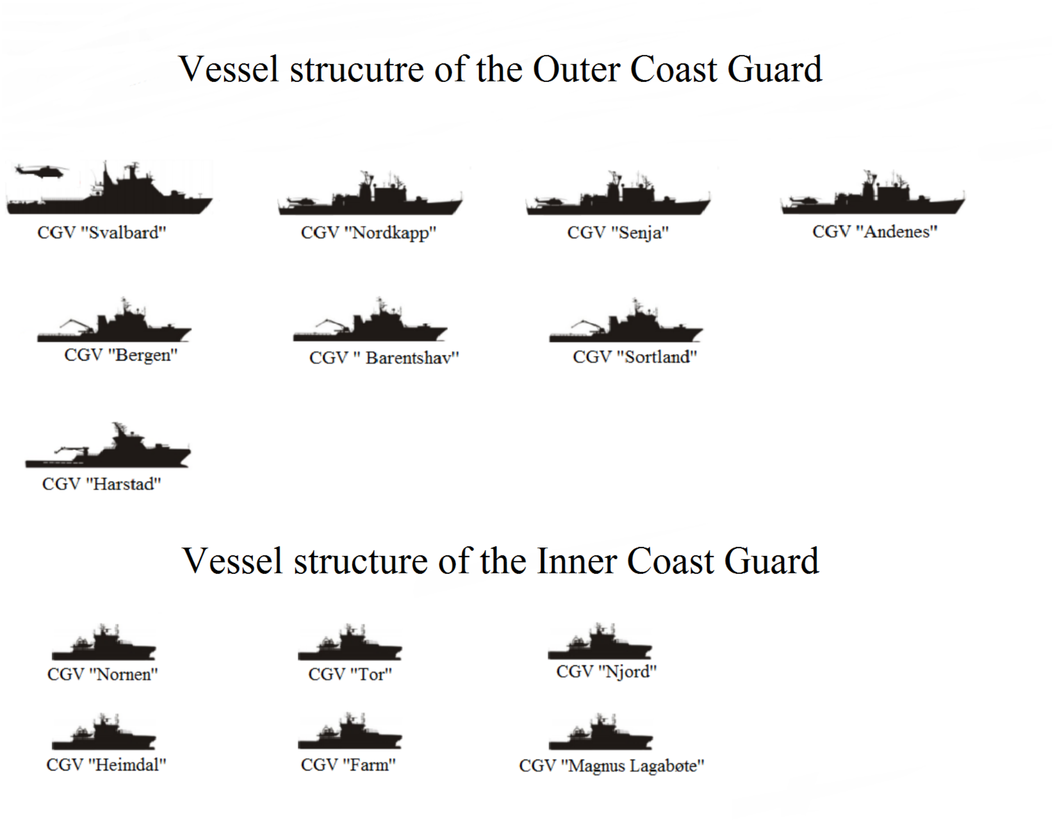

Figure 3.2: Illustration of the Norwegian Coast Guard’s fleet structure. Vessel illustrations borrowed from (Nilsen, 2014)

Table 3.1: Description of the vessels constituting the Inner Coast Guard

Vessel Class/ Vessels:	**Dimmensions:**	**Capability/ Equipment:**	**Complement**
Nornen Class:	Displacement: 810 [tonnes]	Bollard pull: 32 [ton]	13 [persons]
CGV ”Nornen”	LOA: 47,2 [m]	1 x small patrol boat	
CGV ”Tor”	Beam: 10,3 [m]	1 x Smallboat	
CGV ”Heimdal”	Draught: 4,2[m]	Oil recovery capability	
CGV ”Farm			
Reine Class:	Displacement: 791 [tonnes]	Bollard pull: 32[ton]	13[persons]
CGV ”Magnus Lagabøte”	LOA: 49,6 [m]	2 x Sea Bear Mk2	
	Beam: 10,3 [m]	Oil recovery capability	
	Draught: 4,2[m]		

The Outer Coast Guard consists of eight sea-going patrol vessels, whereas some of the vessels have the capability to operate embarked helicopters. The vessels that can operate helicopters are CGV "Svalbard" and the "Norkapp Class" vessels. The helicopter capacity is an important capability for the Norwegian Coast Guard as they can work as an extension of the vessel. This because the helicopters can cover a large geographical area within a short period of time, making sudden appearances at various fishing locations, increasing the Norwegian Coast Guard's ability to detect potential illegal activities. The helicopter capacity is also an important attribute during search and rescue missions. Eight new helicopters are in these days under implementation (The Norwegian Armed Forces Long Term Planning, 2015). CGV "Svalbard" and the "Nordkapp Class" vessels are owned by the Norwegian Armed Forces. CGV "Svalbard" is the only vessel with ice-breaking capability in the Norwegian Coast Guard's inventory.

The remaining vessels of The Outer Coast Guard can be considered as multifunctional patrol vessels. Multifunctional in these terms refers to the vessel's ability to perform expected tasks apart from conducting fishery inspections. The "Barentshav Class" and CGV "Harstad" are designed with special focus on good oil recovery- and tugging capabilities. This makes the vessels able to performe both oil-recovery and tugging operations in case of marine casualties. While CGV "Harstad" is owned by the Norwegian Armed Forces, the "Barentshav Class" is leased from Remøy Management. In table 3.2 a more detailed description of these vessels are provided.

In addition to vessels and helicopters, the Norwegian Coast Guard does also have access to aircraft assistance. The Norwegian Air Force's maritime surveillance aircrafts and the Norwegian Coastal Administration's aircraft are often hired to help assist the Norwegian Coast Guard in their activities.

Table 3.2: Description of the vessels constituting the Outer Coast Guard

Vessel Class/ Vessels:	Dimmensions:	Capability/ Equipment:	Complement
CGV ”Svalbard”	Displacement: 6 375 [tonnes]	DNV Icebreaker Polar-10	50 [persons]
	LOA: 103,7 [m]	Bollard pull: 100 [ton]	
	Beam: 19,1 [m]	2 x Smallboat	
	Draught: 6,5 [m]	Helicopter capacity	
Norcapp Class:	Displacement: 3 300 [tonnes]	Bollard pull: 70 [ton]	50 [persons]
CGV ”Nordkapp”	LOA: 105 [m]	2 x Smallboat	
CGV ”Andenes”	Beam: 14,6 [m]	Helicopter capacity	
CGV ”Senja”	Draguht: 5,6 [m]		
Barentshav Class:	Displacement: 4 000 [tonnes]	Bollard pull: 150 [ton]	24 [persons]
CGV ”Barentshav”	LOA: 93,2 [m]	2 x Smallboat	
CGV ”Sortland”	Beam: 16,6 [m]	Oil recovery capability	
CGV ”Bergen”	Draught: 6 [m]		
CGV ” Harstad”	Displacement: 3 132[tonnes]	Bollard pull: 111 [ton]	
	LOA: 83 [m]	2 x Smallboat	
	Beam: 15,5 [m]	Oil recovery capability	
	Draught: 6 [m]		

3.3 Challenges Faced by the Norwegian Coast Guard

The Norwegian Coast Guard plans their operational activity based on a yearly national strategic risk assessment (The Norwegian Coast Guards Annual Report, 2015). The purpose of this risk assessment is to assure a sustainable utilization of the fisheries' resources by controlling that the fisheries comply with the regulations set through the Norwegian fisheries jurisdiction. The Norwegian Coast Guard therefore prioritizes to route their vessels in near presences of on-going fisheries(Nationl Strategic Risk Assessment, 2017).

The vessels constituting the Outer Coast Guard operate from the Norwegian Baseline and out to the borderlines of the Norwegian Exclusive Economic zone, the fisheries zone outside Jan Mayen, the fisheries protection zone outside Svalbard and the international waters subjected to the North Atlantic Fisheries Commission (North East Atlantic Fisheries Commission, 2016; The Norwegian Coast Guards Annual Report, 2015). The Inner Coast Guard vessels are responsible for near coast operations out to the baseline (SAP 97 (C) Del I A, 2014; The Norwegian Coast Guards Annual Report, 2015). The need for search and rescue-, oil recovery and tugging operations, as well as the other tasks mentioned in section 3.1 are hard to foresee. How the Norwegian Coast Guard should respond to these events is regulated through the Norwegian Coast Guard Act (Lovdata, 1997).

The Norwegian Coast Guard is funded for a given number of patrol days by the Norwegian Government, based on recommendations from the national strategic risk assessment (The Norwegian Coast Guards Annual Report, 2015; The Norwegian Gouverment, 2014). A patrol day represents one day in which a vessel is operative and on patrol. In contrast to commercial vessels and fleets, the Norwegian Coast Guard does not achieve any profit by performing their tasks. What is important to understand is the value of the marine resources that the Norwegian Coast Guard contributes to manage and control, as well as the value of the preparedness by the Norwegian Coast Guard with respect to eventual marine casualties. The number of patrol days performed by the Norwegian Coast Guard during a year is therefore an important indicator of the Norwegian Government's "value for money".

With such a large geographical area to cover, and with a large and complex mission portfolio, many considerations have to be accounted for when designing the fleet structure. Especially when considering what the future might potentially bring. During the last years, the Norwegian Coast Guard has started to notice an increase in the fishery activity. Due to climatic change, the fishery has started to take place at geographical locations previously not experienced as a result of extended pasture-lands for the fish. This challenges the Norwegian Coast Guard's ability to be present at various locations simultaneously (The Norwegian Coast Guards Annual Report, 2015). In addition, great excitement related to future developments in the High North with respect to both the fisheries and commercial maritime segments is ever more present, as outlined in Sandvik and Narvik (2009); The Norwegian Gouverment (2017). This rises questions concerning what type of fleet structure the Norwegian Coast Guard should have in the years to come based on expected missions. What types of vessels and how many of each vessel type needed, leads to the coast guard fleet mix problem, which is particularly complex.

3.4 The Coast Guard Fleet Mix Problem

Bhargava (1991) defined the coast guard fleet mix problem as the determination of which naval assets and how many of these assets to include in a fleet. An asset in this relation is a component that is capable of operating on its own or together with other assets in order to fulfill some, or all missions expected from a coast guard. The assets of interest for a coast guard are primarily patrol boats, patrol vessels, helicopters and aircrafts (Bhargava, 1991).

A recent paper on this topic was given by O'Rourke (2015) concerning cutter procurement for the United States Coast Guard. O'Rourke (2015) discussed how budgetary constraints affect the U.S Coast Guard's fleet mix problem in terms of determining what types of asset capabilities that are needed, as well as the number of assets. The paper illustrated how reduced funding might suggest a fleet composition which contains fewer vessels than the U.S Coast Guard recommends, and how this is contradictory in terms of which statutory mission objectives that are expected, and how this potentially might lead to mission gaps. This because missions required from the U.S Coast Guard are expected to increase in the years to come, potentially addressing new mission capabilities and simultaneous presences at various geographical locations. The questions highlighted are whether the fleet structure should be increased, the statutory missions reduced, or both (O'Rourke, 2015).

In general, determining the optimal mix and size, as well as the effectiveness of a particular coast guard fleet, has proven to be difficult (O'Rourke, 2015; Schofield, 2010; Tomko, 1991). Tomko (1991) and Bhargava (1991) described that determining the optimal fleet size for a coast guard is particularly challenging due to the difficulty in forecasting the exact mission requirements, as well as an asset's suitability and availability for an upcoming period (Bhargava, 1991; Tomko, 1991). In parallel to this, the coast guard fleet mix problem is constantly evolving due to the uncertain interactions of internal and external pressures (Kana et al., 2016). This because a diverse set of stakeholders are involved in the fleet mix problem (Schofield, 2010). With assets of an expected life-cycle of up to 30 years, it is likely that stakeholders' perceptions of what a coast guard should do will change over time. This questions which capabilities that are needed, as well as the number of assets needed (Kana et al., 2016; Schofield, 2010).

Due to the likelihood of stakeholders' perceptions changing, the coast guard fleet mix problem must be viewed from different perspectives Bhargava (1991). Based on the literature reviewed in chapter 2, and the challenges described in this section, determining the trade-offs between provided resources and mission effectiveness seems to be the core challenge when selecting a sufficient coast guard fleet structure. In contrast to commercial maritime fleets, where accomplished tasks and mission effectiveness yields monetary profit, measuring the effectiveness of a coast guard fleet seems difficult since their accomplished tasks often represents non-monetary values. Establishing the "correct" measures for determining mission effectiveness might therefore be somewhat diffuse.

As discussed by both Bhargava (1991) and A. Brown and Salcedo (2003), it is always possible to create scenarios in which a single measure for mission effectiveness is optimized. For example, increased area coverage is likely to reduce illegal activities, but has on the other hand little effect on the amount of marine casualties that happen and how a coast guard can respond to such events. Here, response time might be considered as a more representative measure. If a coast guard is expected to perform a various set of tasks, several measures have to be combined in order to describe a fleet's effectiveness (Bhargava, 1991; A. Brown & Salcedo, 2003). The question becomes how one can determine these measures. One way of assessing effectiveness measures is through the establishment of performance measures (A. Brown & Salcedo, 2003). Performance measures are often used to describe how well specified mission objectives are fulfilled during a given period (Bhargava, 1991; A. Brown & Salcedo, 2003). However, determining the "right" performance measures, describing what constitutes the "better fleet", is difficult since selected measures might result in misleading interpretations. For example, using the number of detected violations, or number of performed inspections as performance measures might be plausible. One could have performed numerous inspections within some areas of responsibility, while not being present at other locations simultaneously. Statistics might then present the performance results as good, while in fact the performance might have been poor. Decision-makers must therefore be aware of how to use statistics appropriately.

Bhargava (1991) described that before decision-makers can start defining mission performance measures for a coast guard fleet, activity measures have to be established. Activity measures help indicate what types of activity levels one could expect, in which a coast guard fleet has to be present. From this, capability needs, based on how the fleet is to be utilized, can be specified. These types of measures are not concerned with actual mission performance, but rather describe what is needed in order for a fleet to fulfill its missions. Bhargava (1991) distinguished between two types of activity measures: those describing capabilities of individual vessel designs, and those aggregating activities over an entire fleet(Bhargava, 1991). Individual vessel capability measures might be: vessel range, speed, equipment or crew size. These measures are relevant as they help to describe how well a particular vessel can respond to various mission demands. Aggregating these measures to the fleet level might help decision-makers to describe the patrol capability of an entire fleet, and how much operating time that is needed in order for the fleet to fulfill its missions (Bhargava, 1991).

Once the need for individual vessel capabilities, and aggregated activity measures for the fleet are established, the question becomes how the fleet should to be utilized. In order to determine how many assets to acquire, one has to determine what types of resources that are needed where, when and to what extent (Tomko, 1991). Ideally, the coast guard should have an optimal mix of assets for each time period considered. However, searching for this optimality is difficult since the demand for a coast guard's services may vary. In relation to this, the question becomes whether or not it is a good idea to have the "optimal" fleet, or if it instead might be sufficient to consider either and over- or undercapacity for some periods (Bhargava, 1991). This expands the coast guard fleet mix problem to also becoming a multi-period and multi-item inventory management problem, determining how each asset should be utilized, as well as the determination of when to acquire and retire assets (Bhargava, 1991; O'Rourke, 2015).

In relation to this, an interesting statement given by Bhargava (1991) is that there are perhaps no unique measures that can describe how "good" a particular coast guard fleet mix is. This because there are no widely accepted sets of constraints that lets decision-makers define the problem. This is due to the fact that several groups are interested in, and affected by the coast guard fleet mix problem, emphasizing the difficulty of measuring the "correct" and required performance (Bhargava, 1991). This was also highlighted by O'Rourke (2015) which illustrated how various coast guard fleet compositions might meet different mission demands under the influence of various stakeholders' perceptions.

Form this, it becomes clear that determining which capabilities and resources that are needed for a coast guard fleet requires novel decision-making methodologies that allows decision-makers to asses the problem at multiple levels. Coincident with this assumption, the methodologies must allow decision-makers to include the effects of future uncertainty in order to reduce the risk of having fleet solutions that do not fulfill stakeholders' expectations.

Chapter 4

Value-Centric Decision Making

4.1 Decision with Multiple Objectives

The implications for decision-making arise when decision-makers have to choose between multiple alternatives. When trying to make "good" decisions, the decision-makers must weight the upside and downside of each alternative. For effective decision-making, decision-makers must be able to forecast the potential outcomes of each alternative, and from this determine which alternative that "best" meets the future expectations (Shapira, 1997). However, using only one evaluation criterion in choosing the "best" alternative is not unique (Papalambros & Wilde, 2000). An evaluation criterion will be influenced by many factors. Examples of such factors are the design application, timing, point of view, judgment of the designer, cash flows, as well as stakeholder's preferences. An initial decision criterion may change over time as a result of changed stakeholder expectations. This questions the "goodness" of a selected alternative (Papalambros & Wilde, 2000; Shapira, 1997).

Gaspar et al. (2012) discussed how to tackle future uncertainty within ship design by also accounting for the contextual aspect, the perceptual aspect and the changes in these through the temporal aspect, based on the five aspects taxonomy presented by (Rhodes & Ross, 2010). Figure 4.1 illustrates the five aspects of complexity in ship design presented by Gaspar et al. (2012).

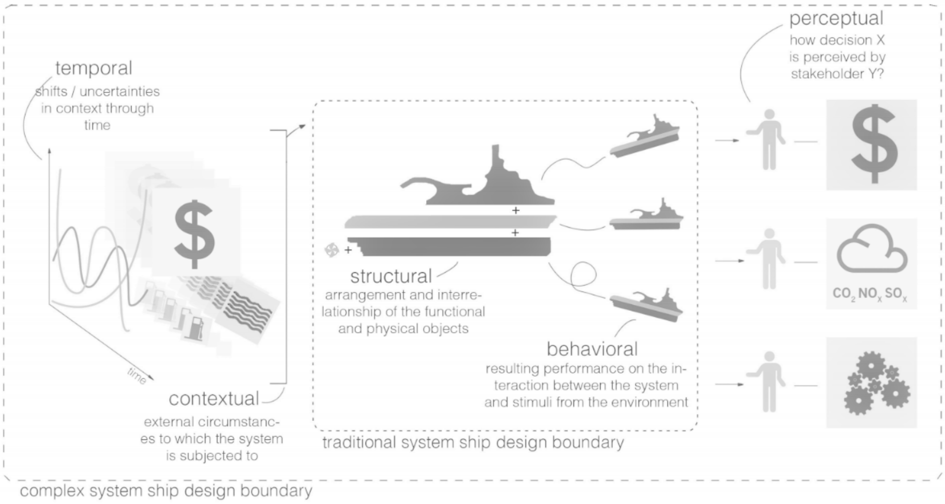

Figure 4.1: The five aspects of complexity in ship design (Gaspar et al., 2012).

By extracting these assumptions to the fleet level, decision-makers must understand how changes to the temporal and contextual aspects affect the structural and behavioral aspect of each vessel design constituting the fleet. This will have high implication on how the fleet meets the elicited needs of a diverse set of involved stakeholders. When considering the composition av alternative fleet structures, the human-system dimensions face greater challenges in terms of understanding what provides system value, as reviewed by Kana et al. (2016). The perceptual aspect seeks to understand how the 'value' of system concepts are perceived by involved stakeholders, as both the temporal and contextual aspects change over time. This because future uncertainties may influence the relative importance of what each stakeholder values in order for the system to be successful, making it difficult to select the "optimal" design solution when the objectives may vary (Rhodes & Ross, 2010).

4.2 Understanding Uncertainty

Determining what the future will bring over a system's life time is impossible. However, it is important to understand the range of circumstances that might occur, and take into account the range of future possible outcomes (de Neufville & Scholtes, 2011). This rises the question on how to deal with future uncertainty when designing complex systems.

McManus and Hastings (2006) described uncertainties as "things that are not known, or only known imprecisely". Future uncertainties will have an effect on decisions made, and some decisions have to be made before all relevant facts are known (Hillier & Lieberman, 2005). When it comes to assessing future requirements, decision-makers can either choose to consider *most-likely* scenarios or *mean values* in forecasting the future, or they can account for a range of multiple future uncertain parameters (de Neufville & Scholtes, 2011). Forecasting the future through most-likely scenarios or by the use of mean values, neglect the potential of fluctuation in central variables representing the system's expected performance. This may lead to bad decisions, as discussed by Savage (2009). Instead, decision-makers should be aware of how potential trend-breakers and disruptive events may affect the system performance in future contexts, and by this account for uncertain future parameters (de Neufville & Scholtes, 2011; Schultz, Mitchell, Harper, & Bridges, 2010). Lin, de Weck, de Neufville, and Ye (2013) handled uncertainty by grouping uncertainties by how they can be influenced, as described below:

- **Endogenous uncertainty**
  Uncertainty that can be actively influenced or managed by decision-makers. An example might be to enable vessels to operate in arctic regions by strengthening their hulls.
- **Exogenous uncertainty**
  Uncertainty that is independent of the decision-making process. Examples of these types of uncertainties might be fuel prices, or political developments expecting a coast guard fleet to perform mission previously not intended.
- **Hybrid uncertainty**
  Uncertainty that can be partially influenced in the decision-making process. An example is shipbuilding cost.

In order to capture the non-linear influence of uncertainty with respect to system performance, Jensen's inequality can be applied, as presented in equation 4.1 (de Neufville & Scholtes, 2011):

$$E[f(\mathbf{x})] \neq f[E(\mathbf{x})] \tag{4.1}$$

Equation 4.1 states that the expected performance level output of a system (E[f($\mathbf{x}$)]), is generally not equal to the average input values (f[E($\mathbf{x}$)]). This is valid as long as f($\mathbf{x}$) is non-linear (de Neufville & Scholtes, 2011).

4.3 Capturing Value in Complex Engineering

Gaspar et al. (2012) discussed how uncertainty assessments can help decision-makers to capture what stakeholders might value during contextual changes and how this can help decision-makers to reveal value robust system solutions (Gaspar et al., 2012). During the last years, the desire to use the term "value" in complex system engineering has been increasing (O. C. Brown & Eremenko, 2009; A. M. Ross & Hastings, 2005; A. M. Ross, O'Neill, et al., 2010). Within traditional engineering approaches, system success has been closely related to requirements and/or cost related characteristics. Although these approaches are intended to lead decision-makers to the creation of useful systems, the designed systems often end up short in delivering their full potential by either costing too much, or by providing less capability than expected (Baldwin, 2008; O. C. Brown & Eremenko, 2009). O. C. Brown and Eremenko (2009) discussed how focus in systems engineering during the past years, especially within aerospace and defense acquisition programs, has been on achieving high system capabilities through rigid system requirements while minimizing cost. The presence of endogenous and exogenous uncertainties have however resulted in ever more complex system solutions in order to meet these high system capabilities (O. C. Brown & Eremenko, 2009). This has resulted in large and complex systems at very high cost levels because decision-makers respond to high marginal costs by aiming to maximize system capability (O. C. Brown & Eremenko, 2009; Schofield, 2010; Wu, 2014). O. C. Brown and Eremenko (2009) emphasized that these challenges come as a result of a requirement-centric mindset, referred to as the "cost-complexity death spiral". In order to escape this "death spiral", decision-makers should move away from a requirement-centered mindset, and aim towards value-centric design methodologies (O. C. Brown & Eremenko, 2009).

Value-centric design and decision methodologies allow for the evaluation of both system design evolution, and cost benefits in a more integrated manner by avoiding the appliance of rigid capability constraints during the early phases of system design processes (Collopy & Hollingsworth, 2009; A. M. Ross, O'Neill, et al., 2010). This is often accomplished by combining scientific principles and cost-based system models with a *valuation model* in order to balance cost and value scoping different ranges of stakeholder value perceptions(O. C. Brown & Eremenko, 2009; Wu, 2014).

The meaning of the word "value" is however ambiguous as it lacks a consensual definition. Value creation can therefore be very difficult, especially when multiple stakeholders are involved. A system attribute deemed valuable by one stakeholder may not appear valuable to others. Value creation then requires an understanding of how to capture user needs, and through this, develop system solutions that meet stakeholder expectations (A. M. Ross, McManus, et al., 2009). This can be accomplished through methodologies allowing decision-makers to measure system utility, as value is often reflected through utility measures (O. C. Brown & Eremenko, 2009)

4.4 Methodologies for Value-Centric Decision Making

In the literature review in chapter 2, many of the presented studies focused on how to capture stakeholder value through Multi-Criteria Decision Making methodologies (MDCM). Multi-criteria decision-making considers decision problems under the presence of a number of decision criteria, from which a decision-maker has to choose the alternative that best meets the requirements set for the decision problem (Triantaphyllou & Shu, 1998). Multi-Criteria Decision making is considered a sub-division within operation research, where operation research is a discipline that deals with the application of advanced analytical methods to help decision-makers making better decisions (Hillier & Lieberman, 2005; Triantaphyllou & Shu, 1998).

Multi-criteria decision-making methodologies uses mathematics and psychology to analyze complex decision problems, helping decision-makers to prioritize and rank a set of solution alternatives based on a set of criteria or attributes. Rather than searching for the "optimum" or "correct" solution, Multi-Criteria Decision Making methodologies focus on describing how well a system meets a set of needs by translating criteria and/or attributes in to utility measures (Ho, Xu, & Dey, 2010).

Although there are multiple MDCM methodologies, as illustrated in figure 4.2, two methodologies were generally represented in the literature review when evaluating coast guard- and naval ship/fleet design problems. These were the analytical hierarchy process, multi-attribute utility theory, where Multi-Attribute Utility theory is often combined with Multi-Attribute Tradespace Exploration (MATE). These methods will be further described in the upcoming sections.

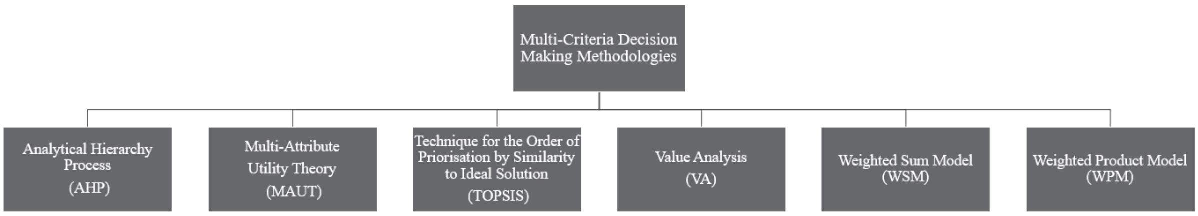

Figure 4.2: Some examples of common Multi-Criteria Decision Making methodolgies (Triantaphyllou, 2000).

4.4.1 The Analytical Hierarchy Process

The Analytical Hierarchy Process aims to assist decision-makers to find a solution alternative that best suits their overall decision goal. The process starts with describing the overall decision problem, from which further is decomposed into hierarchy of sub-problems that can be analyzed independently (Saaty, 1990). Figure 4.3 illustrates an example of such a hierarchy breakdown upon the selection of a fictive vessel.

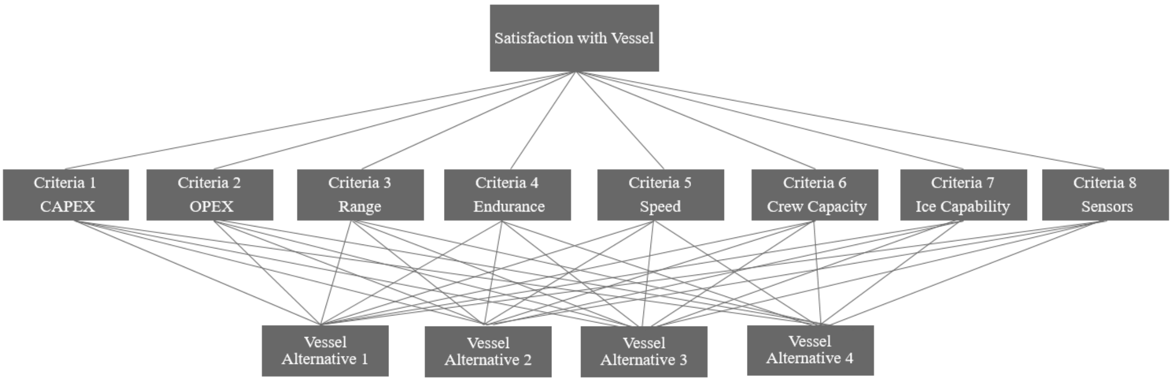

Figure 4.3: Illustration of how a decision problem upon selecting a vessel based on multiple criteria when using the AHP method is decomposed into multiple levels in a hierarchy structured fashion.

The hierarchy is divided into three objectives. The top node of the hierarchy represents the overall objective for the decision problem. The second level of the hierarchy represents criteria from which the objective is to determine how important each criteria is compared to the other criteria through a pairwise comparison upon reaching the objective of the top node. Through this process a priority vector (or weight vector) representing the importance of each criteria in the eyes of the decision-makers can be obtained using a quantitative importance scale ranging from 1 to 9, where 1 represents equal importance between two criteria, and 9 represents that a criteria is extremely more important than the other criteria. The third level represents a set of vessel alternatives which then are pairwise compared against each other for each criteria. Once all the alternatives are compared against each criteria, a total score of how well each vessel alternative meets the criteria can be established, describing which alternative that best meets the overall decision objective. This score can be considered as an utility score (Triantaphyllou & Shu, 1998). In order to avoid inconsistent comparison between criteria and alternatives, a consistency check is often applied (Saaty, 1990).

However, the AHP method can become very complex when the criteria and alternatives become many. This because decision-makers have to compare every criteria pairwise in the second level based on their own experience and knowledge. For instance, every two criteria in the second level has to be compared each time with respect to the top node objective, whereas every alternative in the third level has to be pairwise compared for the same criteria in the third with respect to the corresponding criterion. This might potentially make the AHP method very time consuming to use (A. M. Ross, O'Neill, et al., 2010). Using the AHP method to evaluate value-profitable coast guard fleet structures might therefore be difficult. This because both individual vessels and alternative fleet compositions based on these vessels, have to be evaluated for both capability criteria and activity measure criteria. This might potentially result in many levels within the AHP hierarchy that has to be constructed and evaluated. As a result, the AHP method will not be further considered in this thesis.

4.4.2 Multi-Attribute Utility Theory

Multi-attribute utility theory is an extension of utility theory, a fundamental framework which has been used by decision-makers to help quantify the idea of value. Since stakeholders can have multiple objectives, utility theory aims towards maximizing system value with respect to these objectives (Keeney & Raiffa, 1993). Each objective can be described through a set of attributes, where each attribute contributes to describe how well the objectives for a particular system is met (Keeney & Raiffa, 1993; A. M. Ross & Hastings, 2005). Finding the "correct" attributes that best describes the perceived value of a particular system can therefore be particularly difficult Keeney and Raiffa (1993). This requires dialog and careful considerations between the decision-makers and all involved stakeholders (A. M. Ross, 2006).

According to Keeney and Raiffa (1993), attributes are said to be complete if they as a set is adequate in indicating the degree to which the overall objective is met. The attributes have to give meaning when used in an analysis based on the problem definition. They have to be non-redundant in order to avoid double impact counting effects when calculating the utility of a system. When deciding on which performance attributes to use, a minimal set of attributes might be better in order to capture the value proposition rather than using a diverse set of attributes. This will help to keep the dimension of the problem as small as possible. When stakeholder preference for an attribute is obtained, it can be quantified through a range of acceptable values(Keeney & Raiffa, 1993). This range can then be translated to a utility metric ranging from 0 to 1, were the least acceptable range is equal to 0, and the most preferred to 1 (A. M. Ross & Hastings, 2005). Mapping the range of values for a attribute creates a single-attribute utility curve describing the stakeholders perception of perceived value for that particular attribute (Keeney & Raiffa, 1993; Whitcomb, 1998).

Within the design of complex systems, multiple attributes are often of interest to stakeholders, and comparing the trade-offs between multiple single-attribute utility curves can be very difficult. Instead, there is a need to aggregate the attributes under consideration into a single utility metric that accounts for the stakeholders combined preferences on all attributes (A. M. Ross, O'Neill, et al., 2010). In Keeney and Raiffa (1993) a *multi-attribute utility function* is presented, which allows decision-makers to aggregate stakeholder benefit into a single multiple attribute utility metric (Keeney & Raiffa, 1993). The general multi-attribute utility function presented by (Keeney & Raiffa, 1993) is shown in equation 4.2:

$$\Lambda U(X) + 1 = \prod_{i=1}^{N} [\Lambda \lambda_i U_i(X_i) + 1] \tag{4.2}$$

where Λ is the solution to the equations 4.3, 4.4, 4.5 and 4.6:

$$\Lambda + 1 = \prod_{i=1}^{N} [\Lambda \lambda_i U_i(X_i) + 1] \tag{4.3}$$

$$\sum_{i=1}^{N} \lambda_i < 1, \qquad \Lambda > 0 \tag{4.4}$$

$$\sum_{i=1}^{N} \lambda_i > 1, \qquad -1 < \Lambda < 0 \tag{4.5}$$

$$\sum_{i=1}^{N} \lambda_i = 1, \qquad \Lambda = 0 \tag{4.6}$$

In this equation, $U(X)$ is the multi-attribute utility score of a system alternative under consideration, which is an aggregation of the single-attribute utility functions $U_i(Xi)$, were i varies from 1 to the number of attributes. λ_i represents the weighting, or importance of attribute i, and Λ is a scaling constant (Keeney & Raiffa, 1993).

If each attribute of the system contributes independently to create utility, then λ_i on each attribute i sum to 1. Under these assumptions, the multi-attribute utility score can be calculated using a simple weighted sum of the single-attribute utilities, as shown in equation 4.7 and 4.8 (Keeney & Raiffa, 1993).

$$U(X) = \sum_{i=1}^{N} U_i(X_i)\lambda_i \tag{4.7}$$

$$\sum_{i=1}^{N} \lambda_i = 1 \tag{4.8}$$

In this function, U(X) is the multi-attribute utility score of an alternative. $U_i(X_i)$ is the single-attribute utility, and λ_i is the weighting factor of attribute i (Keeney & Raiffa, 1993).

According to A. M. Ross, O'Neill, et al. (2010), multi-attribute utility theory is an appropriate method for valuing engineering systems since each potential system solution can be ranked based on multiple sources of non-monetary value under uncertainty (A. M. Ross, O'Neill, et al., 2010). This is done in the Responsive Systems Comparison method which combines Tradespace Exploration analysis with Epoch-Era analysis in order to derive valuable system solutions when subjected to future uncertainty (A. M. Ross et al., 2008).

4.4.3 Tradespace Exploration

Section 4.1 and 4.2 discussed briefly how decisions with multiple objectives can get affected due to the presence of future uncertainty. The adverse consequences that potential uncertainties pose are often related to as risk. To overcome the challenges that future uncertainty poses, risk analysis may be applied to reduce these adverse consequences (Schultz et al., 2010).

McManus and Hastings (2006) presented a framework to aid decision-makers in the understanding of uncertainties. The framework focuses on mitigating potential risks, and instead exploit opportunities. Figure 4.4 shows a simplified version of the framework. By assessing how design actions at the system level can reduce risk, design strategies can be implemented to instead exploit opportunities previously not considered (McManus & Hastings, 2006). In this framework, McManus and Hastings (2006) discuss how Tradespace Exploration analysis might be used to assess the implications of different design actions McManus and Hastings (2006). Through the use of Tradespace Exploration analysis, decision-makers can identify designs that are robust, versatile, flexible and and capable of interoperability (McManus & Hastings, 2006; A. M. Ross & Hastings, 2005).

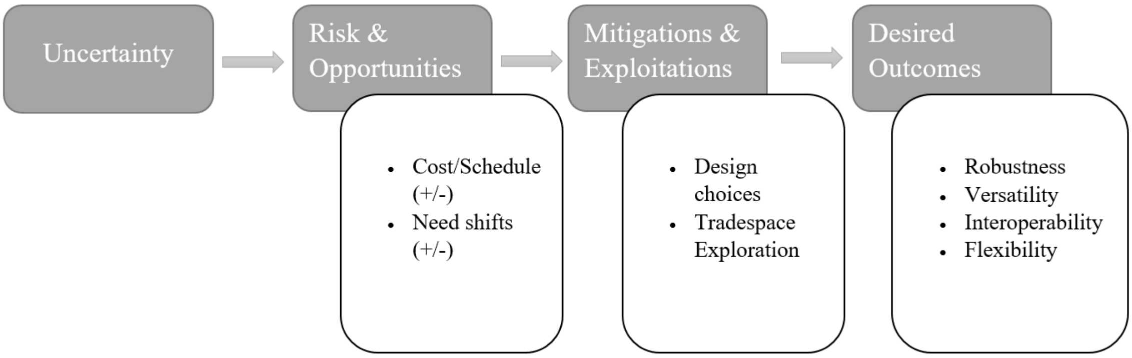

Figure 4.4: Example of how uncertainty poses risk which then is mitigated through design actions, resulting in an desired outcome (McManus & Hastings, 2006).

Robustness, versatility, interoperability and flexibility are taxonomies often referred to as ”illities”. They can be describes as follows McManus and Hastings (2006).

Robustness, versatility, interoperability and flexibility are taxonomies often referred to as ”illities”. They can be describes as follows McManus and Hastings (2006).

- **Robustness** - Refers to a system’s ability to do its basic task under unexpectedly adverse environments (McManus & Hastings, 2006).
- **Versatility** - Refers to a system’s ability (without applying changes to the original system solution) to perform tasks not originally included in the requirements definition. Versatility may also describe a systems ability to perform a variety of tasks well (McManus & Hastings, 2006).
- **Interoperability** - Refers to a system’s ability to operate with other systems not originally considered, especially the ability operate with future systems (McManus & Hastings, 2006).
- **Flexibility** - Refers to a system’s ability to be modified to do jobs not included in the requirements definition. The modifications may be applied to the system design, or to the operation of the system. This can help to improve the system’s current function, or to completely change the system’s function (McManus & Hastings, 2006).

Tradespace Exploration is a decision analysis approach that allows decision-makers to calculate and evaluate the performance of multiple design and/or system solutions. While optimization algorithms often focus on finding the ”optimum” or ”best” solution, Tradespace Exploration focus on revealing cost-utility tradeoffs between a numerous number of system solutions (A. M. Ross & Hastings, 2005). According to A. M. Ross and Hastings

(2005), choosing only between local point solutions is a minimalistic approach to a trade study since involved stakeholders often choose a single point solution, and do not consider other points on the tradespace (A. M. Ross & Hastings, 2005). Fixation on single point solutions can result in incomplete knowledge of the bigger design problem and stakeholders lose the opportunity to gain knowledge of better value solutions (Wu, 2014). This is often the case under a requirement-centered mindset during system design (O. C. Brown & Eremenko, 2009). A tradespace instead allows decision-makers to consider the elicited need of multiple stakeholders. One great benefit of the tradespace approach is that each tradespace is constructed around concept-neutral criteria on form of perceived value and cost. This allows decision-makers to compare many different system concepts within the same tradespace (A. M. Ross & Hastings, 2005). A systematic way of performing Tradespace Exploration analysis was given by A. M. Ross et al. (2004).

4.4.4 Multi-Attribute Tradespace Exploration

A. M. Ross et al. (2004) presented a conceptual design methodology, Multi-Attribute Tradespace Exploration. This can be used as a decision-making tool to capture value profitable system solutions, potentially coast guard fleet structures. The great benefit of Multi-Attribute Tradespace Exploration is that the methodology unites Model-Based Design, Tradespace Exploration and Multi-Attribute Utility theory (A. M. Ross et al., 2004).

The procedure of the Multi-Attribute Tradespace Exploration begins with the identification of stakeholder needs. When the needs are obtained, attribute levels, design variables and stakeholder preferences are chosen in order to evaluate and compare possible system solutions using utility- and cost measures. When these measures are defined, a full enumeration of all possible system solutions can be performed, were each solution is presented as a point on the tradespace. Figure 4.5 illustrates the steps of the Multi-Attribute Tradespace Exploration approach. Each point in the figure represents a unique design and/or system alternative, where each point is represented by a given cost on the x-axis, and a given utility score on the y-axis. The utility describes how well each specific design and/or system meets a set of attributes (A. M. Ross & Hastings, 2005).

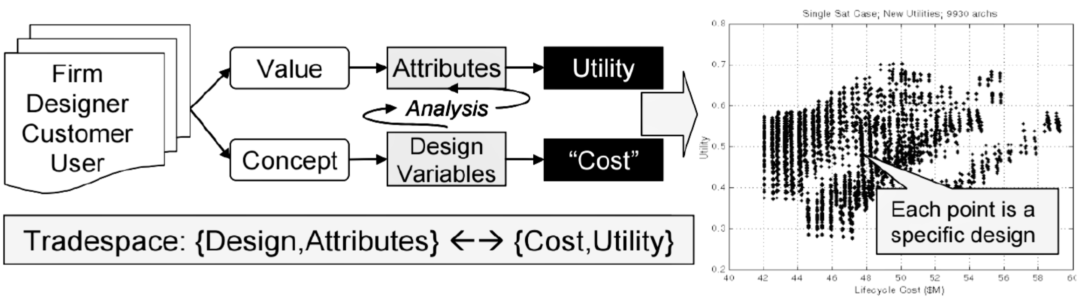

Figure 4.5: Illustration of the steps in the Multi Attribute Tradespace Exploration process. A tradespace represents design parameters and stakeholders' perceived value thorough cost utility plots (A. M. Ross, McManus, et al., 2010).

From a tradespace, decision-makers should seek for the frontier set solutions called non-dominated solutions. Tracing the solutions on this frontier gives decision-makers the Pareto frontier. Choosing between the Pareto solutions involves making cost-utility trade-offs (A. M. Ross & Hastings, 2005). This means that the solutions on the Pareto-front are the systems that for a specific cost provides the highest utility (A. M. Ross & Hastings, 2005).

As discussed in previous sections, stakeholders' preferences may change due to future uncertainty. Figure 4.6 illustrates such changes, and how tradespace analysis can be used to capture these changes. In the figure, the colored dots represents three different design solutions. The mapping from the "original" tradespace to the "revised" tradespace illustrates how the system solutions did not shift in the same direction, nor with the same magnitude when subjected to changes in requirements or preferences. This shows that some design solutions are more sensitive to value delivery when the context needs changes, and that tradespace exploration can provide valuable information concerning such shifts (A. M. Ross & Hastings, 2005). One way of capturing such changes is through the Epoch-Era framework (A. M. Ross & Rhodes, 2008).

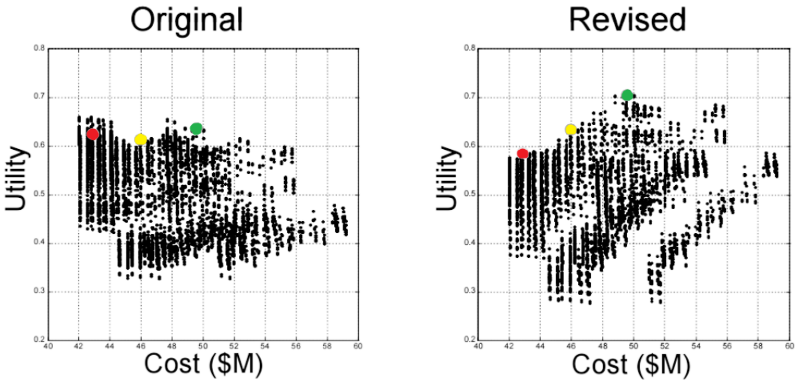

Figure 4.6: Example of a tradespace shift. Notice how the changes in stakeholders' needs can change the perceived stakeholder value (A. M. Ross & Hastings, 2005).

The exploration process begins when decision-makers together with stakeholders start comparing the point solutions on the tradespace against each other (A. M. Ross et al., 2004). Through the exploration process, system solutions that have high trade-offs among the attributes relative to stakeholders' needs can be identified, potentially revealing system solutions for given cost-levels previously not discovered (Ricci, Rhodes, & Ross, 2014; A. M. Ross, 2006; A. M. Ross et al., 2004; A. M. Ross, McManus, et al., 2009; Vascik et al., 2016).

4.4.5 Epoch-Era Analysis

Epoch-Era Analysis (EEA) is an approach where the objective is to clarify how potential changing operating contexts over time will affect the perceived value of a system (A. M. Ross & Rhodes, 2008). An epoch represents a fixed period of time and needs, in which a system operates (A. M. Ross & Rhodes, 2008). Each epoch is characterized through a set of variables, where the variables can define anything that might have an effect on the usage and value of the system. These variables are often related to exogenous uncertainties such as financial situations, political scenarios, operational aspects etc (A. M. Ross & Rhodes, 2008). Combinations of these variables establish a single epoch. Different combinations of single epochs generates Eras. An Era is an ordered sequence of epochs describing a systems progression and needs over time, as illustrated in figure 4.7.

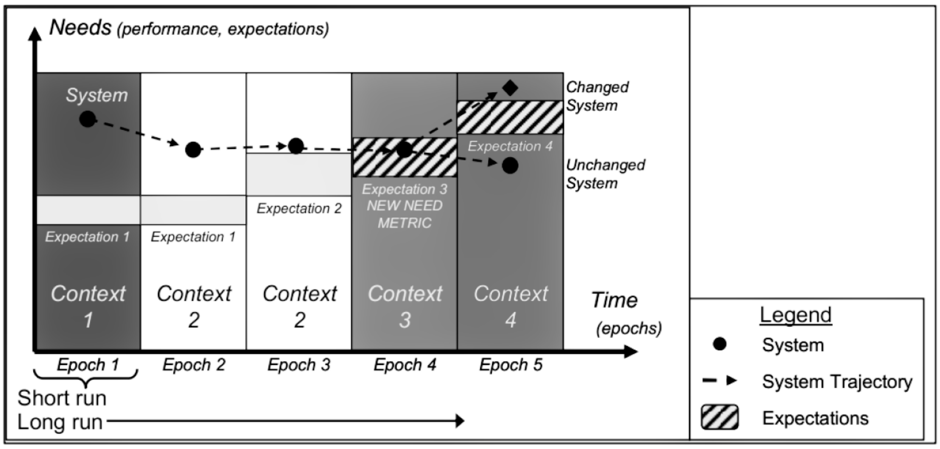

Figure 4.7: Illustration of how system expectation changes through epochs addressing the need of system change (A. M. Ross & Rhodes, 2008).

Recombining single epoch sequences allows for analyzing many different Eras, making it possible to assess potential operating scenarios (A. M. Ross & Rhodes, 2008). The process of creating Eras can be done in many ways. Two common ways are by narrative and numerical procedures. The narrative procedure involves ”hand-picking” epochs to fit imagined scenarios with the aid of expert opinions. Numerical procedures involves creating computer algorithms for epoch assembly, often through probabilistic models like Monte Carlo- or Markov models (A. M. Ross & Rhodes, 2008). Combining the Multi Attribute Tradespace Exploration presented by (A. M. Ross & Hastings, 2005), with the Epoch-Era framework presented by (A. M. Ross & Rhodes, 2008), allows decision-makers to explore the impact of exogenous uncertainties in relation to system development which has resulted in another value-centric design methodology, the Responsive System Comparison Method as presented by A. M. Ross et al. (2008).

4.5 Handling System of Systems Challenges using Tradespace- and Epoch-Era Analysis

When considering coast guard fleet structures, decision-makers might face System of Systems (SoS) challenges. System of Systems engineering is considered a complex engineering discipline, and the problem has received a lot of attention in the literature, highlighting the lack of quantitative models and consistency (Baldwin, 2008; Chattopadhyay et al., 2009; Crossley, 2010; Keating et al., 2008; Maier, 1996; Mekdeci, 2013; Vascik et al., 2016).

A SoS is by Baldwin (2008) defined as an arrangement of systems or assets that are integrated into a larger system that delivers unique capabilities (Baldwin, 2008). Crossley

(2010) described that SoS challenges arise when a need or set of needs, has to be met by a mix of assets, where each asset is capable of operating independently, but must interact with other systems in order to complete mission objectives (Crossley, 2010). Determining which single asset and constituent system capabilities that are needed over time is difficult to assess because of managerial and operational independence of component assets within the SoS (Maier, 1996). The result of this independence is both local component system stakeholders and global SoS stakeholders (Chattopadhyay et al., 2009; Maier, 1996).

Chattopadhyay et al. (2009) presented the "System of Systems Tradespace Exploration Method" to help decision-makers compare the performance of various SoS architectures based on the same performance attributes and cost basis during early phases of SoS design. By introducing the concept of "level of attribute combination complexity", Chattopadhyay et al. (2009) proposed three levels of attribute combination to describe SoS attributes: "Low-level combination", "medium-level combination" and "high-level combination", as illustrated in figure 4.8. "Low-level combination" is used if each component asset constituting the SoS provides a unique subset of attributes, and the mission objective is differentiated between these components. If the SoS concept of operation has a more complex structure such that more than one asset is involved in delivering a single performance attribute, the SoS attribute can be considered by taking the average of the systems performance attributes represented by "medium-level combination". However, when using "medium-level combination", decision-makers should be aware that this level of combination may involve time-weighted averaging. If multiple SoS components deliver performance to the same SoS attribute simultaneously, "high-level combination" by attribute fusion at a detailed level instead of just averaging is required. By combining these SoS modeling assumptions with the Epoch-Era framework, SoS dynamics can be assessed over multiple future scenarios in order derive which aspects of a SoS that provide value over time (Chattopadhyay et al., 2009).

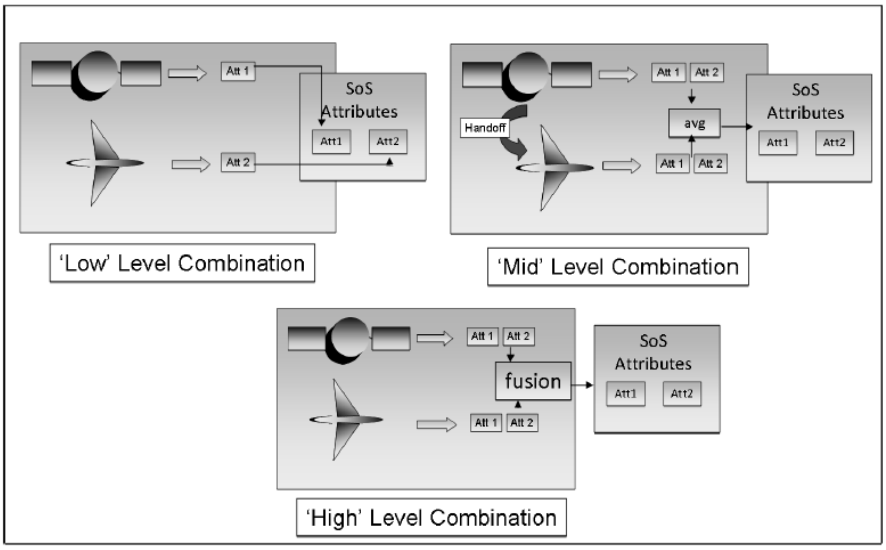

Figure 4.8: Illustration of the three levels of attribute combination complexity in System of Systems design (Chattopadhyay et al., 2009).

However, defining the SoS, as well as the SoS attributes according to Chattopadhyay et al. (2009) can become challenging, as decision-makers must try to understand how constituent systems, like a fleet of coast guard vessels, delivers value to a single performance attribute based on the operational context. An extension of Chattopadhyay et al. (2009) work was done in Vascik et al. (2016) who presented six models to characterize basic value judgments that can be applied to determine the single attribute performance from a set of constituent systems. These models apply different types of aggregation methods to aggregate system level single-attributes to single-attribute performance attributes for constituent systems (Vascik et al., 2016)

4.6 The Net Present Value Method

A. M. Ross, O'Neill, et al. (2010) discussed the use of the Net Present Value method (NPV) as a way of quantifying value in engineering. The Net Present Value method is often used to quantify the monetary "value" of a system in e.g NOK or USD. In general, the NPV method is often used to indicate how much an investment in an asset adds to the monetary net worth of the stakeholder(s) making the investment. The NPV method obtains this by quantifying the discounted cash flow generated by an asset or a system over time. The discounted cash flow is then an estimation of how the future cash flow for an asset or system might be over time, where a discount rate is used to discount the cash flow to present-day value (Berk & DeMarzo, 2013). Value in relation to the NPV method can then be interpreted as being the discounted cash flow of a system over time, also known as " the time value of money " (Berk & DeMarzo, 2013; A. M. Ross, O'Neill, et al., 2010). This means that cash flow for the near future is more valuable than the cash flow at later stages in the time period because they are discounted. It is important to note that the cash flow can be both positive and negative (Berk & DeMarzo, 2013). According to Berk and DeMarzo (2013), the NPV can be calculated according to equation 4.9:

$$NPV = D_0 + \int_{t_j}^{t_i} \frac{D(t)}{(1+r(t))^t} \sim D_0 + \sum_{t_j}^{t_i} \frac{D(t)}{(1+r(t))^t} \sim D_0 + \sum_{t_j}^{t_i} \frac{D(t)}{(1+r)^t} \tag{4.9}$$

In the equation, D_0 defines the cash flow before time t_j, for example an investment. D(t) is the cash flow at time t. r(t) is the discount rate at time t, and $[t_j,t_i]$ represents the time interval in which the NPV is quantified. The simplest variant of the NPV method (the expression to the right in equation 4.9) is often used. However considering the NPV method as an value-centric design methodology that alone can determine system value in the eyes of involved stakeholders might be a plausible assumption. This because the perceived value of an asset or system is only assumed to come from monetary returns (A. M. Ross, O'Neill, et al., 2010). The NPV method will therefore not capture non-monetary value that an asset or system might provide through their operational context. In addition, if the simplest form of the NPV method is applied, an assumption is being made that the discount rate is constant, neglecting potential uncertainties (Berk & DeMarzo, 2013).

4.7 Mathematical Optimization

Before deriving the Responsive Systems Comparisons method, an introduction to two other decision-making methodologies highly represented in the literature review will be given. Most of the fleet design problems reviewed in the literature review in chapter 2, used linear optimization algorithms to determine necessary fleet structure, solving resource allocation- and inventory routing problems.

Optimization algorithms present in general a framework used to find the best set of elements from some set of alternatives (Lundgren, Ronnqvist, & Varbran, 2012). The objective using this framework is often on determining which resources to allocate where, and/or which systems to acquire in order for an organization to cover engaged activities in the most effective way (Birge & Louveaux, 2010; Lundgren et al., 2012). This section will provide basic insight into the assumptions underlying linear deterministic and stochastic optimization approaches.

4.7.1 Deterministic Optimization

In deterministic optimization, all input parameters describing a specified system are assumed deterministic. These models include no randomness when it comes to describing the future development of a system. Deterministic models will then always provide the same output based on its initial state (Birge & Louveaux, 2010). However, by performing sensitivity analysis, the effect of changing parameter values with respect to the optimal solution can be investigated. By "tuning" the input parameters, decision-makers can assess how robust a particular solution is to changes, providing valuable information as demonstrated by Halvorsen-Weare, Gundegjerde, Halvorsen, Hvattum, and Nonås (2013). According to (Hillier & Lieberman, 2005; Lundgren et al., 2012), a generic deterministic problem can be generalized on the following form:

$$min\, z = c^T x \tag{4.10a}$$

$$s.t \quad Ax = b, \tag{4.10b}$$

$$x \geq 0, \tag{4.10c}$$

In the mathematical expression above, c, A and b are known deterministic parameter values. The expression in 4.10a is the objective function, in this case minimizing some cost, while the expressions in 4.10b and 4.10c define the set of feasible solutions. Optimization models often search for a minimal-cost solution under some requirements or for a maximum profit solution under limited resources (Birge & Louveaux, 2010; Lundgren et al., 2012).

4.7.2 Stochastic Optimization

Stochastic optimization allows decision-makers to solve problems that involve uncertainty describing possible future scenarios using random variables. The random variables are assumed accurate through probabilistic descriptions, generally in the form of probability measures (Heyman & Sobel, 2003). Birge and Louveaux (2010) divides the set of decisions to be made into two groups, and proposes the following generic two-stage stochastic problem in the following form:

$$min\ z = c^T x + E_\xi[min\ q(\omega)^T y(\omega)] \tag{4.11a}$$

$$s.t \quad Ax = b, \tag{4.11b}$$

$$T(\omega)x + Wy(\omega) = h(\omega), \tag{4.11c}$$

$$x \geq 0,\ y(\omega) \geq 0, \tag{4.11d}$$

In the expressions above, 4.11a represents the objective function, in this case minimizing the costs. This expression consist of two stages. The first stage contains the deterministic cost c^T which should be minimized for the decision variables x. In the second stage a number of random events $\omega \in \Omega$ can be realized by taking the expected value E_ξ of the function which minimizes the stochastic costs $q(\omega)$ for the second stage decision variables $y(\omega)$. ξ is a random vector consisting of all the elements in ω. The expression in 4.11b is the deterministic constraints subjected to the deterministic cost c^T in 4.11a. Expression 4.11c is the stochastic constraint, where $T(\omega)$ is the uncertain parameter related to the first stage decision, and W represents the fixed recourse in the second stage. The last expression 4.11d is the non-negativity requirements. The aim of the two-stage model is in this case to choose the first stage decision variables so that the expectation of the overall cost is minimized (Diez & Peri, 2010).

The optimization methods presented will not be considered in the case study. As discussed in section 4.4.3, one drawback of using these methods is that they will only provide one solution. There are no immediate discussions of tradeoffs between different objectives or measures of value since it is difficult to find the ”correct” constraints, as outlined in section 3.4. However, discussion on the use of optimization algorithms in relation the coast guard fleet mix problem will be given in chapter 8

Chapter 5

The Responsive System Comparison Method

The Responsive System Comparison (RSC) method uses Multi-Attribute Tradespace Exploration together with Epoch-Era Analysis to quantify and evaluate system performance through various operating contexts (A. M. Ross et al., 2008). The objective is to evaluate and gain knowledge about key system trade-offs across varying epochs, assessing the value robustness of various system solutions through multiple epoch sequences. This method will help decision-makers to gain insight into strategies for how to transition a system in response to varying context (A. M. Ross, McManus, et al., 2009). According to (A. M. Ross et al., 2008), one of the great strengths of using the RSC method is that it enables dialog and knowledge building between stakeholders and system developers. In figure 5.1 a flowchart illustrating the nine step variant of the RSC method is presented, and each step is further described below:

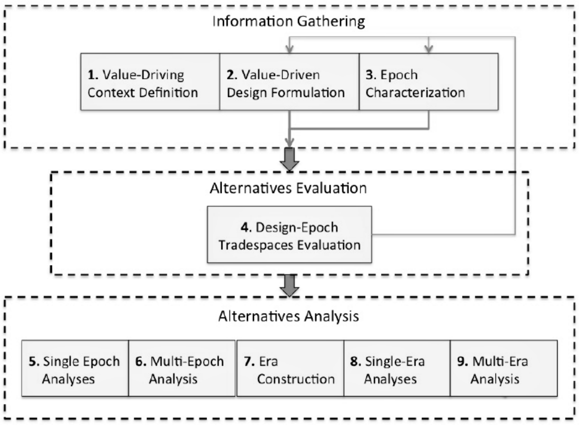

Figure 5.1: Flowchart of the nine steps variant of the RSC method (Schaffner et al., 2014).

5.1 Value-Driving Context Definition

This process focus on capturing the overall problem. It is here necessary to describe and understand why the problem is important, and which stakeholders that care about the problem, as well as potential solutions to the problem. From this a value proposition is defined based on stakeholder objectives and needs. In this process, contextual factors that might affect the problem and/or its solution should be identified. From this a system architecture with potential of satisfying stakeholders' preferences should be outlined (Schaffner, Shihong, Ross, & Donna, 2013).

5.2 Value-Driven Design Formulation

Based on the value proposition from step 1, attributes reflecting how well stakeholders' objectives are met, should be defined. Based on these attributes, a set of design variables must be defined in order to meet the selected attributes. The design variables are represented as discrete variables. How good a particular system meets the selected attribute preferences are often quantified through a normalization process which translate how well a particular solution meets the defined attributes through a utility metric (Schaffner et al., 2013).

5.3 Epoch Characterization

Based on the outcomes from step 1 and 2, step 3 seeks to characterize the contextual uncertainties and potential changes of needs that might prevent system success. The uncertainties are parametrized into epoch variables and the span of these enumerated variables is the epoch space (Schaffner et al., 2013). During this process, epoch constraints may be applied in order to derive system feasibility based on system requirements for a particular context of operation. If such constraints are not available or sufficient to apply, stakeholder preferences in terms of attribute weights, can be applied to visualize stakeholders' value perceptions during context changes (A. M. Ross, Rhodes, & Hastings, 2009).

5.4 Design-Epoch Tradespace Evaluation

Based on the epochs derived from step 3 and the performance attributes and design variables from step 4, all possible system solutions can now be plotted in a tradespace. The tradespace data is usually provided as cost-utility scatter plots where the utility is modelled through the application of a suitable utility function. These plots provide decison-makers with an overview of possible tradeoffs between system utility and cost, based on the attributes and design variables from step 2. As mentioned in section **??**, the solutions on the Pareto front is often used as criteria for further analysis of how well a system meet stakeholder preferences when the operating context change (Schaffner et al., 2013). In figure 5.2, the highlighted marks illustrates solutions on the Pareto frontier for a given epoch.

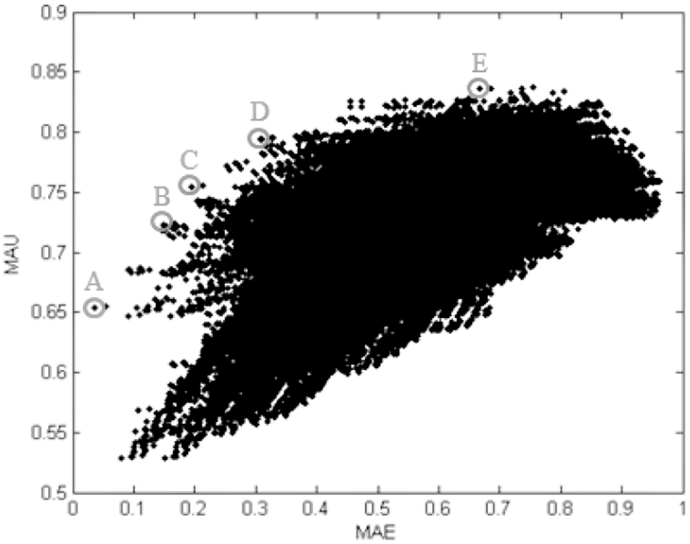

Figure 5.2: Some highlighted Pareto solution (Vascik et al., 2016).

5.5 Singel-Epoch Analysis

In step 5, the goal is to explore and identify which design- or constituent system solutions that perform particularly well during an epoch. Through this process, decision-makers can compare what the Pareto optimal solutions have in common, and what changes that are needed for a non-Pareto solution to become Pareto optimal (Schaffner et al., 2013).

5.6 Multi-Epoch Analysis

In step 6, the objective is to determine the most value-robust systems, comparing multiple tradespaces across each epoch considered. As the tradespace might shift from epoch to epoch, some solution might become feasible and other infeasible (A. M. Ross, McManus, et al., 2009; Schaffner et al., 2013). Introducing a Pareto trace metric allows decision-makers to keep track of the designs that occur on the Pareto front across all epochs. A high Pareto trace indicates that a design is passively value robust, meaning that the design is robust in delivering "value" based on stakeholders expectations (A. M. Ross, Rhodes, & Hastings, 2009). Figure 5.3 shows an example distribution of a Pareto trace across a number of epochs. The y-axis represent how frequent a design, represented on the x-axis, occurs on the Pareto front A. M. Ross, Rhodes, and Hastings (2009).

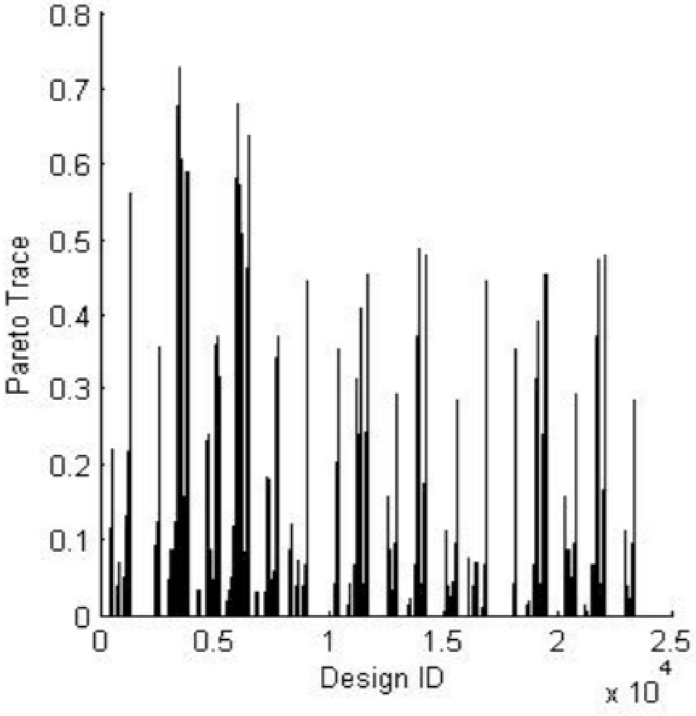

Figure 5.3: Example distribution of pareto trace for given designs during an epoch (A. M. Ross, Rhodes, & Hastings, 2009)

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5.7 Era Construction

In step 7, the objective is to generate potential scenarios from which the system may operate in. As described in section 4.4.5, an Era consists of epochs put in logical sequences, or said with other words, a sequence of tradespace changes over over time. Recombining single epoch sequences allows for analyzing many different Eras (Schaffner et al., 2013).

5.8 Single-Era Analysis

Based on the constructed era's in process 7, the goal of single-era analysis is to identify the effects of time-dependent variations of potential future uncertainties by evaluating multiple single eras. Through this process, decision-makers can identify strengths and weaknesses of a design or constituent system, and from this assess long run strategies to enhance system value over the systems life-cycle (Schaffner et al., 2013).

5.9 Multi-Era Analysis

In the last step of the Responsive Systems Comparison method, process 8 is extended by comparing the dynamic properties of system across multiple eras (Schaffner et al., 2013). To this date, no publications seems to have covered this step of the Responsive Systems Comparisons method as the computational burden and time quickly increases.

Chapter 6

Case Study

The main objective of this case study is to visualize through a value-centric perspective how multiple stakeholder objectives can be captured, interpreted and analyzed in the selection of coast guard fleet structures. Methodology for the analysis will be selected, and a generic model will be presented.

6.1 Case Assumptions

When determining coast guard fleet structures, multiple performance attributes and design variables can be considered relevant in terms of describing a fleet's overall performance. In addition, as described in chapter 3.4, multiple stakeholders will be involved in the fleet design process, increasing the modeling complexity. To limit the scope of this case study, some assumptions have been made. As a result, this case study will not fully represent the real life situation when considering the coast guard fleet mix problems. The drawbacks associated with the use of the selected methodology, and suggestions on improvements will be discussed in chapter 8.

The performance attributes and design-variables introduced in the case study are selected to visualize some of the trade-compromises that have to be made during the design of coast guard fleet structures. This means that other potential attributes and design variables might be considered more relevant. However, including many attributes might result in the possibility of double counting, which then requires careful consideration when applying equations 4.2-4.8, as described in chapter 4.4.2. The performance of all evaluated fleets during the case study are assessed based on physical characteristics and system level performance of different vessel types. These characteristics are based on values from similar studies, and from performance measurement of coast guard vessels found in *IHS Jane's Fighting Ships* (Saunders, 2012-2013). In order to reduce the SoS challenges, the study is limited to only considering sea-going patrol vessels. This means that assets like helicopters and planes will not be considered as part of a fleet. However, having the capability of operating a helicopter from a vessel will be considered handled in a black-box environment.

The number of stakeholders considered in this case study is limited to only include a few sets. This is in order to reduce the scope of this thesis. Many influential offices, service organizations and vendors, that significantly impact a coast guard's resources and ability to perform statutory missions will therefore not be accounted for.

The geographical area referred to in this case study has neither defined boundaries, nor defined activity levels in terms of density and location of commercial maritime actors. It has been difficult to collect good and sufficient data that can aid in forecasting the extent of how for example fishery activities, offshore activities and maritime traffic, within a geographical area might develop, with the aim of determining how many vessels that would be needed. Collecting AIS data from actual coast guard vessels, that can be used to describe patrol patterns, has been difficult since these vessels often do not transmit on AIS transponders. This is to maintain the ability to make sudden appearances. As a result no probabilistic methods, as described in section 4.4.5, have been considered. This is perhaps the biggest limitation of this case study as it becomes difficult to recommend a sufficient fleet structure. Instead a narrative approach to describe potential activity levels will be conducted with focus on visualizing the potential of the selected method. The weightings used to weight each performance attribute are assumed to be based on "combined" stakeholder preferences. Since the stakeholders presented in this case study are "fictional", the weightings are selected to illustrate how they impact each performance attribute during changing stakeholder perceptions. The cost models presented assumes all cost data to be deterministic.

Although the operational context considered in this study is similar to the ones presented in chapter 3, it is important to ones more emphasize that the performance attributes and design variables selected in this case study, neither represent actual values from the Norwegian Coast Guard, nor the Norwegian Coast Guard's preferences in terms of which capabilities and number of vessels they value during different operational contexts. The author of this thesis created all performance attributes, weights and stakeholder preference levels to facilitate research purposes on how a value-centric decision methodology can be used to enhance the grounds for decision-making when assessing the coast guard fleet mix problem.

6.2 Case Description

A fictive Coast Guard has for some time operated a fleet consisting of six sea-going vessels which now are reaching the end of their life time. The Coast Guard has requested the need for a fleet renewal in order to meet future statutory mission demands. The Coast Guard's priority mission has been to patrol and control the fishery activities within a geographical area, assuring a sustainable management and utilization of the marine resources. In addition, the Coast Guard has been decreed by law to assist in emergency response operations in case of marine casualties. This include search and rescue missions, oil recovery operations and tugging operations. The Coast Guard's mission description is assumed to be established by a Government to assure that the Government's maritime interests and sovereignty is maintained within the geographical area.

The stakeholders assumed to be involved in the coast guard fleet design process in this case study are the Government and the Coast Guard, where the Coast Guard is compound of a staff and personnel operating the Coast Guard's vessels. In collaboration with the Coast Guard, the Government wants to assess and evaluate potential fleet structures that can meet the statutory mission objectives set for the Coast Guard.

The main design criteria for the new fleet will be centered around the fleet's ability to patrol and control the various fishery activities taking place within the geographical area. Since the fleet is expected to perform a set of additional tasks when required, specific system capabilities must be considered incorporated into the fleet design. This gives the following problem statement:

Problem Statement: To derive potential coast guard fleet structures that can replace the capabilities of the current fleet and carry out defined mission tasks.

6.3 Selecting Methodology

With respect to the objectives of this thesis, the Responsive Systems Comparison Method outlined in chapter 5 is selected. The methodology allows decision-makers to compare the perceived utility-values from multiple fleet alternatives using the Tradespace Exploration approach. With the use of Epoch-Era analysis, different operating contexts as a result of exogenous uncertainties can be modeled. This will help to describe and visualize how the perceived utility in the eyes of involved stakeholders might change with changing operating contexts. This allows decision-makers to compare different fleet alternatives against each other, potentially revealing important value tradeoffs. Another reason for selecting this particular method is that Sj SST Plan are not familiar with the method's potential, and wants it demonstrated through a simple, but illustrative case study addressing the coast guard fleet mix problem.

6.4 Modeling With the Responsive Systems Comparison Method

6.4.1 Value-Driving Context Definition for the Coast Guard Fleet

The objective for the new fleet will be to assure that the Government's interests and sovereignty are maintained within the given geographical area, primarily by monitoring and controlling the fishery activities. It is at this point neither clear how the fishery activities will develop in the years to come, nor the activity levels of other commercial maritime branches. It is expected that some offshore development might start taking place within the geographical area. It is also expected increased traffic from offshore companies and shipping companies. In addition, some of the activity might take place near arctic regions. Depending on the extent and types of exogenous perturbations that occur in the maritime environment, the Coast Guard might face challenges when it comes to maintaining sufficient presence, which rises the question of how many vessels the Coast Guard should acquire, and what performance and system capabilities the vessels constituting the fleet should have.

Due to tight budget restrictions, the Government wants a coast guard fleet that has low acquisition- and operating costs, and that can fulfill all expected mission tasks. For the Coast Guard department, the ability to be present at various locations simultaneously while having high situational awareness is of great importance. The following value attributes are considered to fulfill this ability:

- The number of vessels.
- Mission range pr. vessel.
- Vessel speed.
- Crew size pr. vessel.
- Helicopter capability pr. vessel.

- Sensor capability pr. vessel.
- Good seakeeping capabilities.

The number of vessels contributes to increase the Coast Guard's ability to be present at various locations simultaneously. This influence depends on the activity development of commercial maritime segments. The number of vessels is therefore considered to be an important value attribute by the Coast Guard. Sensor and helicopter capability contribute to increase the Coast Guard's situational awareness, helping them to prioritize areas of interest based on the maritime activity. It is assumed that a helicopter can be used as an extension of a vessel to perform patrol missions. This is considered especially valuable during search and rescue missions. Vessel range, speed, seakeeping capability and crew size contribute to define the Coast Guard's response and patrol capabilities. These attributes are also considered important for search and rescue missions.

When considering oil recovery and tugging operations, the following attributes become important in addition to mentioned attributes:

- The number of vessels with oil recovery capability.
- The number of vessels with tugging capability.
- Oil recovery tank capacity pr. vessel.
- Bollard pull pr. vessel.

The question is to what extent these additional system capabilities should be incorporated into the fleet design. It is difficult to foresee the number of, as well as the extent of, potential maritime casualties for an upcoming period.

The perceived value of the new fleet based on the described attributes can then be defined as the fleet's ability to adapt and respond to various mission needs during the fleet's life-cycle. The combined stakeholder value proposition can now be described as:

Value proposition: To develop a coast guard fleet that creates value through acquisition affordability, operational affordability while accomplishing defined mission tasks.

6.4.2 Value-Driven Design Formulation for the Coast Guard Fleet

Performance Attributes and Design Space:

Based on the context definition and requirements presented above, attributes for the fleet can be defined. These are quantitative sets of overarching vessel performance and capabilities which the fleet must have in order to meet strategic objectives. In table 6.1, performance attributes considered important for the coast guard vessels that will constitute the fleet is presented. The attributes are described on a range from "worst" to "best" representing stakeholder preferences.

The unit ranges for sensor and ice capability, are represented on a qualitative scale (low,medium,high). This scale refers to different levels of capabilities, where the unit notation "high", refers to the most preferred system capability level of that particular attribute. For example, sensor capability can consist of various levels of detection, tracking and communication capabilities, which can be further described by detailed quantitative scales. However, selecting the "right" sensor package needs a more refined and detailed study, and could have been treated in separate tradespaces since these systems represent significant cost levels.

For ice capability, "high" means that a vessel is certified with ice-breaking capabilities, "medium" means that a vessel has ice-strengthen hull without ice-braking capability, and "low" means that a vessel is not certified to operate in arctic environments. This could have been assessed in more detail, since applying different polar classes affects the CAPEX cost of a vessel (Appolonov, Nesterov, Paliy, & Timofeev, 2007).

While these qualitative scales are not necessarily realistic assumptions, they are sufficient for the demonstration purpose of this case study. Similar assumptions when using the Responsive Systems Comparison method has been done in previous literature (A. M. Ross & Hastings, 2005; Schaffner et al., 2014; Vascik et al., 2016).

Table 6.1: Vessel performance attributes

Attribute	**Unit**	**Range**	
		"Worst"	**"Best"**
CAPEX pr. Vessel	[mNOK]	high	low
OPEX pr. Vessel	[mNOK]	high	low
Nuumber of Vessels	[# of vessels]	5	8
Mission Range pr. Vessel	[nm]	4 000	10 000
Max Speed pr. Vessel	[kts]	10	28
Crew Size pr. Vessel	[# people]	20	100
Helicopter Capability pr. Vessel	[# installed]	0	2
Small Boat Capability pr. Vessel	[# installed]	0	3
Sensor Capability pr. Vessel	[low,medium,high]	low	high
Ice Capability pr. Vessel	[low,medium,high]	low	high
Oil Recovery Capacity pr. Vessel	[tonnes]	0	1 500
Bollard Pull Capacity pr. Vessel	[ton]	0	150

In order to evaluate alternative fleet compositions, a set of vessel designs has to be considered. Before individual vessel designs are selected, an overarching capability goal for the coast guard fleet is described in order to better grasp which attributes from table 6.1 that, at the system level of a vessel, are considered to provide value for the fleet during different mission contexts. These are listed below:

1. Control Fishery Activity:
    1.1. Detect offensives - *Identify vessels performing illegal activities that are not in compliance with the fishery jurisdiction:*
        1.1.1. Number of vessels - *Improves the ability to be present at various locations simultaneously.*
        1.1.2. Vessel range - *Indicates a vessels patrol capability and endurance.*
        1.1.3. Vessel speed - *Indicates response capability*
        1.1.4. Helicopter capability - *Although helicopters are not considered as direct assets in the SoS environment of this case study, having the capability of operating an embarked helicopter from a vessel is considered to increase a vessels range and response capability.*
        1.1.5. Ice capability - *Ability to operate in near arctic regions*

    1.1.6. Sensor capability - *Situational awareness. Sharing information between vessels and helicopters makes it possible to coordinate and prioritize areas of interest.*

  1.2. Perform inspections - *Run alongside and boarding of fishing vessels in order to perform inspections assuring that the jurisdiction is followed*

    1.2.1. Helicopter capability - Bring crew to fishing vessels in order to perform inspections.

    1.2.2. Ice capability - *Perform inspections of fishing vessels operating in arctic regions.*

    1.2.3. Sensor capability - *Track fishing vessels*

    1.2.4. Small boat capability - *Launch and dispatch crew to board fishing vessels in order to perform inspections.*

    1.2.5. Crew size - *Prepare, execute and document inspection results.*

  1.3. Maintain presence - *Provide a deterrent effect to reduce illegal activities by presence of the Coast Guard*

    1.3.1. Number of vessels - *Improves the ability to be present at various locations simultaneously.*

    1.3.2. Vessel range - *Indicates a vessels patrol capability and endurance.*

    1.3.3. Vessel speed - *Indicates response capability*

    1.3.4. Helicopter capability - *Although helicopters are not considered as direct assets in the SoS environment of this case study, having the capability of operating an embarked helicopter from a vessel is considered to increase a vessels range and increase the Coast Guard presence within the geographical area.*

    1.3.5. Ice capability - *Ability state the Coast Guards present in arctic regions*

    1.3.6. Sensor capability - *Situational awareness. Sharing information between vessels and helicopters makes it possible to coordinate and prioritize areas of interest.*

2. Search and Rescue Capability (SAR) - *Provide assistance and participate in search and rescue missions*

  2.1. Number of vessels - Increased preparedness.

   2.2. Vessel range - Ability to perform operations over longer periods without the need of frequent bunkering. Also describes a vessels ability to respond
   2.3. Vessel speed - Ability to respond to casualties
   2.4. Helicopter capability - Increased search radius and respons capability. Quick evacuation of people.
   2.5. Ice capability - Perform SAR operations in and near arctic regiong
   2.6. Sensor capability - Track and pinpoint location of eventual marine casualties.
3. Oil Recovery Capability - *Stabilize oil spills and perform oil recovery operations*
   3.1. Number of vessels with oil recovery capabilities - Increased preparedness to perform oil recovery operations if needed
   3.2. Vessel range - Ability to perform operations over longer periods without the need of frequent bunkering
   3.3. Vessel speed - Ability to respond to casualties
   3.4. Ice capability - Ability to perform oil recovery near arctic regions.
   3.5. Sensor capability - Track and pinpoint location of eventual marine casualties.
   3.6. Oil recovery tank size - Storage capacity
4. Tugging Capability - *Perform tugging operations*
   4.1. Number of vessels with tugging capability - Increased preparedness to perform tugging operations if needed
   4.2. Vessel range - Ability to perform operations over longer periods without the need of frequent bunkering
   4.3. Vessel speed - Ability to respond to casualties
   4.4. Sensor capability - Track and pinpoint location of eventual marine casualties.
   4.5. Ice capability - Ability to perform oil recovery near arctic regions.
   4.6. Bollard pull Capacity

Based on the attributes selected in table 6.1, and the mission capability description above, eight different vessel designs are considered. Table 6.2 shows the main dimensions and performance characteristics of the eight vessels considered. The vessels are assumed to be capable of performing safe operations up to sea state 5, and can survive sea state 9

(Faltinsen, 1990; Saunders, 2012-2013). The range measures are assumed valid for 12 knots cruising speed. Table 6.3 and 6.4 show each vessel's equipment capability.

Table 6.2: Vessel dimension and performance description

Vessel Number	**Displacement [tonnes]**	**LOA [m]**	**Beam [m]**	**Draught [m]**	**Range [nm]**	**Max Speed [kn]**	**Crew Capacity**
Vessel 1	1 890	83.0	13.0	3.7	5 000	20	40
Vessel 2	2 400	90.0	14.4	4.0	6 000	21	23
Vessel 3	2 500	95.0	14.4	4.0	6 500	23	50
Vessel 4	2 600	98.0	14.7	4.0	7 000	25	65
Vessel 5	4 000	93.0	16.0	6.0	6 500	18	24
Vessel 6	6 700	127.0	16.5	7.0	10 000	28	100
Vessel 7	9 800	135	19	6.5	10 000	22	85
Vessel 8	6 375	104	19.5	6.5	9 000	16	50

Table 6.3: Vessel equipment capability part I

Vessel Number	**Helicopter Capability [#]**	**Small Boat Capability [#]**	**Sensor Capability [low, medium, high]**	**Arctic Capability [low, medium, high]**
Vessel 1	0	1	low	low
Vessel 2	0	1	medium	low
Vessel 3	1	1	medium	medium
Vessel 4	1	2	medium	medium
Vessel 5	0	2	medium	medium
Vessel 6	1	3	high	medium
Vessel 7	1	2	medium	medium
Vessel 8	1	2	medium	high

Table 6.4: Vessel equipment capability part II

Vessel Number.	**Oil Recovery Tanks [tonnes]**	**Bollard Pull [ton]**
Vessel 1	0	50
Vessel 2	1000	50
Vessel 3	500	70
Vessel 4	0	70
Vessel 5	1 000	150
Vessel 6	0	50
Vessel 7	500	100
Vessel 8	1 000	100

The vessels presented in table 6.2 are then mapped into different fleet alternatives, creating a fleet space. Based on table 6.2-6.4, each vessel type with corresponding equipment capability and capacities become the design variables used to match the performance attributes in table 6.1. The following assumptions and constraints are applied to the fleet space:

- A fleet must consist of at least five vessels.
- A fleet can at most consist of eight vessels.
- Since there is a chance that the Coast Guard must be present in arctic regions, each fleet must have at least one vessel with ice-breaking capability.
- Since the fleet must be capable of participating in search and rescue missions, it is assumed that a fleet must have at least three vessels with helicopter carrying capacity due to preparedness requirements.

With these constraints applied, a fleet space consisting of 212 different fleet alternatives is created where the number of vessels constituting a fleet varies from 5 to 8 vessels. Since the geographical area has no defined boundaries, and that no data is present to forecast mission demand in order to determine the required number of vessels, some assumptions have been made. It is assumed that a vessel can operate 300 days a year. Based on table 6.1, the worst case situation for the Coast Guard is a fleet reduction to five or fewer vessels. Due to the potential of increased activity levels, a reduced structure might face challenges in being present at various locations simultaneously. If it is assumed that the commercial activity may represent contexts requiring between 1 500 to 2 400 patrol days from the Coast Guard in order to meet mission objectives and demands, a structure of five vessels will face challenges in meeting activity measures requiring 2 400 patrol days. A fleet structure of eight vessels will be able to meet activity measure requiring 2 400 patrol days, but during periods with low activity, such a structure might provide an overcapacity.

6.4.3 Epoch Characterization

To capture the contextual uncertainties outlined in the case description, a set of epoch variables are established. The selected epoch variables must be viewed against the attributes and design variables under consideration. This will help decision-makers to assess which fleet compositions that continues to deliver value during changes in the temporal aspect of system complexity through time.

Table 6.5 shows a qualitative and binary description of the epoch variables considered for this case study. The variables selected represent a small set of potential uncertainties, and has a relatively small resolution. This low resolution can be questioned, as there might be other epoch variables which has great value changing properties for a coast guard fleet. However, selecting a too high resolution on the epoch variables when no realistic data is present can result in evaluating differences between variables that are too small to influence the fleet as a whole. This will only result in increased computational effort since more tradespaces have to be evaluated (A. M. Ross & Rhodes, 2008). Based on the mission description, the selected performance attributes and design variables, the following epoch variables are assumed to impact stakeholders' value perception of the coast guard fleet the most.

Table 6.5: Epoch variables selected for the analysis

Exogeneous Uncertainty Categories:	**Epoch Variables:**	**Nr. of Levels:**	**Notes:**	**Binary range:**
Political Development:	Budget constraints:	[-]	Illustrated in tradespace	[-]
Development in the Fisheries:	Fishery activity:	2	[low,high]	[0,1]
	Geographical spread:	2	[low,high]	[0,1]
Commercial Development:	Offshore activity:	2	[low,high]	[0,1]
	Maritime traffic:	2	[low,high]	[0,1]
Development in Arctic Regions:	Arctic activity:	2	[low,high]	[0,1]

Based on table 6.5, each epoch is described by combining the binary ranges of each epoch variable. Enumerating all variables creates an epoch space consisting of 32 different contextual epochs in which a cost guard fleet might have to operate. Some examples of potential epoch representations are given below:

The binary combination **"0 0 0 0 0"** represents respectively an epoch where the fishery activity is low (0), the geographical spread is low (0), the offshore activity is low (0), the maritime traffic is low (0) and the activity near arctic regions is low(0).

The binary combination **"1 1 0 0 0"** represents an epoch where the fishery activity is high (1), the geographical spread is high (1), the offshore activity is low (0), the maritime traffic is low (0) and the activity near arctic regions is low(0).

The binary combination **"1 1 1 1 1"** represents an epoch where the fishery activity is high (1), the geographical spread is high (1), the offshore activity is high (1), the maritime traffic is high (1) and the activity near arctic regions is high (1).

The epoch variable "Arctic activity" is assumed to represent both fishery activity, offshore activity and maritime traffic in near arctic regions depending on the binary combinations of the variables.

6.4.4 Design-Epoch Tradespace Evaluation of Multiple Coast Guard Fleets

In this step, the utility and cost of each fleet alternative is calculated. Each of the performance attributes in table 6.1 are connected to a single-attribute utility function. This function is used to evaluate the total utility-value of each fleet alternative generated from the mapping process of the vessel designs presented in table 6.2-6.4. The different epoch variables presented in table 6.5 are assumed to change stakeholder preferences in terms of which performance attributes that becomes important when the operational context change. Aggregating the single-attribute utility scores with attribute preferences from the stakeholders, creates multi-attribute utility scores for each fleet alternative. Based on these scores, each fleet alternative can be ranked from worst to best. Figure 6.1 shows a process flow diagram of the steps performed when aggregating multi-attribute utility scores for each fleet alternative. The flowchart shows how single-attribute utility scores, with respect to each attribute under consideration, is calculated for all 212 fleet alternatives. Aggregating the single-attribute utility scores with stakeholder preferences creates mulit-attribute utility scores for each fleet alternative.

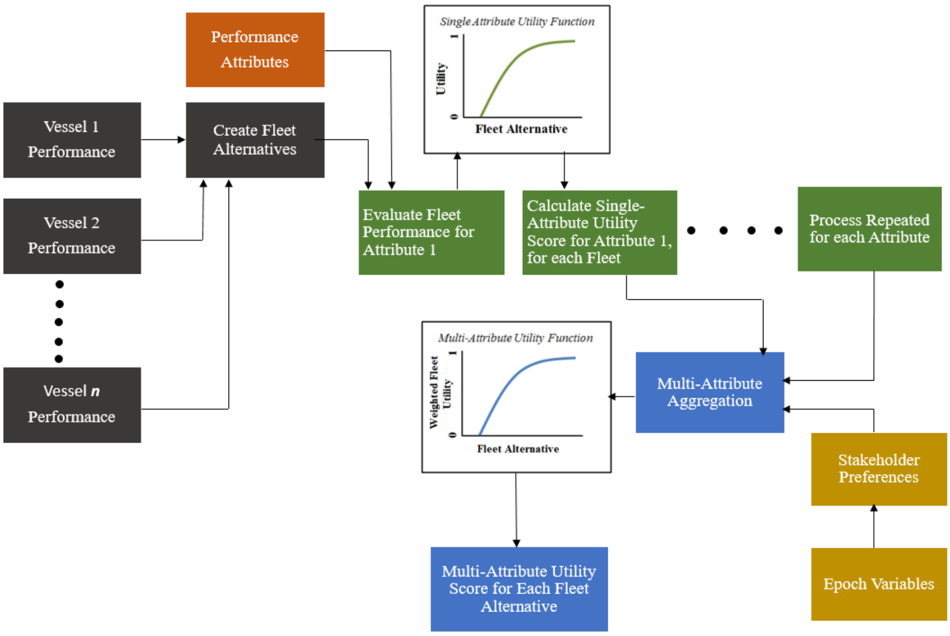


Figure 6.1: Process flow diagram of the steps performed when aggregating multi-attribute utility scores for each fleet alternative under consideration. Adopted from (Vascik et al., 2016).

Calculating Single-Attribute Utility Scores for each Fleet Alternative

The single-attribute utility function created for this case study aggregates vessel level performance based on the attributes in table 6.1, and the vessel equipment specifications in table 6.2-6.4, into single-attribute utility scores for each fleet. This function consists of three terms, and is given in equation 6.1:

$$u_{ij} = \sum P_{vi} \cdot n_{vj} \cdot \phi, \quad \forall\ i \in I, j \in J, v \in V \tag{6.1}$$

Here u_{ij} is the single-attribute utility score of fleet alternative j in set of possible fleet alternatives J, for attribute i in the set of attributes I. P_{vi} is the normalized utility score of vessel v in the set of vessels V, with respect to attribute i. n_{vj} is the number of vessel types v in fleet j, and ϕ is a multiple unit function that adjusts the utility value of fleet alternative j with respect to the number of vessels constituting the fleet.

The normalization score P_{vi} is calculated according to equation 6.2 (Ishizaka & Nemery, 2013):

$$P_{vi} = \frac{f_i(v) - f_i(min)}{f_i(max) - f_i(min)}, \qquad \forall\ i \in I, v \in V \tag{6.2}$$

In this equation, $f_i(v)$ is the performance- or capability level of vessel v with respect to attribute i. The terms $f_i(max)$ and $f_i(min)$ are respectively the maximum and minimum attribute values considered for attribute i, outlined in table 6.1. For example, vessel 3 gets a normalized utility score with respect to range performance as:

$$P_{Vessel3,Range} = \frac{6500 - 4000}{10000 - 4000} = 0.417 \tag{6.3}$$

The performance adjustment ϕ is describe by equation 6.4:

$$\phi = \sum_{i=1}^{n_{vj}} \frac{1}{i} \tag{6.4}$$

The performance adjustments are applied to adjust the utility score when combining different vessels into fleets, since each vessel constituting the fleet will provide value through the same system-level performance attribute, as discussed in section 4.5 concerning SoS attribute aggregation. Without this adjustment, the utility function will always recommend the decision-maker to add a vessel to the fleet, since this will provide a higher "utility value" due to the terms P_{vi} and n_{vj} in equation 6.1. For a SoS this is not necessarily the case. An example is illustrated considering a fleets patrol capability with respect to range. Depending on the boundaries of the geographical area, adding a vessel to a fleet might not necessarily increase the fleet's patrol capability with respect to range, as illustrated in figure 6.2. The circles around each vessel is assumed to represent the vessel's action radius, and the square surrounding the vessels are assumed to illustrate the geographical boundary in which the vessels operate. As the figure shows, the vessel's action radius overlaps, meaning that there is a convergence point in which adding more vessels to the fleet will not increase the fleet's utility with respect to patrol capability. Other variants of the performance adjustment equation could be considered depending on what types of attributes that are under consideration. However, the assumption made is considered valid for the other attributes presented in table 6.1.

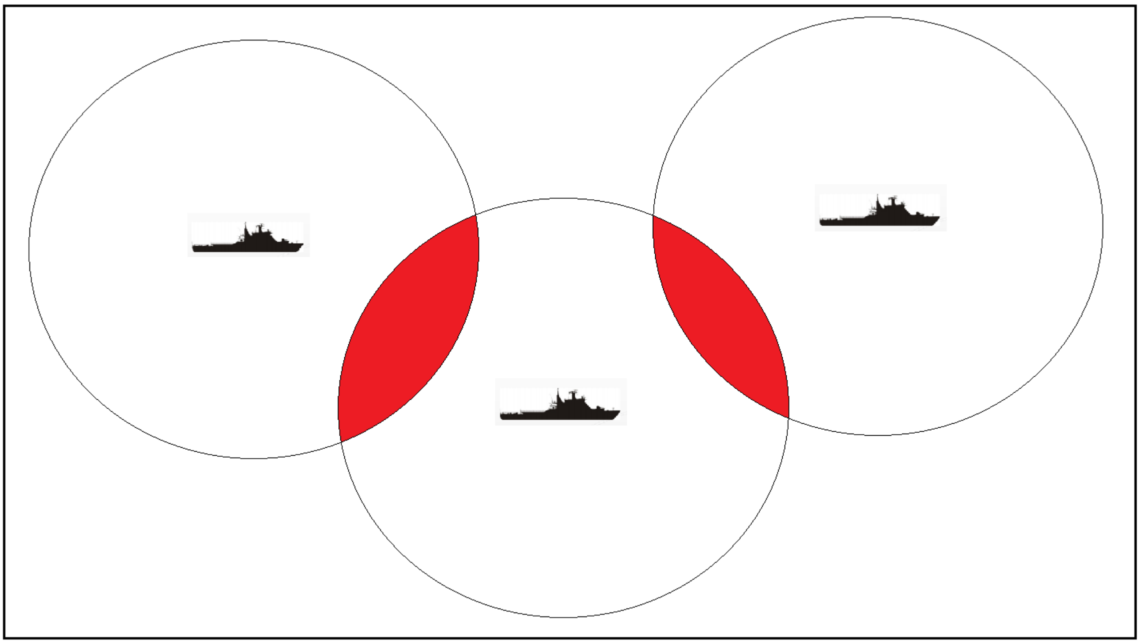


Figure 6.2: Illustration of how vessel action range might overlap within a defined geographical boundary. Vessel illustrations borrowed from (Nilsen, 2014)

Multi-Attribute Utility Function

Through a weighted sum aggregation of the single-attribute utility scores, multi-attribute utility scores for each fleet alternative is calculated using equation 6.5:

$$U_j = \sum_{i=1}^{I} u_{ij} \cdot \lambda_i, \qquad \forall \quad j \in J \tag{6.5}$$

Here, U_j represents the multi-attribute utility score of fleet alternative j in the set of fleets J, $u_i j$ is the single-attribute utility score for fleet j with respect to attribute i in the set of attributes I, as described in equation 6.1. λ_i denotes the weight preference of attribute i. The assigned weights are based on elicited information that reflect stakeholder preferences during different epochs.

Cost Model

The capital expenditures (CAPEX) and operational expenditures (OPEX) of each fleet alternative were mentioned as important attributes in table 6.1. While the utility scores of each fleet alternative might vary with different epochs, the cost associated with each fleet will not change as it is assumed to be deterministic. The cost data and equations used in this case study are based on values and equations found in Amdahl et al. (2001), Levander (2012) and Stopford (2009). The costs are calculated in NOK, and the cost data can be found in appendix D and E

The capital expenditure (CAPEX) is considered as a function of:

- **Vessel Steel Weight**

  The steel weight is based on the vessel's internal volume, and is calculated using equation 6.6:

  $$S_{wv} = K \cdot ((L_v \cdot B_v \cdot D_v) + ((L_h \cdot B_h \cdot H_h)\delta_h)), \quad \delta_h \in \{0, 1\} \tag{6.6}$$

  where S_{wv} is the vessel steel weight. K is the steel weight coefficient. L_v, B_v and D_v are respectively a vessel's length, beam and depth. L_h, B_h and H_h represent receptively the length, breadth and hight of hangar facilities if included on the vessels, represented by the binary variable δ_h taking the value 1 if a vessel has hangar facilities, and 0 if not. For vessels having ice strengthen hulls, the steel weight will be higher than without. This additional increase can vary between 30% to 50% of the steel weight depending on class notation (Appolonov et al., 2007). For vessels having "medium" ice capability a 30% increase is applied, and a 50% increase is applied if a vessel has "high" ice capability. The steel weight cost C_S^V is then calculated using equation 6.7:

  $$C_S^V = S_{wv} \cdot C_S^U \tag{6.7}$$

  where C_S^U is the unit cost pr. ton prefabricated hull.

- **Machinery**

  The machinery cost is based on installed main power, and is found using equation 6.8. C_M^V is the total machinery cost, C_M^U is the unit cost pr. installed BHP and I_P^V is the installed BHP on a vessel.

  $$C_M^V = C_M^U \cdot I_P^V \tag{6.8}$$

- **Accommodation**

  The cost associated with a vessel's accommodation size is calculated based on crew number using equation 6.9, where C_A^U the unit cost pr. crew member and n_C^V is the number of crew members each vessel can hold:

  $$C_A^V = C_A^U \cdot n_C^V \tag{6.9}$$

- **Sensor Capability**

  The cost associated with installed sensor capability is represented by the unit cost C^U_{SE}, and is dependent on the vessel's sensor capability level.

- **Small Boat Capability**

  The cost associated with having installed small boats is calculated using equation 6.10. Here C^U_{SB} is the unit cost of installing a small boat including launch and recovery systems. n^V_{sb} is the number of installed small boats on a vessel, and C^V_{SB} is the cost of having small boats installed.

$$C^V_{SB} = C^U_{SB} \cdot n^V_{sb} \tag{6.10}$$

- **Oil Recovery Tanks**

  The cost associated with oil recovery capability is calculated according to equation 6.11. C^V_{OT} is the cost of having installed oil recovery tanks on a vessel. C^U_T is the unit cost pr. tank volume installed, and T^V_v is the oil recovery tank volume installed on a vessel.

$$C^V_{OT} = C^U_T \cdot T^V_v \tag{6.11}$$

- **Tugging Capability**

  The cost associated with tugging capability is calculated according to equation 6.12.

$$C^V_{TG} = C^U_{TG} \cdot I^V_{BP} \tag{6.12}$$

The CAPEX of a vessel is then calculated according to equation 6.13:

$$C^V_{CAPEX} = C^V_S + C^V_M + C^V_A + C^U_{SE} + C^V_{SB} + C^V_{OT} + C^V_{TG} \tag{6.13}$$

The CAPEX for a fleet is then found by summing the CAPEX cost associated with each vessel constituting each fleet.

The OPEX costs pr. year are based on crew payroll, provision, maintenance, insurances and fuel consumption. It is assumed that a vessel can operate 300 days a year.

- **Crew Payroll**

Crew payroll is calculated according to equation 6.14, where C_{CP}^{V} is the annual crew payroll for a vessel, C_{A}^{C} is the average payment for each crew member pr. year, and n_{C}^{V} is the number of crew members on vessel v.

$$C_{CP}^{V} = C_{A}^{C} \cdot n_{C}^{V} \tag{6.14}$$

- **Provision Costs**

  The provision costs are calculated using equation 6.15, where C_{PV}^{V} is the annual provision cost for a vessel, C_{PV}^{CD} is the provision cost pr. crew day, OP^{V} is the number of operational days for a vessel and n_{C}^{V} is the number of crew members on a vessel.

  $$C_{PV}^{V} = C_{PV}^{CD} \cdot OP^{V} \cdot n_{C}^{V} \tag{6.15}$$

- **Maintenance and Insurance Costs**

  The maintenance costs pr. year for a vessel, C_{MA}^{V}, are calculated as 0.7% of the vessels CAPEX. The insurance costs pr. year for a vessel, C_{I}^{V}, are calculated as 0.8% of the vessels CAPEX.

- **Fuel Costs**

  The annual fuel costs are calculated according to equation 6.16, where C_{F}^{V} is the annual fuel cost pr. vessel, C_{FC}^{V} is the fuel cost for a vessel pr. day and OP^{V} is the number of operational days for a vessel.

  $$C_{F}^{V} = C_{FC}^{V} \cdot OP^{V} \tag{6.16}$$

The total OPEX for a cost is found according to equation 6.17:

$$C_{OPEX}^{V} = C_{CP}^{V} + C_{PV}^{V} + C_{MA}^{V} + C_{I}^{V} + C_{F}^{V} \tag{6.17}$$

The OPEX for a fleet is then found by summing the OPEX cost associated with each vessel constituting a fleet.

In reality, the CAPEX and OPEX may be subjected to uncertainty. Especially with respect to OPEX. As described by Stopford (2009), ship building is highly cyclical, and the demand for a new vessel in good times might drive the new building cost up, and vise versa (Stopford, 2009). The OPEX cost could have been considered as an epoch variable, since the annual funding for a coast guard affects how many patrol days a coast guard can produce.

6.4.5 Tradespace Exploration and Single Epoch Analysis

In this step, the utility score and cost of each fleet alternative is plotted in a tradespace. From this, the objective is to describe what the tradespace visualizes, and how promising fleet alternatives can be assessed by applying a Pareto frontier.

6.4.6 Multi-Epoch Analysis of Alternative Coast Guard Fleets

In this step, tradespaces for all 32 epochs are developed. A Pareto trace measure is applied to evaluate which fleets that are passive value-robust throughout all the 32 epochs. The Pareto trace collects the fleets that are on the Pareto frontier, without letting the fleet composition being changed. This is done to select promising fleet alternatives for the single-era analysis.

6.4.7 Era Construction of a Potential Context Realization

Since this thesis lacks sufficient data, only one era will be created for demonstration purposes of the RSC method. The eras are constructed according to the narrative approach applied by Gaspar et al. (2012). Using a narrative approach can be sufficient to describe the potential realization of different operational contexts. A narrative approach might also help to better visualize and capture stakeholder expectations. Epoch 32 will be used as the baseline epoch. The reason for this is that epoch 32 is assumed to describe the operating context experienced by the Coast Guard at present date. Each era is assumed to have a duration of 20 years constituted by four epochs having a duration of five years each. In order to reduce the computational burden, only a set of fleets will be analyzed based on the results from the multi-epoch analysis. An era analysis will help decision-makers to understand how a coast guard fleet can maintain its value through the uncertainty of a long run potential futures.

Era 1

During the first five years, the fishery activity and the geographical spread of the fisheries are assumed low. No activity takes place near arctic regions, and the offshore development and maritime traffic are assumed to be low. For the next five years, the fisheries activity starts increasing and gets a higher geographical spread. The stakeholders consider the number of vessels constituting the fleet as important because the Coast Guard might have to be present at various locations simultaneously. Further, the stakeholder starts weighting vessel range, speed, vessel crew size, sensor capability and helicopter capability as important attributes.

The next five years represents an epoch where the fishery activity and geographical spread of the fisheries are still high. In addition, offshore development starts taking place, resulting in increased maritime traffic. The stakeholders then also starts valuing oil recovery- and tugging capability as important attributes in order have sufficient preparedness in case of marine casualties.

The last five years of this era represents an epoch similar to the previous five years, but now the geographical spread of both fisheries and other commercial actors also start taking place near arctic regions. Due to the high geographical spread including near arctic regions, stakeholders adjust their preferences on vessel range, arctic capability and helicopter capability to be considered as the most important attributes. Oil recovery- and tugging capability are still considered as important.

Using the concept of "time value of money", the NPV of each fleet's operations cost is calculated for the entire era, using equation 6.18. Since potential risks associated with socio-economic investments are not properly investigated in this thesis, a 4% discount rate is assumed for the calculations (The Norwegian Government, 1999).

$$NPV_j = -I_j^C + \sum_{t=1}^{20} \frac{C_j^O}{(1-r)^t} \tag{6.18}$$

Here, NPV_j is the Net Present Value of fleet alternative j. I_j^C is the investment cost, CAPEX, for fleet alternative j. C_j^O is the yearly operational costs, OPEX, of fleet alternative j. t is the time period considered, and r is the discount rate. It is here assumed that operating the fleet as many days as possible yields stakeholder value pr. NOK spent.

6.5 Modeling Approach

For this case study the computer software MATLAB developed by Mathworks is used to model the first eight steps of the Responsive Systems Comparison method. All MATLAB scripts developed for this case study can be found in appendix F

Chapter 7

Results

7.1 Tradespace Exploration and Single-Epoch Analysis of Potential Coast Guard Fleets

From the case study, tradespaces for all 32 epochs was created. Figure 7.1 shows the tradespace for epoch 32, which is considered to be the baseline epoch. In this epoch, all mentioned activity levels from table 6.5 in section 6.4.3 are considered low. This is a good starting point to assess which fleet alternatives that looks promising for further investigations. In figure 7.1, all the blue points represent a feasible fleet alternative. The x-axis shows the CAPEX cost for each fleet alternative, and the y-axis, the corresponding multi-attribute utility score for this particular epoch. For epoch 32, sensor capability, helicopter capability, crew capacity and small boat capability were considered as important attributes in order to provide stakeholder value. One of the great benefits of tradespace visualization now becomes clear. Figure 7.1 shows how each potential fleet alternative positions itself against surrounding alternatives, making it possible to scope the utility-values of multiple fleet alternatives against different cost levels. This makes it possible to assess how good each fleet alternative is to provide value to involved stakeholders.

When exploring the tradespace, finding the Pareto frontier helps visualize which fleet alternatives that provides the highest utility, for a given cost. Figure 7.2 shows the Pareto frontier for epoch 32 highlighted as red points. On the Pareto frontier, the highest cost-utility tradeoffs are found were the slope of the multi-attribute utility function increases most rapidly, known as the ”knee-point” (A. Ross, McManus, Rhodes, & Hastings, 2010). It should be noted that all of the fleets have one ice-breaker (vessel 8) due to the ice-breaker restriction applied to the fleet space during the case study presentation.

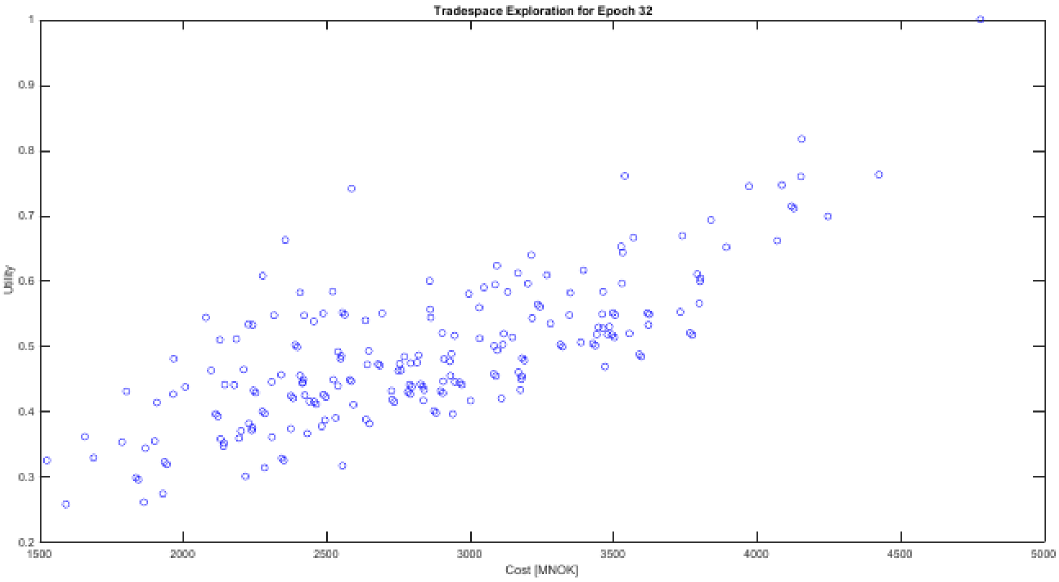


Figure 7.1: Initial tradespace representing epoch 32. All the blue points represent a feasible fleet alternative. The tradespace clearly shows how each fleet alternative gets positioned against surrounding fleet alternatives based on cost and perceived utility

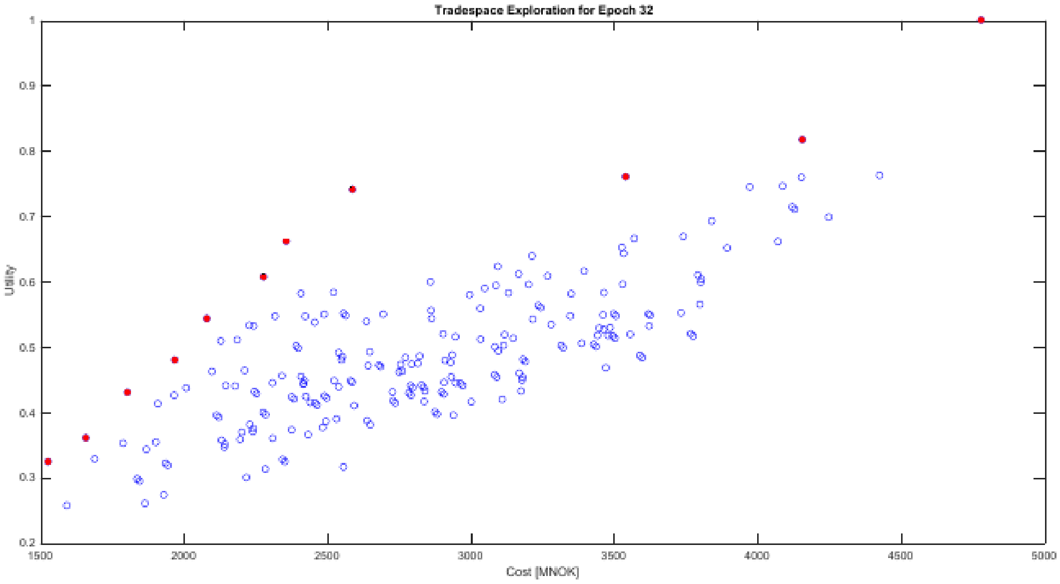


Figure 7.2: Pareto frontier for epoch 32 indicated by the red points. These points provide the highest utility for a given cost.

Figure 7.3 shows an example of how a tradespace can be used to identify an affordable solution region under the consideration of some cost and utility constraints. Extending the analysis by allowing decision-makers to consider fleet solutions beyond the maximum cost constraint might aid decision-makers to reveal whether or not solution alternatives within the constrained area fulfill the expected needs, or if solution alternatives beyond the maximum cost constraint will better fulfill the needs. This allows decision-makers to communicate with involved stakeholders on which compromises that have to be made, and why.

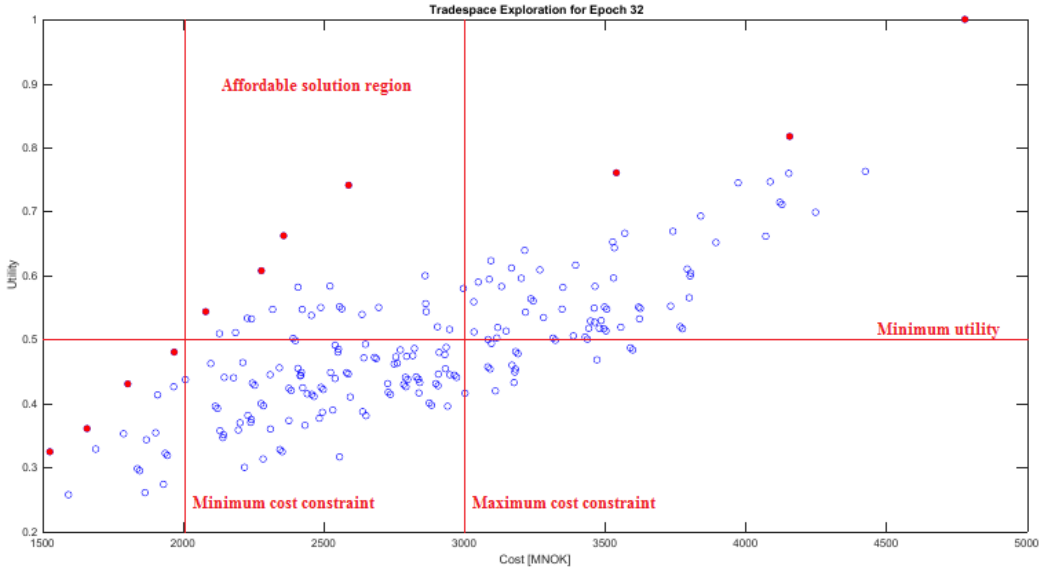


Figure 7.3: Visualization of an affordable solution region based on cost and utility preferences.

Figure 7.4 shows some promising fleet alternatives highlighted on the Pareto frontier indexed by fleet number. If future uncertainties are neglected for a second, it can be seen that fleet number 86 provides the highest utility, but also the highest cost. Fleet number 165 and 196 are placed at the "knee-point". Fleet number 1 has a much higher cost than fleet number 165, but almost the same utility-value. And fleet number 177 is at the low end on the utility scale. Table 7.1 provides a description of which vessels and how many that constitutes each highlighted fleet alternative.

Fleet number 86 gets the highest utility-value because the fleet consists of 7 vessels of vessel type 6. This vessel can be considered as a high endurance vessel with high performance characteristics. However, the question in this relation becomes whether the increased utility of fleet number 86 is worth the increased cost compared to for example fleet number 165 or 196 in terms of fulfilling mission requirements. This questions whether fleet number 86 is a better fleet than number 165 and 196. What differs fleet number 86 from fleet number 165 and 196 is that fleet number 165 mainly consists of vessel 4, and fleet number 196 of vessel 3. Vessel 6 has higher range capacity, better sensor capability, increased crew capacity, increased small boat capacity and higher speed potential compared to vessel 4 and 3.

Depending on the operational context of the Coast Guard, it might well be that fleet number 86 is the alternative that best satisfy expected mission requirements, resulting in a willingness to accept the increased cost compared to the other fleet alternatives. However, if decision-makers in compliance with involved stakeholders struggles to favor fleet number 86 over fleet number 165 or 196, choosing between fleet number 165 and 196 might potentially provide highly successful fleet compositions with respect to mission requirements, although their respective utility-values are somewhat lower. The question that has to be answered by the decision-makers and stakeholders is whether the increased performance of vessel 6 is an absolute necessity, or if compromises can be made.

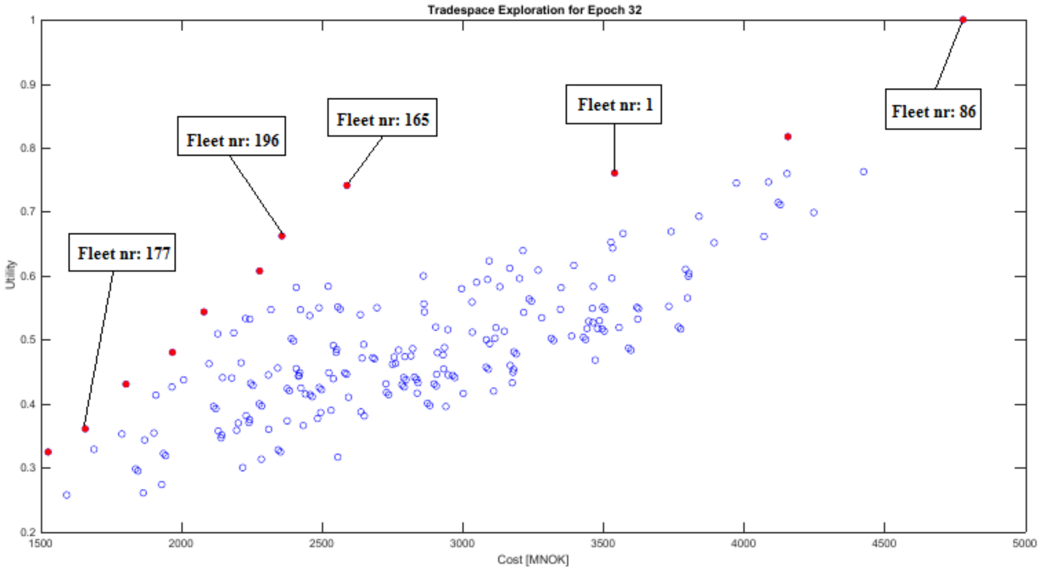


Figure 7.4: Tradespace visualization of epoch 32 with some highlighted fleet alternatives on the Pareto frontier. Fleet number 165 and 196 are found at the "knee-point" on the Pareto frontier, meaning that these fleet alternatives provides the highest cost-utility tradeoffs

Another interesting observation made from figure 7.4 is the cost and utility difference between fleet number 1 and 165. Fleet number 165 is at the "knee-point" in the tradespace, meaning that this fleet alternative provides the highest utility-value relative to cost for this particular epoch. If future uncertainties are still neglected, and no budget constraints are applied, a value-centric design approach using tradespace visualization can help to reveal how for example fleet number 1 provides almost the same utility value as fleet number 165, but at a much higher cost. The difference between fleet number 1 and 165 is that fleet number 1 has seven vessels of type 7 while fleet number 165 has seven vessels of type 4. What differs these vessels are that vessel 7 has higher range, increased crew capacity, oil recovery capability and increased tugging capability. Since range, oil recovery capability and tugging capability are not considered as important attributes for epoch 32, the extra capabilities of fleet number 1 does not improve the fleet's utility in the eyes of the stakeholders during this particular epoch.

Table 7.1: Vessel specification for the fleet alternatives highlighted on the Pareto frontier in figure 7.4. Note that fleet number 1 has almost the same utility value as fleet number 165, but at a much higher cost

Fleet number:	Number of Vessels:	Utility-Value [-]:	Cost [mNOK]:
Fleet nr. 86	7 x Vessel 6 1 x Vessel 8	1	4 780
Fleet nr. 1	7 x Vessel 7 1 x Vessel 8	0.760	3 451
Fleet nr. 165	7 x Vessel 4 1 x Vessel 8	0.741	2 589
Fleet nr. 196	7 x Vessel 3 1 x Vessel 8	0.662	2 358
Fleet nr. 177	4 x Vessel 4 1 x Vessel 8	0.361	1 659

Figure 7.5 illustrates another situation in which a vale-centric mindset can reveal interesting tradeoffs between the fleet alternatives considered in epoch 32 compared to a requirement-centered mindset by the ue of tradespace visualization. In figure 7.5, an upper limit cost constraint is applied. If only extensive attributes are considered, for example by requiring that a vessel must have a range of 10 000 nautical miles, a design action might be to maximize the number of vessels with range capacity of 10 000 nautical miles that can be acquired up to the constraint limit. This might result in only considering fleet structures like fleet number 22 and 104 illustrated by the green point solutions in figure 7.5. Fleet number 22 and 104 both consist of vessels (except from vessel 8) with range capacity of 10 000 nautical miles. However, as seen in the figure, other fleet alternatives might provide higher utility than these alternatives. The reason for this is that fleet number 165 and 196 has a fleet structure consisting og eight vessels, while fleet number 22 and 104 have a fleet structure consisting of five vessels, as described in table 7.2. If the need for the Coast Guard's services increases in response to mentioned epoch variables in section 6.4.3, choosing between fleet number 165 or 196 might be a better choice than choosing between fleet number 104 or 22 with respect to the cost constraint as fleet number 165 and 196 might provide greater value to the stakeholders. This because fleet number 165 and 196 might be able to maintain presence at multiple locations simultaneously due to a larger fleet structure, despite that the vessels constituting fleet number 165 and 196 do not have range capacity of 10 000 nautical miles. This illustrates potential trade-compromises that have to be made, emphasizing the dilemma described in section

3.4 concerning which vessel capabilities and performance criteria that are actually needed, as well as the deployment need regarding how the fleet should be utilized. If sufficient data had been present for this case study, suggesting that for example a fleet structure of five vessels would be sufficient, selecting fleet number 177 might also be considered as a good alternative since this fleet has low acquisition costs and is Pareto optimal.

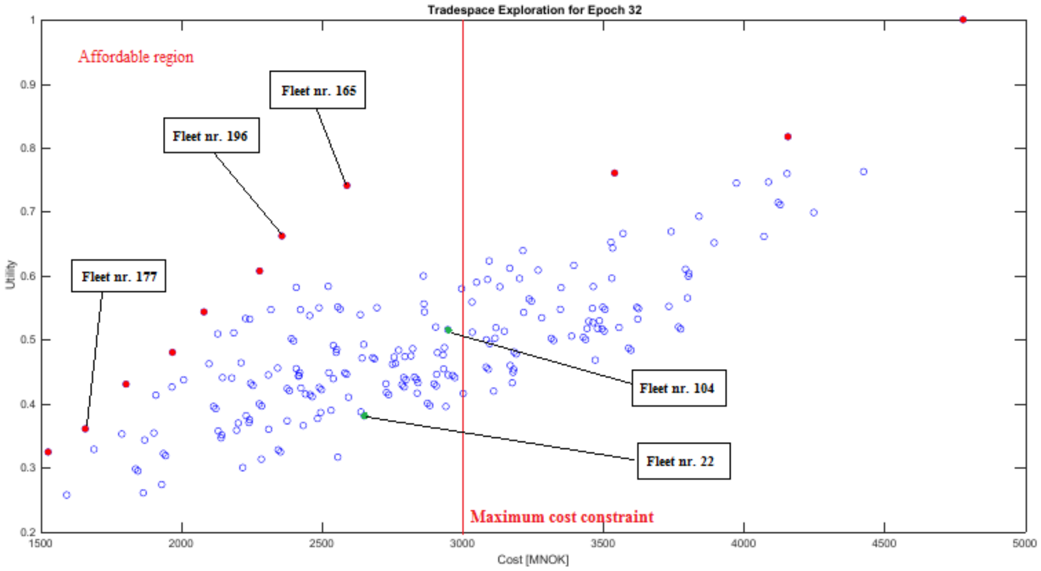


Figure 7.5: Tradespace visualization with some highlighted fleet alternatives on the Pareto frontier and some that are not. The tradespace visualization allows decision-makers to compare tradeoffs between different solutions based on stakeholders needs and perceptions of value attributes.

Table 7.2: Vessel description for fleet nr. 104 and 22 during epoch 32. Note how fleet alternative 104 has lower utility and higher cost compared to fleet number 165 and 196.

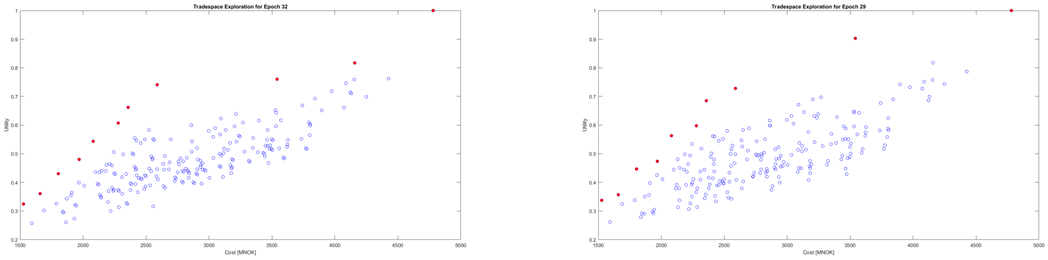
Fleet number:	Number of Vessels:	Utility-Value [-]:	Cost [mNOK]:
Fleet nr. 104	4 x Vessel 6 1 x Vessel 8	0.480	2 911
Fleet nr. 22	4 x Vessel 7 1 x Vessel 8	0.370	2 203
Fleet nr. 165	7 x Vessel 4 1 x Vessel 8	0.741	2 589
Fleet nr. 196	7 x Vessel 3 1 x Vessel 8	0.662	2 358
Fleet nr. 177	4 x Vessel 4 1 x Vessel 8	0.361	1 659

Based on the tradespace exploration of epoch 32, fleet number 86, 1, 165 and 196 are considered as promising fleet alternatives for further investigation.

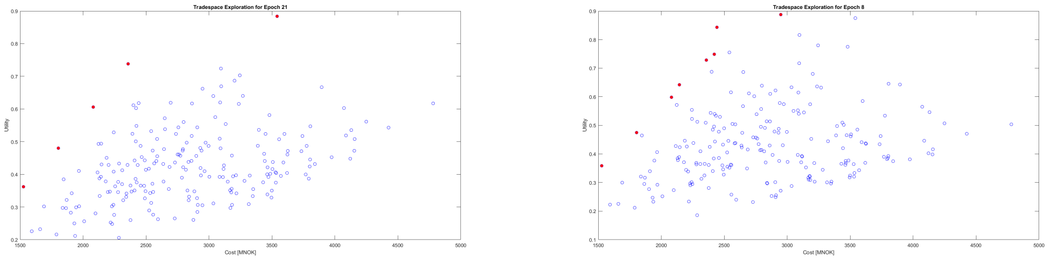
7.2 Multi-Epoch Analysis of Potential Coast Guard Fleets

In the previous section, epoch 32 was considered fixed when exploring the tradespace. This step seeks to reveal how future uncertainty might change which attributes that involved stakeholders value. Figure 7.6 illustrates how a tradespace might shift in different directions based on four different epochs. Sub-figure 7.6a shows the tradespace for epoch 32. The sub-figures clearly indicates how shifts in stakeholder perceptions drives the tradespaces in different direction with different magnitudes.

Epoch 29 represents an epoch where the fishery activity is high, the geographical spread is high and all other epoch variables are low, indicating a shift from epoch 32 by increased fishery activities. During this epoch, it is assumed that the stakeholders start valuing range, speed, crew capacity, sensor capability, small boat capability and helicopter capability as important attributes. Figure 7.7 shows how the fleet alternatives from epoch 32 positions themselves in epoch 29. The figure shows that the fleets that were on the Pareto frontier in epoch 32 still are on the Pareto frontier in epoch 29. However, fleet number 1 provides a higher utility-value in this epoch since vessel range is considered as more important than in epoch 32. This indicates that fleet number 1 might be a good fleet alternative if the activity levels increases.



(a) Tradespace exploration for epoch 32 (b) Tradespace exploration for epoch 29



(c) Tradespace exploration for epoch 21 (d) Tradespace exploration for epoch 8

Figure 7.6: Tradespace exploration for four different epochs. The tradespaces clearly indicate how shifts in stakeholder preferences drive the tradespaces in different direction with different magnitudes

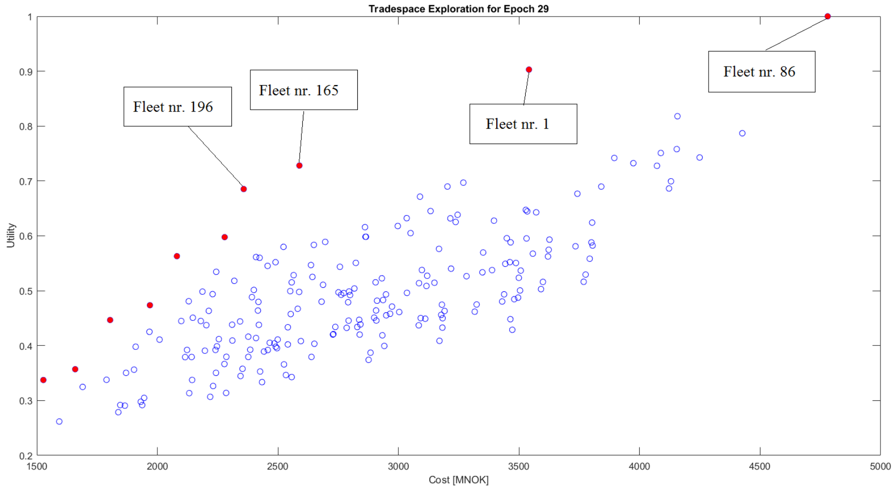


Figure 7.7: Tradespace exploration for epoch 29 with some highlighted fleets on the Pareto frontier. The fleets considered from epoch 32 are still on the Pareto frontier in epoch 29, but fleet number 1 has gained a higher utility value due to changed stakeholder preferences.

When considering epoch 21, a clear tradespace shift occurs as seen in figure 7.8. In this epoch, the fishery activity and geographical spread of the fisheries are assumed high. In addition, it is assumed that the offshore development is high. The stakeholders then also value oil recovery capability as an important attribute in order to maintain expected emergency preparedness. In figure 7.8 fleet number 86 and 165 moves down from the Pareto frontier since only vessel 8 has oil recovery capability, and the other vessels constituting these fleets have no oil recovery capability. Fleet number 1 and 196 remain on the Pareto frontier, since vessel 7 and 3 have oil recovery capabilities in addition to vessel 8. As seen from the figure, fleet number 196 is still located at the "knee-point" in this tradespace. What gives fleet number 1 a higher utility-value compared to fleet number 196, is that the vessels constituting fleet number 1 meets the attribute ranges set in table 6.1 near the preferred values for almost all the attributes under consideration.

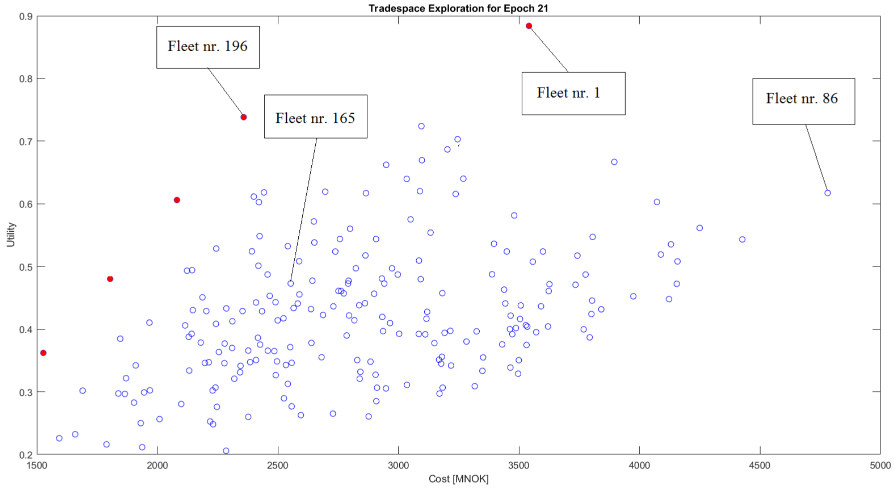


Figure 7.8: Tradespace exploration for epoch 21 illustrating how some fleet alternatives move away from the Pareto frontier as they are unable to fulfill all expectations set by the stakeholders.

For epoch 8, a new tradespace shift occurs. In this epoch, the fishery activity and geographical spread of the fisheries are assumed high. In addition, it is assumed that the offshore development and marine traffic is high. For this epoch, tugging capability is added as an important attribute. Figure 7.9 now shows that a new set of fleets appear on the Pareto frontier, and that the fleets found on the Pareto frontier in previous epochs, except from fleet number 196, moves down from the frontier. Fleet number 196 stays on the Pareto frontier due to the cost level of this fleet, and because all the vessels constituting that fleet to some extent has all the attributes considered important for epoch 8. Fleet number 86 and 165 are not on the Pareto frontier any more. They do however, still provide value as they are able to perform missions that not include oil recovery operations. Fleet number 1 is close to the Pareto frontier.

The vessels constituting the fleets on the Pareto frontier for epoch 8 are given in table 7.3. As seen in the table, vessel type 5 now constitutes many of the fleets on the Pareto frontier for epoch 8. This because vessel 5 has the highest oil recovery tank capacity and the highest bollard pull potential. The combination of vessel 5 with either vessel 3 or

7, in addition to vessel 8, gives high utility scores since these fleets cover many of the attributes considered in table 6.1 at the highest preference levels of the stakeholders.

The results from epoch 8 are perhaps particularly interesting for discussion. Fleet nr. 1 and 196 consist of vessels that all have the capabilities required for the various mission contexts that can be expected, but with lower oil recovery and tugging capability compared to vessel 5. The question in this relation is whether a fleet with multi-functional vessels are better than a fleet with different system-level capabilities.

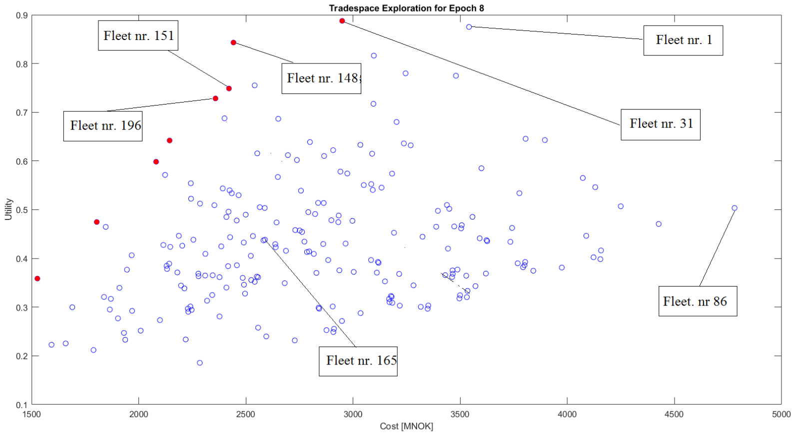


Figure 7.9: Tradespace exploration for epoch 8. New fleet alternatives with different vessel mix occur on the Pareto frontier

Table 7.3: Vessel specification for the fleet alternatives highlighted on the Pareto frontier in 7.9 for epoch 8

Fleet number:	Number of Vessels:	Utility-Value [-]:	Cost [mNOK]:
Fleet nr. 31	4 x Vessel 5 3 x Vessel 7 1 x Vessel 8	0.888	2 949
Fleet nr. 148	4 x Vessel 5 3 x Vessel 3 1 x Vessel 8	0.843	2 442
Fleet nr. 151	3 x Vessel 5 4 x Vessel 3 1 x Vessel 8	0.749	2 421
Fleet nr. 196	7 x Vessel 3 1 x Vessel 8	0.728	2 358

In order to determine which fleet alternatives that are passive value-robust, a Pareto trace was applied, tracing the fleet alternatives that were present on the Pareto frontier in all 32 epochs. This allows decision-makers to gain an understanding of which fleet alternatives that excel in handling contextual and perceptual changes without being altered. The results from the Pareto trace is shown in figure 7.10. The x-axis represents fleet number, and the y-axis represents the frequency of how often a particular fleet alternative occurred on the Pareto frontier. Figure 7.10 shows that some of the fleet alternatives were present on the Pareto frontier in all 32 epochs.

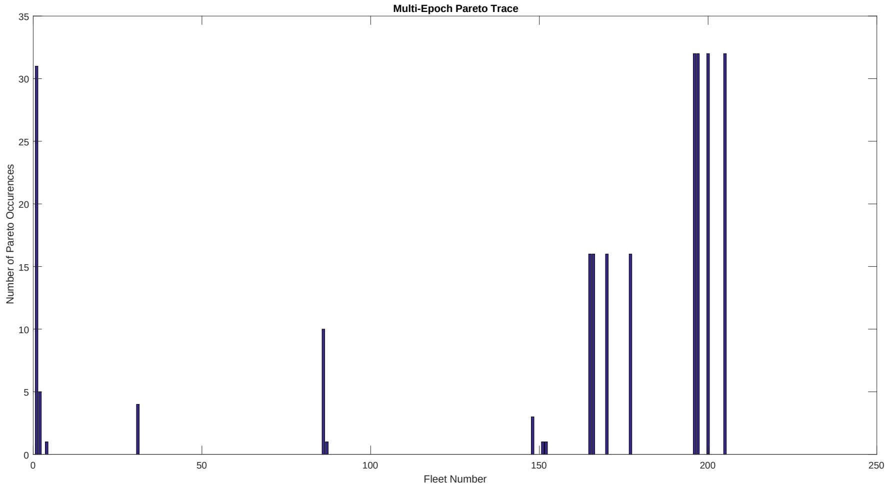


Figure 7.10: Pareto trace of all the fleet alternatives under consideration across all 32 epochs. Some fleets are never on the Pareto frontier, while others frequently occur on the Pareto frontier.

Table 7.4 gives a description of the fleets that occurred on the Pareto frontier during the multi-epoch analysis, and the number of vessel types that constitute each fleet. Table 7.5 shows the trace number, average utility and CAPEX cost of each fleet alternative. The trace number indicates how many times a particular fleet occurred on the frontier.

From the tables, many interesting observations can be made. First, non of the fleets consist of either vessel type 1 or vessel type 2. The reason for this is that these vessels only meet the attributes set in table 6.1 at the low end of the preference scale. These vessels do not get high utility scores, since other vessel alternatives meets stakeholders' value preferences better.

Further it can be seen that fleet number 205, 200, 197 and 196 has the highest trace numbers, being on the Pareto frontier in all 32 epochs. What makes these fleets passively value-robust is that the vessels constituting these fleet for all the attributes considered in table 6.1, are either at the midpoint or above the midpoint on all the preference scales. In addition, these fleets provide the highest utility for given cost levels compared to surrounding fleet alternatives in the tradespaces. As seen in table 7.4, these fleets have the same types of constituent systems. The only difference between these fleets are varying number of vessel type 3. Fleet number 205 has the lowest average utility score among these fleets because it might not be able to fulfill required missions if the required activity measures increases. However, adding more of vessel 3 to this fleet allows the fleet to transition into fleet number 200 ,197 or 196 making this constituent system able of meeting varying activity levels.

Fleet number 1 has the second highest Pareto trace of 31 occurrences and this fleet alternative also has the highest average utility score. The fleet is mainly constituted of vessel 7. The performance and system capabilities of vessel 7 are close to the ideal attribute preferences of the stakeholders in table 6.1. However, fleets consisting of fewer numbers of vessel type 7 are not on the Pareto frontier as many times as fleet number 1. This is because fleet alternatives consisting of fewer vessel of type 7 has a higher cost than comparable fleet sizes. Since only weight preferences for each attribute are applied, and no performance and capability constraints, the Pareto trace will only search for the solutions having the highest utility-value at given cost levels.

Fleet number 86, which had the highest utility-value during the single-epoch analysis of epoch 32 and 29, only occurred on the Pareto frontier 10 times. Although vessel 6, which mainly constitutes this fleet, meets most of the attribute preference scales in 6.1 at the high end, it has no oil recovery capability making it unable to fulfill stakeholder preferences, favoring designs that can perform oil recovery operations. The only vessel in this fleet that can perform some oil recovery is vessel 8. In addition, this fleet has the highest cost, questioning whether or not this is a good fleet alternative with respect to stakeholders' objectives in relation to mentioned cost attributes. The same yields for fleet number 165, which mainly consists of vessel type 4 which do not have oil recovery capability, and almost the same performance and equipment capabilities as vessel type 3.

If the Pareto trace was to be used as the only measure when determining the preferred fleet solution, most of the fleets presented in table 7.5 should not be considered for further analysis as only some yields high trace numbers. An obvious drawback of using only the Pareto trace measure is that fleet alternatives that are close to the Pareto frontier are left out. This could have been solved by including a fuzzy Pareto trace measure as described in Vascik et al. (2016). This allows for including alternatives that are within a certain range from the Pareto optimal alternatives. Instead, the average utility of the fleet alternatives presented in table 7.4 is used to identify fleet alternatives that provides high utility-values through all 32 epochs.

As seen from table 7.5, some of the fleet alternatives that had a low trace number have high average utility-values, indicating that these fleet alternatives might be close to the Pareto frontier through many of the epochs. These fleets are fleet number 4, 31, 148, 149 , 151 and 152. What is particularly interesting with these alternatives is that they are constituted by different vessel types, in contrast to the other mentioned fleets which only consist of one vessel type in addition to vessel 8, due to the ice-breaker constraint. The vessels that are present in these fleets are different combinations of vessel 3 and 5, 4 and 5, 5 and 6, and 5 and 7. A question that has to be considered at this point is whether it is a good strategy to only consider fleet alternatives mainly consisting of one vessel type that has some of all capabilities, or if a mix of different vessel types with different capability levels might be more preferable with respect to attribute expectations. Further discussion on this particular topic will be given in chapter 8.

Table 7.4: Fleet structure of the fleets that occurred on the Pareto frontier during the multi-epoch analysis.

Fleet	Number of each vessel type constituting each fleet							
Number:	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Vessel 7	Vessel 8
205	0	0	4	0	0	0	0	1
200	0	0	5	0	0	0	0	1
197	0	0	6	0	0	0	0	1
196	0	0	7	0	0	0	0	1
177	0	0	0	4	0	0	0	1
170	0	0	0	5	0	0	0	1
166	0	0	0	6	0	0	0	1
165	0	0	0	7	0	0	0	1
152	0	0	3	0	3	0	0	1
151	0	0	4	0	3	0	0	1
148	0	0	3	0	4	0	0	1
86	0	0	0	0	0	7	0	1
31	0	0	0	0	4	0	3	1
4	0	0	0	0	2	0	5	1
2	0	0	0	0	0	0	6	1
1	0	0	0	0	0	0	7	1

Table 7.5: Results from the multi-epoch analysis. The table shows which fleet alternatives that occurred on the Pareto frontier based on the trace number. The average utility of each fleet alternative through the 32 epochs is also given.

Fleet Number:	Trace Number:	Average Utility [-]:	Cost [mNOK]:
205	32	0,372	1 527
200	32	0,492	1 804
197	32	0,620	2 081
196	32	0,754	2 358
177	16	0,331	1 659
170	16	0,436	1 969
166	16	0,548	2 279
165	16	0,548	2 859
152	1	0,505	2 144
151	1	0,615	2 421
148	3	0,630	2 553
86	10	0,813	4 157
31	4	0,670	2 949
4	1	0,708	3 245
2	5	0,728	3 095
1	31	0,887	3 541

Based on the average utility-values and CAPEX costs of the fleets presented in table 7.4 and table 7.5, fleet number 1, 12, 148, 151, 196 and 205 are considered as interesting fleet alternatives for the Single-Era analysis.

7.3 Single-Era Analysis of Potential Coast Guard Fleet

Figure 7.11 shows the era representation described in section 6.4.7. In figure 7.11, the x-axis describes the yearly progression of the era, while the y-axis describes the perceived utility of each fleet alternative over the duration of the era.

Figure 7.11 shows which fleet alternatives that have the potential of maintaining high utility throughout the sequence of potential futures. The results clearly show how stakeholder perceptions of which attributes that become important during the contextual changes impact which fleet alternatives that move up or down along the utility scale.

Interesting observations are made from year 10 to 15. This contextual situation represents a period with high activity levels. It can be seen that fleet number 12, 148, 151 and 196 has almost the same utility-value despite different fleet compositions. This indicates that different fleet compositions in relation to stakeholder preferences might provide the same value, and that era representations might help to visualize this. What makes fleet number 1 and 196 to receive higher utility values from year 15 to 20 is that helicopter capability is considered especially important. Since fleet alternative 148 and 151 has fewer vessels with helicopter capability the perceived utility gets somewhat lower. Fleet number 1 has the highest utility during the era due to the fact that all the vessels constituting this fleet best meet stakeholder preferences having all capabilities wanted from the stakeholder. Fleet alternative 196 also provides high utility during the era. The vessel constituting this fleet also have all capabilities close to the ideal attribute preferences of the stakeholders. Fleet 205 has the lowest utility score due to reduced fleet structure compared to the other fleets. This means that this fleet might potentially face challenges in fulfilling stakeholder expectations if the activity levels require the Coast Guard to patrol up to 2 400 patrol days pr. year. However, adding more vessels to this fleet can as previously mentioned transition the fleet to become fleet number 196.

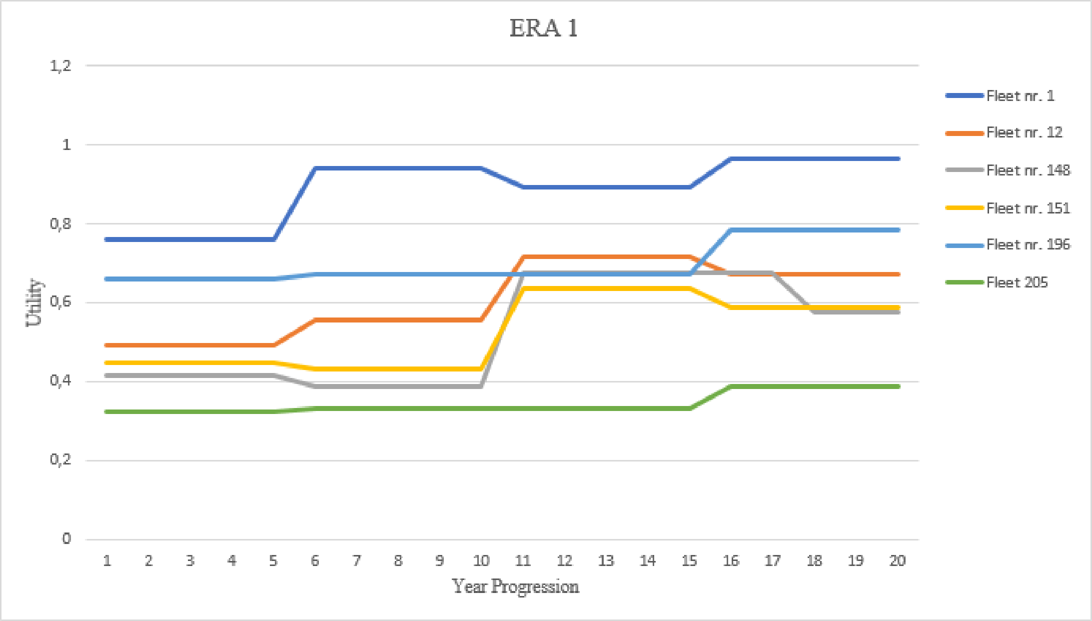


Figure 7.11: Single-era visualization and utility considerations for a set of selected fleet alternatives.

Using the concept of "time value of money", the NPV of each fleet's operations cost was calculated for the entire era. The results are given in table 7.6. The results show that the cash flow for upcoming years are more important than the cash flow for later years. The results also shows that fleet number 1 and 12 form one group with similar NPV values. Fleet number 148, 151 and 196 form anther group with similar NPV values. Based on the utility-values and NPV values, fleet number 1, 12, 148, 151 and 165 might all be considered as robust fleets that might continue to fulfill stakeholders expectations.

Table 7.6: Calculation of the net present values for each fleet alternative based on yearly operational cost.

[mNOK]	Fleet nr. 1	Fleet nr. 12	Fleet nr. 148	Fleet nr. 151	Fleet nr. 165	Fleet nr. 205
NPV Ops Yr. 1:	496	436	349	347	348	214
NPV Ops Yr. 2:	477	418	335	333	334	206
NPV Ops Yr. 3:	458	402	322	320	321	198
NPV Ops Yr. 4:	441	387	310	308	309	190
NPV Ops Yr. 5:	424	372	298	296	297	183
NPV Ops Yr. 6:	407	358	286	285	286	176
NPV Ops Yr. 7:	392	344	275	274	275	169
NPV Ops Yr. 8:	377	331	265	263	265	162
NPV Opr Yr. 9:	362	318	255	253	254	156
NPV Ops Yr. 10:	348	306	245	243	244	150
NPV Ops Yr. 11:	335	294	235	234	235	144
NPV Ops Yr. 12:	322	282	226	225	226	139
NPV Ops Yr. 13:	309	272	218	216	217	133
NPV Ops Yr. 14:	297	261	209	208	209	128
NPV Ops Yr. 15:	286	251	201	200	201	123
NPV Ops Yr. 16:	275	241	193	192	193	119
NPV Ops Yr. 17 :	264	232	186	185	185	114
NPV Ops Yr. 18:	254	223	179	178	178	110
NPV Ops Yr. 19:	244	215	172	171	171	105
NPV Ops Yr. 20:	235	206	165	164	165	101
NPV Ops. Total:	7 003	6 149	4 924	4 895	4 913	3 020
CAPEX:	3 541	3 097	2 442	2 421	2 589	1 527
NPV Total:	3 462	3 052	2 482	2 474	2 324	1 493

Form the results it becomes clear that the approach used to determine potential value-profitable fleet solutions is able to capture which vessel combinations that best meet stakeholders' perceptions at the system- and performance-level of a vessel. This indicates which fleet compositions that might continue to deliver stakeholder value over the fleet's life-cycle.

However, due to the lack of realistic and sufficient activity data, it is difficult to recommend one fleet alternative that best will meet stakeholders' objectives based on how the fleet might have to operate. The model is not able to quantitatively determine how good a particular fleet is to perform various set of tasks based on mission demands. Since no expert opinion has been present to assess the quality of the different fleet solutions in table 7.6, it will be difficult to derive qualitative recommendations. This questions the attributes, design variables, epoch variables and utility aggregation model used for this case study.

Chapter 8

Discussion

The objective of this thesis was to investigate how a value-centric decision approach might help to better assess the coast guard fleet mix problem by focusing on capturing stakeholder value. In this relation it is important to discuss whether this objective has been met.

Section 3.4 in chapter 3 described some of the main challenges faced when considering the coast guard fleet mix problem. As described, the coast guard fleet mix problem involves answering two questions. The first question is to answer what vessel capabilities that are needed based on how the fleet is to be utilized. The second question involves answering how the fleet is to be utilized based on different activity measures. The results from the case study shows that using a value-centric decision approach, like the Responsive Systems Comparison method, might help to assess the first question considering which vessel capabilities that are needed. The main benefit of using the Responsive Systems Comparison Method based on the results from the case study, is that it allows decision-makers to include different stakeholder objectives and attribute preferences when evaluating different coast guard fleet solutions. This enables dialog and knowledge building towards finding fleet solutions that will continue to deliver value to involved stakeholders. The cost-utility plots from a tradespace are intuitive and communicating, and does not require highly skilled competence in order to draw some basic conclusions. Exploring multiple tradespaces help visualize how potential risks related to future operating context might make a fleet composition less desirables, and suggests fleet solutions that help mitigate potential adverse consequences.

The Responsive Systems Comparison method allows stakeholders to better understand each others perceptions of which aspects that constitute the better fleet alternative, making it possible to match and assess top-down requirements with bottom-up expectations within a coast guard enterprise. The Responsive System Comparison method can therefore be said to enable stakeholders to better understand how a coast guard fleet might behave across various environments. This helps to better view which compromises that have to be made and why they have to be made by scoping trades at stake between design variables and resulting costs. Kana et al. (2016) discussed this as one of the great challenges in relation to naval systems design. By opening the solution space rather than closing it too early through the application of extensive attribute requirements, decision-makers can assess promising fleet structures at different cost level, and how these structures might deliver value over their life-cycle. This illustrates one of the benefits of considering a value-centric mindset when assessing the coast guard fleet mix problem.

The results from the case study in chapter 7 showed how a set of attributes and design variables can be used to evaluate the span of multiple fleet alternatives subjected to uncertain operating context. The presented tradespaces clearly showed how uncertainty (the temporal aspect) related to future missions might change the perception of which fleet structure that better suits stakeholder needs through changing Pareto frontier. However, since it is difficult to make recommendations based on this, the results from the case study might be deficient. This is due to two circumstances. First of all, the lack of sufficient activity data of commercial maritime traffic within a defined geographical area has made it difficult to really exploit the full potential of the Epoch-Era framework. In the case study, each epoch was only represented on a general basis through simplified binary variables in order illustrate how changing operational context might change which attributes that stakeholders might value upon different context realizations. The case study neither mentions any likelihoods of the different epochs being realized, nor what the different epochs actually require of a coast guard's resources. By collecting sufficient amount of activity data, it might be possible to represent various activity levels statistically, like the density and geographical spread of various fisheries during different periods. This will create a more realistic epoch space. Through such a collection it can be interesting to try representing the statistics through a Markov Process by the use of a Markov chain. A Markov chain might make it possible to evaluate the probability of transitioning from one context realization to another, assuming that potential context realizations can be modeled as different states. A Monte Carlo simulation can then be used to simulate the probability density distribution of these transition probabilities. For this to be valid, the Markov property must be valid referring to the memoryless property of a stochastic process, which assumes that future states of a process is only dependent upon the present state under consideration (S. M. Ross, 2014). Considering incorporation of

Markov processes within the Epoch-Era framework might help to better assess the needed vessel capabilities and how many vessels that might be required based on potential context realizations. From this, decision-makers can assess whether some constraints have to be applied to the design- and epoch space, increasing the understanding between design actions and cost-utility trades.

The second aspect that limits this case study from recommending a fleet structure is the approach used to measure and evaluate the utility-values of each fleet alternative. The utility-values presented in each tradespace only described how well a particular fleet met the considered stakeholders' expectations of required vessel performance and equipment capabilities. In the case study, a multi-attribute utility function based on multi-attribute utility theory was considered. This function only accounted for a limited set of attributes, where the single-attribute utility-score of a vessel in relation to different attributes where evaluated based on minimum and maximum attribute preferences. This gave fleets consisting of high performance vessels the highest utility scores during the epochs. The reason for this was that the considered multi-attribute utility function "favored" the fleets having the highest utility score for different cost levels represented by the Pareto frontier. However, the performance adjustment ϕ made it possible to adjust the utility scores based on which vessels that were mapped into different fleet alternatives. In order to increase the perceived utility of a fleet, higher cost levels followed, questioning how much a utility gain in terms of increased vessel performance is worth. An interesting aspect of including the performance adjustment factor was that it illustrated that at some point, adding more vessels or more vessel equipment to a fleet will not necessarily increase the utility. This can be considered as an realistic interpretation. However, other interpretations of ϕ should be considered in order to assess the sensitivity of utility changes.

The way the multi-attribute utility function favored vessels with multi-functional capabilities resulted in some interesting results during the exploration process of epoch 8 in section 7.2 when considering the presented attributes. In most of the epochs, fleets consisting of mainly one vessel type, either vessel 3 or 7 in addition to vessel 8, appeared on the Pareto frontier most frequently. In epoch 8 however, different fleet mixes, mainly constituted by combinations of vessel type 3, 4 or 7 with vessel 5, were present on the same Pareto frontier. The aspect that kept these fleets from entering the Pareto frontier in other epochs was that vessel 5 did not have helicopter capability, which was considered as an especially important attribute through most of the epochs. In addition, this vessel had lower max speed and crew capacity compared to most of the other vessels. As seen from the era results, fleets having vessel 5 only achieved high utility-values during epochs where the need for high oil recovery and tugging capabilities were considered important. This made it seem like vessel 5 was not able to perform mission tasks related to monitoring and controlling the fishery activity. This is wrong based on the attributes considered important for controlling the fishery activity. This questions the considered attributes in table 6.1, and the multi-attribute utility aggregation model presented in section 6.4.4. It becomes clear that the utility aggregation model is not able to consider operational attributes through how a System of Systems, in this case the vessels constituting a fleet, might interact with each other during various operational scenarios. The lack of hydrostatic performance characteristics of the vessels made it difficult to evaluate whether for example a helicopter can be operated while simultaneously performing oil recovery- or tugging operations. If a helicopter can not be operated while performing such operations, or vice versa, is the perceived utility-value of the fleets consisting of only vessel 3 or 7 as high as presented in table 7.4? Might instead a fleet constituted by a mix of vessels with different capabilities be more capable of performing a various sets of tasks? Answering these questions using multi-attribute utility theory addresses the need for a definition of how to measure a fleet's flexibility and adaptability in terms of how a fleet can respond to various mission demands. At this point, describing operational attributes for a fleet that is still valid for application with multi-attribute utility theory feels somewhat diffuse. This because the term "value" now becomes a dynamic property that will vary based on how the vessels constituting a fleet might be deployed in relation to each other. Such an attribute consideration might involve complex System of Systems attribute aggregations since operational performance measures have to be incorporated in the attribute sets in order to describe how well a particular fleet can meet dynamic operational preferences. Considering the different multiple unit functions presented by Vascik et al. (2016) might potentially reveal other attribute aggregation models that can capture operational attributes. The great benefit of a multi-attribute utility function is that is allows for ranking systems according to set of attributes. However, representing operational aspects through a multi-attribute utility function might be unfavorable as one of the limitations with multi-attribute utility theory is that it quantifies the aggregated benefit of a given system using an abstract dimensionless metric which might resonate poorly with stakeholders (A. M. Ross, O'Neill, et al., 2010).

Recommending a fleet alternative based on the results from the case study might require combinations of different approaches to better understand how good a particular fleet might be. The reviewed literature from chapter 2 showed that open source material has primarily considered the coast guard fleet mix problem using mathematical optimization.

The reviewed papers mainly focused on assuring that station mission demands was covered for upcoming periods, by finding the optimal allocation- and/or deployment strategies for a set of vessels, based on how they were to be utilized. An interesting consideration at this point is whether different deployment models using mathematical optimization, as outlined in section 4.7, can be combined with the Responsive Systems Comparison method to increase the exploration process. Deployment models might better capture the need for a coast guard's deployment based on potential activity levels at different locations. Based on tradespace results, different fleet alternatives can be tested in deployment models to see how they meet defined constraints. Through sensitivity analysis, decision-makers can assess how sensitive these models are to changes in constraint parameters.

Testing different objective functions can help to assess how a fleet might have to respond to various situations. This can for instance be least cost functions aiming to find the fleet alternative that can fulfill deployment constraints at the lowest cost considering a set of different fleet alternatives. Another objective function to consider might be one measuring fleet flexibility. Such an objective function might aim to derive which fleet alternative that is most flexible in its ability to meet changing mission requirements, measuring fleet flexibility and adaptability. This particular objective function might be interesting to investigate further due to the uncertainty of a coast guard's mission demands. This function might reveal the fleet mix which best meets a coast guard's mission requirements when subjected to both budgetary constraints and other constraints. This might be a starting point for discussing fleet performance measures. A performance measure might be to evaluate expected response, as well as the outcome of this response, based on different demands for the coast guard fleet's services. As reviewed by Bhargava (1991), it must be discussed with experts how to interpret mission performance definitions, since mission performance will depend on how performance is measured, compared and aggregated across various mission contexts. Considering how future mission demands are hard to foresee, conducting the right aggregation might be difficult (Bhargava, 1991).

Since later years demand for a coast guard fleet's service might be subjected to high variance, applying a two-stage stochastic model might be considered sufficient. Such a model allows decision-makers to account for future uncertainty. In addition, discrete event simulation should be considered when evaluating the coast guard fleet mix problem, and this thesis should have reviewed literature within this topic. This has not been done. A fleet size and mix model combined with a discrete event simulation model could introduce potential disruptions stochastically, which would bring additional realism to the analysis. Combining such methods with the Responsive System Comparison method might allow decision-makers to explore the bigger picture when selecting a sufficient coast guard fleet. First different fleet structures can be assessed using value-centric decision methodologies scoping cost-utility trades, then testing promising alternatives with fleet size and mix-and/or simulation models, finding the fleet alternatives that performs best. This might give decision-makers and involved stakeholders a better decision support tool to discuss different trade compromises.

The cost model presented in the case study considered cost as deterministic. This is a poor representation of investment costs and cash flows since they might be affected by stochastic disruptions (Schofield, 2010; Stopford, 2009). Determining the affordability of acquiring and operating a coast guard fleet is equally important as determining which vessel capabilities that are needed. The presented tradespace results briefly discussed affordable regions, but with no uncertainty or randomness related to different cash flows. What should have been considered for the case study was measures that better grasp potential variations in cash flows for a coast guard when reviewing affordable fleet solutions. Acquisition by itself comprises many different activities that may have different funding profiles, and some decision-makers may be more interested in certain cost elements then others. Including Multi-Attribute Expense (MAE) measures in a tradespace, replacing cost with MAE on the x-axsis, makes it possible to assess cost elements using the principle behind multi-attribute utility theory. This makes it possible to consider various cost elements as different epoch variables, creating epoch scenarios for various affordability situation as done in both (Schaffner et al., 2013; Vascik et al., 2016). While it is always simpler to work with just one cost metric, it prevents decision-makers from considering how different elements of cost affects the acquisition process.

Chapter 9

Conclusion and Recommendations for Further Work

The decision to acquire a fleet of coast guard vessels is typically irreversible and of longterm impact. Once vessels are built and bought, they typically remain within the fleet for a few decades, emphasizing the importance of acquiring vessels that can sustain valuable throughout their life-cycle. Based on the reviewed literature and the results presented in this thesis, the Responsive Systems Comparison method is considered to be a methodology suitable for assessing value-profitable coast guard fleet structures when the future operating context is uncertain. The method's ability to capture stakeholder value by assessing multiple cost-utility tradeoffs between a large number of different alternatives, seems to be the greatest advantage of this methodology. The methodology visualizes the importance of keeping the solution space open before considering extensive requirements. This allows decision-makers and involved stakeholders to scope designs-trades at various levels. The literature emphasized this as important, especially within defense acquisitions, in order to derive successful systems by moving away from a requirement-centered mindset.

The case study presented in this thesis is perhaps a bit too simple as it did not consider a realistic situation within a defined geographical boundary in which a coast guard fleet was to operate. To improve this case study, further work on the problem should aim to collect data that can be used to represent more realistic epochs providing detailed description of various activity levels, and the probabilities of these activity levels occurring. Combining improved epoch descriptions with expert opinion using the presented utility aggregation model might help to better describe the perception of how good each fleet alternative might be in performing expected mission tasks. Reconsidering the attribute preference scales presented in the case study, as well as considering other potential attributes more relevant for the coast guard fleet mix problem should be assessed. To better assess the cost elements affecting the coast guard fleet mix problem, applying Multi-Attribute Expense measures should be considered to better grasp the relative importance of different cost elements when deriving system affordability.

What is particularly interesting for further consideration is how combining fleet size and mix models and simulation models with the Responsive Systems Comparison method might increase the tradespace exploration process, as it aligns the perspectives on value-centric decision making with well documented optimization algorithms. Introducing these models with the Responsive Systems Comparison method might help to describe how capable different fleet structures presented in a tradespace might be to respond to different contextual situations. This will hopefully enhance decision-makers and involved stakeholders understanding of how many vessels that are actually needed, and which vessel capabilities to include in the vessel designs. This makes it possible to assess whether fleet structures consisting of only multi-functional vessels might be better compared to a mix of vessels with different capability levels, and vice verca. Further, introducing different assets like helicopters and planes should be considered in order to improve the realism of the case study, addressing the need for considering high-level System of Systems attribute aggregation, as discussed by Chattopadhyay et al. (2009). New epoch variables like technology development related to system enhancement should also be considered, discussing interoperability potentials.

Although the presented case study faced limitations and did not mange to recommend a fleet structure, it illustrated the Responsive System Comparison method's potential, and how it might be used to assess the coast guard fleet mix problem focusing on stakeholder value. Through the recommendations for further work, developing a framework combining value-centric thinking with deployment models might improve decision-support within this topic.

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Appendix A

Thesis Contract

NTNU – Trondheim
Norwegian University of
Science and Technology

Master Thesis in Marine Systems Design
for
Marius Oddmund Buland
"Addressing the Coast Guard Fleet Mix
Problem From a Value-Centric Perspective"
Spring 2017

Background

The coast guard fleet mix problem is particularly complex. The problem involves determining which vessel capabilities that are needed , and how the fleet is to be utilized, addressing the issue of determining how many vessels that are actually needed. In contrast to commercial maritime fleets, where accomplished missions yields monetary profit, determining the optimal coast guard fleet mix is difficult as accomplished tasks often represents non-monetary values. Recommending sufficient fleet structure might therefor be somewhat diffuse as it is difficult to measure the return on these types of investments.

The decision to acquire a fleet of coast guard vessels is typically irreversible and of longterm impact. Once vessels are built and bought, they typically remain within the fleet for a few decades. This emphasize the importance of acquiring vessels that can sustain valuable to stakeholders throughout their life-cycle. This addresses the need for methodologies that are suitable for assessing value-profitable coast guard fleet structures, by focusing on how to capture involved stakeholders value perceptions in relation to which aspects that constitute the better coast guard fleet when the future operating context is uncertain.

Primary Objective

The primary objective of this thesis is to describe the challenges faced when considering the coast guard fleet mix problem, and how a value-centric decision methodology can be used during an early design phase to assess the problem by focusing on stakeholder value before any major commitment of resources has occurred.

Scope of Work

The candidate should seek to cover the following main points:

1. Perform a literature study scoping what others have done within the field of assessing maritime fleet compositions with especially focus on coast guard- and naval fleet compositions. The candidate shall also derive relevant literature considering value-centric decision methodologies.
2. Derive the role and tasks of the Norwegian Coast Guard as an introduction to the coast guard fleet mix problem, before presenting some of the challenges faced when considering the coast guard fleet mix problem on a generic basis.
3. Briefly describe the challenges related to decision-making with multiple objectives, and how uncertainty affects the decision-making process.
4. Describe and compare different methodologies relevant for the coast guard fleet mix problem, and from this discuss why especially value-centric decision methodologies might help to support decisions in relation to this topic.
5. Present a generic and illustrative case study where a value-centric decision methodology is demonstrated on the coast guard fleet mix problem.
6. Discuss and conclude on the method applicability to assess the coast guard fleet mix problem based on results from the case study. From this, further work on the topic shall be presented.

Ownership

According to current rules, NTNU has the ownership of this thesis if not stated otherwise. Use of this thesis outside NTNU has to be approved by NTNU (or external partner(s) when this applies). If nothing has been agreed in advance, the department can use the work from this thesis as if the work was carried out by an employee at NTNU. If parts of the thesis contains sensitive or classified information, research and results within this area shall be handed in as a separate appendix to main supervisor and collaborating partner(s) where the project work is rooted. After evaluation of the candidate's work, the appendix shall be marked for destruction. Collaborating partner(s) can keep the appendix according to current rules for storage of classified material within their company.

Supervision

Professor Bjørn Egil Asbjørnslett will be the candidates main supervisor at NTNU. Phd. Candidate and Research Assistant Sigurd Solheim Pettersen will be the candidates co-supervisor at NTNU.

The candidate will collaborate with the Norwegian Naval Staff (SST Plan) during the work of this thesis. Contact person will be Commander Oddgeir Nordbotten, Staff Officer at SST Plan.

Appendix B

List of Acronyms

AHP - Analytical Hierarchy Process

BHP - Break Horse Power

CGV - Coast Guard Vessel

Cutter - Vessel with length greater than or equal to 65 foot

EEA - Epoch Era Analysis

LOA - Length Over All

MAE - Multi-Attribute Expense

MAUT - Multi-Attribute Utility Theory

MDCM - Multi-Criteria Decsion Making

NOK - Norwegian Kroner

NPV - Net Present Value

NEAFC - North East Atlantic Fisheries Commission

RSC Method - Responsive Systems Comparison Method

SoS - System of Systems

VA - Value Analysis

WPM - Weighted Product Model

WSM - Weighted Sum Model

Appendix C

List of Symbols

B_h - Breadth of hangar facility [m]

B_v - Vessel beam [m]

C_A^C - Average payment for each crew member pr. year [NOK/person pr. year]

C_A^U - Unit cost pr. crew member accommodation [NOK/person]

C_{CAPEX}^V - CAPEX of a vessel [NOK]

C_{CP}^V - Yearly crew payroll for a vessel [NOK]

C_F^V - Annual fuel cost pr. vessel [NOK/year]

C_{FC}^V - Fuel cost for a vessel pr. day [NOK/day]

C_I^V - Insurance cost for a vessel pr. year [NOK/year]

C_j^O - Yearly operating cost of fleet alternative j [NOK]

C_M^V - Total machinery cost [NOK]

C_M^U - Unit cost pr. installed BHP [NOK/BHP]

C_{MA}^V - Maintenance for a vessel pr. year [NOK/year]

C_{OPEX}^V - OPEX cost for a vessel pr. year [NOK/year]

C_{OT}^V - Cost of installed oil recovery tanks on a vessel [NOK]

C_{PV}^V - annual provision cost for a vessel [NOK]

C_{PV}^{CD} - Provision cost pr. crewday [NOK/Crewday]

C_{SB}^V - Total cost of installed small boats [NOK]

C^U_{SE} - Unit cost sensor [NOK]

C^V_S - Steel weight cost [NOK]

C^U_S - Unit cost pr. ton prefabricated hull [NOK/ton]

C^U_{SB} - Unit cost of installing a small boat [NOK/unit]

C^U_T - Unit cost pr. volume installed oil recovery tank $[NOK/m^3]$

C^V_{TG} - Cost of installed bollard pull [NOK]

C^U_{TG} - Unit cost pr. installed ton bollard pull [NOK/ton]

D_v - Vessel depth [m]

H_h - Height of hangar facility [m]

I^V_{BP} - Installed bollard pull capacity on a vessel [ton]

I^C_j - Investment cost for fleet alternative j [NOK]

I^V_P - Installed BHP on a vessel [BHP]

K - Steel weight factor $[ton/m^3]$

L_h - Length hangar facility [m]

L_v - Length of vessel [m]

n_{cv} - Number of crew member a vessel can hold [# persons]

n^V_C - Number of crew members on a vessel [# persons]

n^V_{sb} - number of installed small boats on a vessel [# units]

n_{vj}- Number of vessels v constituting fleet alternative j

P_{vi} - Normalization score for vessel v with respect to attribute i

r - Discount rate

S_{wv} - Steel weight of a vessel [ton]

T^V_v - Oil recovery tank volume installed on a vessel m^3.

u_{ij} - Single-Attribute utility score f fleet alternative j with respect to attribute i

U_j - Aggregated multi-attribute utility score for fleet alternative j

ϕ - Multiple unit function. Used to adjust SoS utility

Appendix D

CAPEX Cost of each Vessel

Table D.1: CAPEX Cost Vessel 1

Vessel 1:		
Steel Cost Hull:		
LOA	[m]	83
Beam	[m]	13
Depth	[m]	6,8
Draght	[m]	3,7
K	[ton/m3̂]	0,21
Steel Weight Hull	[ton]	1540,812
Added weight polar	% add of steelweight	1
Total weight	[ton]	1540,812
Unit cost pr. ton steel	[NOK/ton]	35000
Steel Cost Hull	[NOK]	53928420
Cost Main Machinery		
Installed Power	[BHP]	12605,608
Unit Cost pr. BHP	[NOK/BHP]	3500
Cost Main Machinery	[NOK]	44119627
Hangar Cost:		
Hangar length	[m]	0
Hangar breadth	[m]	0
Hangar height	[m]	0
Steel Weight Hangar	[ton]	0
Steel Cost Hangar	[NOK]	0
Cost Accomodation:		
Crew	[# persons]	40
Unit Cost Accomodation	[NOK/person]	500000
Cost Accomodation	[NOK]	20000000
Cost Sensro:		
Sensor type	[-]	[medium]
Cost sensor	[NOK]	100000000
Cost Smalboat:		
Smal Boats	[# installed]	1
Unit Cost Smalboat	[NOK/unit]	200000
Cost Smalboat	[NOK]	200000
Cost Oil Recovery Tanks:		
Oil Recovery Tanks	[m3̂]	0
Unit Cost pr. Cubic Oil Recovery Tank Installed	[NOK/m3̂]	30000
Cost Oil Recovery Tanks	[NOK]	0
Cost ATHS:		
Bollard Pull	[tonnes]	50
Unit Cost pr. ton bollard pull installed	[NOK/ton]	30000
Cost Intsalled Bollar Pull	[NOK]	1500000
CAPEX VESSEL 1:	[NOK]	219748047
	[mNOK]	219,74805

Table D.2: CAPEX Cost Vessel 2

Vessel 2:		
LOA	[m]	90
Beam	[m]	14,4
Depth	[m]	6,8
Draght	[m]	4
K	[ton/m3̂]	0,21
Steel Weight Hull	[ton]	1850,688
Added weight polar	% add of steelweight	1,3
Total weight	[ton]	2405,8944
Unit cost pr. ton steel	[NOK/ton]	35000
Steel Cost Hull	[NOK]	84206304
Cost Main Machinery		
Installed Power	[BHP]	12605,608
Unit Cost pr. BHP	[NOK/BHP]	3500
Cost Main Machinery	[NOK]	44119627
Hangar Cost:		
Hangar length	[m]	24
Hangar breadth	[m]	10
Hangar height	[m]	7
Steel Weight Hangar	[ton]	352,8
Steel Cost Hangar	[NOK]	12348000
Cost Accomodation:		
Crew	[# persons]	45
Unit Cost Accomodation	[NOK/person]	500000
Cost Accomodation	[NOK]	22500000
Sensor type	[-]	[medium]
Cost sensor	[NOK]	100000000
Smal Boats	[# installed]	1
Unit Cost Smalboat	[NOK/unit]	200000
Cost Smalboat	[NOK]	200000
Cost Oil Recovery Tanks:		
Oil Recovery Tanks	[m3̂]	1000
Unit Cost pr. Cubic Oil Recovery Tank Installed	[NOK/m3̂]	30000
Cost Oil Recovery Tanks	[NOK]	30000000
Cost ATHS:		
Bollard Pull	[tonnes]	50
Unit Cost pr. ton bollard pull installed	[NOK/ton]	30000
Cost Intsalled Bollar Pull	[NOK]	1500000
CAPEX VESSEL 2:	[NOK]	294873931
	[mNOK]	294,87393

Table D.3: CAPEX Cost Vessel 3

Vessel 3:		
LOA	[m]	95
Beam	[m]	14,4
Depth	[m]	7,0
Draght	[m]	4
K	[ton/m3̂]	0,21
Steel Weight Hull	[ton]	2010,96
Added weight polar	% add of steelweight	1,3
Total weight	[ton]	2614,248
Unit cost pr. ton steel	[NOK/ton]	35000
Steel Cost Hull	[NOK]	91498680
Cost Main Machinery		
Installed Power	[BHP]	12605,60765
Unit Cost pr. BHP	[NOK/BHP]	3500
Cost Main Machinery	[NOK]	44119626,76
Hangar Cost:		
Hangar length	[m]	24
Hangar breadth	[m]	12
Hangar height	[m]	7
Steel Weight Hangar	[ton]	423,36
Steel Cost Hangar	[NOK]	14817600
Cost Accomodation:		
Crew	[# persons]	50
Unit Cost Accomodation	[NOK/person]	500000
Cost Accomodation	[NOK]	25000000
Sensor type	[-]	[medium]
Cost sensor	[NOK]	100000000
Smal Boats	[# installed]	1
Unit Cost Smalboat	[NOK/unit]	200000
Cost Smalboat	[NOK]	200000
Cost Oil Recovery Tanks:		
Oil Recovery Tanks	[m3̂]	0
Unit Cost pr. Cubic Oil Recovery Tank Installed	[NOK/m3̂]	30000
Cost Oil Recovery Tanks	[NOK]	0
Cost ATHS:		
Bollard Pull	[tonnes]	50
Unit Cost pr. ton bollard pull installed	[NOK/ton]	30000
Cost Intsalled Bollar Pull	[NOK]	1500000
CAPEX VESSEL 3:	[NOK]	277135906,8
	[mNOK]	277,1359068

Table D.4: CAPEX Cost Vessel 4

Vessel 4:		
LOA	[m]	98
Beam	[m]	14,4
Depth	[m]	7,5
Draght	[m]	4
K	[ton/m3̂]	0,21
Steel Weight Hull	[ton]	2222,64
Added weight polar	% add of steelweight	1,3
Total weight	[ton]	2889,432
Unit cost pr. ton steel	[NOK/ton]	35000
Steel Cost Hull	[NOK]	101130120
Cost Main Machinery		
Installed Power	[BHP]	12605,608
Unit Cost pr. BHP	[NOK/BHP]	3500
Cost Main Machinery	[NOK]	44119627
Hangar Cost:		
Hangar length	[m]	24
Hangar breadth	[m]	12
Hangar height	[m]	7
Steel Weight Hangar	[ton]	423,36
Steel Cost Hangar	[NOK]	14817600
Cost Accomodation:		
Crew	[# persons]	65
Unit Cost Accomodation	[NOK/person]	500000
Cost Accomodation	[NOK]	32500000
Sensor type	[-]	[medium]
Cost sensor	[NOK]	100000000
Smal Boats	[# installed]	2
Unit Cost Smalboat	[NOK/unit]	200000
Cost Smalboat	[NOK]	400000
Cost Oil Recovery Tanks:		
Oil Recovery Tanks	[m3̂]	500
Unit Cost pr. Cubic Oil Recovery Tank Installed	[NOK/m3̂]	30000
Cost Oil Recovery Tanks	[NOK]	15000000
Cost ATHS:		
Bollard Pull	[tonnes]	70
Unit Cost pr. ton bollard pull installed	[NOK/ton]	30000
Cost Intsalled Bollar Pull	[NOK]	2100000
CAPEX VESSEL 4:	[NOK]	310067347
	[mNOK]	310,06735

Table D.5: CAPEX Cost Vessel 5

Vessel 5:		
LOA	[m]	93
Beam	[m]	16
Depth	[m]	8,5
Draght	[m]	6
K	[ton/m3̂]	0,21
Steel Weight Hull	[ton]	2656,08
Added weight polar	% add of steelweight	1,3
Total weight	[ton]	3452,904
Unit cost pr. ton steel	[NOK/ton]	35000
Steel Cost Hull	[NOK]	120851640
Cost Main Machinery		
Installed Power	[BHP]	8716,6436
Unit Cost pr. BHP	[NOK/BHP]	3500
Cost Main Machinery	[NOK]	30508253
Hangar Cost:		
Hangar length	[m]	0
Hangar breadth	[m]	0
Hangar height	[m]	0
Steel Weight Hangar	[ton]	0
Steel Cost Hangar	[NOK]	0
Cost Accomodation:		
Crew	[# persons]	24
Unit Cost Accomodation	[NOK/person]	500000
Cost Accomodation	[NOK]	12000000
Sensor type	[-]	[medium]
Cost sensor	[NOK]	100000000
Smal Boats	[# installed]	2
Unit Cost Smalboat	[NOK/unit]	200000
Cost Smalboat	[NOK]	400000
Cost Oil Recovery Tanks:		
Oil Recovery Tanks	[m3̂]	1000
Unit Cost pr. Cubic Oil Recovery Tank Installed	[NOK/m3̂]	30000
Cost Oil Recovery Tanks	[NOK]	30000000
Cost ATHS:		
Bollard Pull	[tonnes]	150
Unit Cost pr. ton bollard pull installed	[NOK/ton]	30000
Cost Intsalled Bollar Pull	[NOK]	4500000
CAPEX VESSEL 5:	[NOK]	298259893
	[mNOK]	298,25989

Table D.6: CAPEX Cost Vessel 6

Vessel 6:		
LOA	[m]	127
Beam	[m]	16,5
Depth	[m]	9,0
Draght	[m]	7
K	[ton/m3̂]	0,21
Steel Weight Hull	[ton]	3960,495
Added weight polar	% add of steelweight	1,3
Total weight	[ton]	5148,6435
Unit cost pr. ton steel	[NOK/ton]	35000
Steel Cost Hull	[NOK]	180202523
Cost Main Machinery		
Installed Power	[BHP]	49349,613
Unit Cost pr. BHP	[NOK/BHP]	3500
Cost Main Machinery	[NOK]	172723645
Hangar Cost:		
Hangar length	[m]	24
Hangar breadth	[m]	16,5
Hangar height	[m]	7
Steel Weight Hangar	[ton]	582,12
Steel Cost Hangar	[NOK]	20374200
Cost Accomodation:		
Crew	[# persons]	100
Unit Cost Accomodation	[NOK/person]	500000
Cost Accomodation	[NOK]	50000000
Sensor type	[-]	[high]
Cost sensor	[NOK]	200000000
Smal Boats	[# installed]	3
Unit Cost Smalboat	[NOK/unit]	200000
Cost Smalboat	[NOK]	600000
Cost Oil Recovery Tanks:		
Oil Recovery Tanks	[m3̂]	0
Unit Cost pr. Cubic Oil Recovery Tank Installed	[NOK/m3̂]	30000
Cost Oil Recovery Tanks	[NOK]	0
Cost ATHS:		
Bollard Pull	[tonnes]	0
Unit Cost pr. ton bollard pull installed	[NOK/ton]	30000
Cost Intsalled Bollar Pull	[NOK]	0
CAPEX VESSEL 6:	[NOK]	623900368
	[mNOK]	623,90037

Table D.7: CAPEX Cost Vessel 7

Vessel 7:		
LOA	[m]	135
Beam	[m]	19
Depth	[m]	8,0
Draght	[m]	6,5
K	[ton/m3̂]	0,21
Steel Weight Hull	[ton]	4309,2
Added weight polar	% add of steelweight	1,3
Total weight	[ton]	5601,96
Unit cost pr. ton steel	[NOK/ton]	35000
Steel Cost Hull	[NOK]	196068600
Cost Main Machinery		
Installed Power	[BHP]	18774,30926
Unit Cost pr. BHP	[NOK/BHP]	3500
Cost Main Machinery	[NOK]	65710082,41
Hangar Cost:		
Hangar length	[m]	24
Hangar breadth	[m]	19
Hangar height	[m]	7
Steel Weight Hangar	[ton]	670,32
Steel Cost Hangar	[NOK]	23461200
Cost Accomodation:		
Crew	[# persons]	85
Unit Cost Accomodation	[NOK/person]	500000
Cost Accomodation	[NOK]	42500000
Sensor type	[-]	[medium]
Cost sensor	[NOK]	100000000
Smal Boats	[# installed]	2
Unit Cost Smalboat	[NOK/unit]	200000
Cost Smalboat	[NOK]	400000
Cost Oil Recovery Tanks:		
Oil Recovery Tanks	[m3̂]	500
Unit Cost pr. Cubic Oil Recovery Tank Installed	[NOK/m3̂]	30000
Cost Oil Recovery Tanks	[NOK]	15000000
Cost ATHS:		
Bollard Pull	[tonnes]	100
Unit Cost pr. ton bollard pull installed	[NOK/ton]	30000
Cost Intsalled Bollar Pull	[NOK]	3000000
CAPEX VESSEL 7:	[NOK]	446139882,4
	[mNOK]	446,1398824

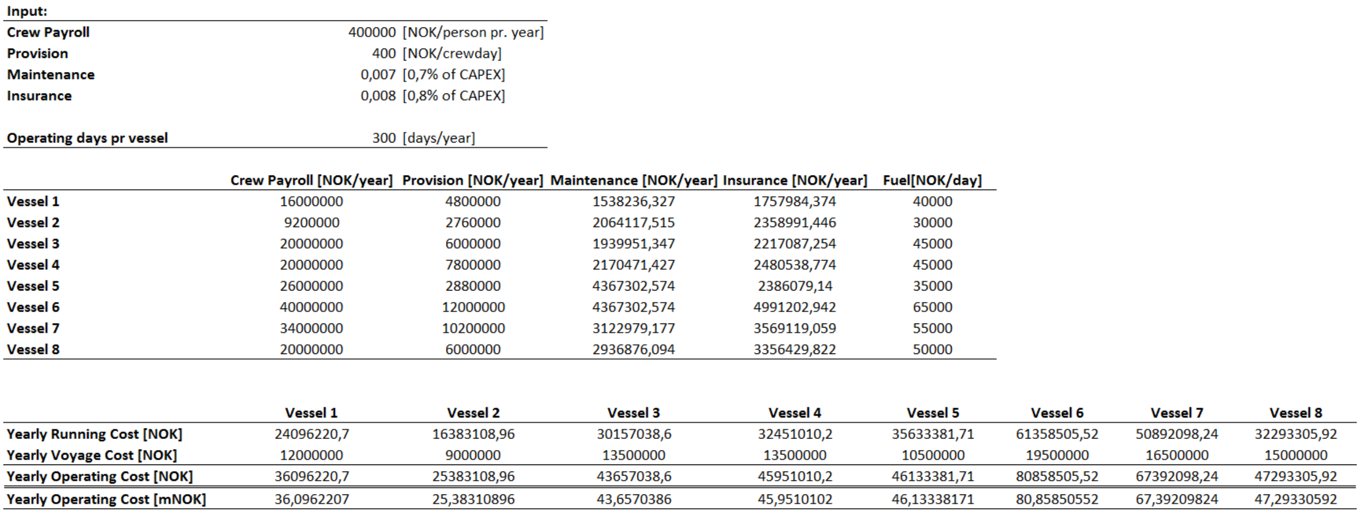
Table D.8: CAPEX Vessel 8

Vessel 8:		
LOA	[m]	104
Beam	[m]	19,5
Depth	[m]	8,0
Draght	[m]	6,5
K	[ton/m$\hat{3}$]	0,21
Steel Weight Hull	[ton]	3407,04
Added weight polar	% add of steelweight	1,5
Total weight	[ton]	5110,56
Unit cost pr. ton steel	[NOK/ton]	35000
Steel Cost Hull	[NOK]	178869600
Cost Main Machinery		
Installed Power	[BHP]	16092,265
Unit Cost pr. BHP	[NOK/BHP]	3500
Cost Main Machinery	[NOK]	56322928
Hangar Cost:		
Hangar length	[m]	24
Hangar breadth	[m]	19
Hangar height	[m]	7
Steel Weight Hangar	[ton]	670,32
Steel Cost Hangar	[NOK]	23461200
Cost Accomodation:		
Crew	[# persons]	85
Unit Cost Accomodation	[NOK/person]	500000
Cost Accomodation	[NOK]	42500000
Sensor type	[-]	[medium]
Cost sensor	[NOK]	100000000
Smal Boats	[# installed]	2
Unit Cost Smalboat	[NOK/unit]	200000
Cost Smalboat	[NOK]	400000
Cost Oil Recovery Tanks:		
Oil Recovery Tanks	[m$\hat{3}$]	500
Unit Cost pr. Cubic Oil Recovery Tank Installed	[NOK/m$\hat{3}$]	30000
Cost Oil Recovery Tanks	[NOK]	15000000
Cost ATHS:		
Bollard Pull	[tonnes]	100
Unit Cost pr. ton bollard pull installed	[NOK/ton]	30000
Cost Intsalled Bollar Pull	[NOK]	3000000
CAPEX VESSEL 8:	[NOK]	419553728
	[mNOK]	419,55373

Appendix E

OPEX Cost of each Vessel

Table E.1: OPEX Costs



Input:		
Crew Payroll	400000	[NOK/person pr. year]
Provision	400	[NOK/crewday]
Maintenance	0,007	[0,7% of CAPEX]
Insurance	0,008	[0,8% of CAPEX]
Operating days pr vessel	300	[days/year]

	Crew Payroll [NOK/year]	Provision [NOK/year]	Maintenance [NOK/year]	Insurance [NOK/year]	Fuel[NOK/day]
Vessel 1	16000000	4800000	1538236,327	1757984,374	40000
Vessel 2	9200000	2760000	2064117,515	2358991,446	30000
Vessel 3	20000000	6000000	1939951,347	2217087,254	45000
Vessel 4	20000000	7800000	2170471,427	2480538,774	45000
Vessel 5	26000000	2880000	4367302,574	2386079,14	35000
Vessel 6	40000000	12000000	4367302,574	4991202,942	65000
Vessel 7	34000000	10200000	3122979,177	3569119,059	55000
Vessel 8	20000000	6000000	2936876,094	3356429,822	50000

	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5	Vessel 6	Vessel 7	Vessel 8
Yearly Running Cost [NOK]	24096220,7	16383108,96	30157038,6	32451010,2	35633381,71	61358505,52	50892098,24	32293305,92
Yearly Voyage Cost [NOK]	12000000	9000000	13500000	13500000	10500000	19500000	16500000	15000000
Yearly Operating Cost [NOK]	36096220,7	25383108,96	43657038,6	45951010,2	46133381,71	80858505,52	67392098,24	47293305,92
Yearly Operating Cost [mNOK]	36,0962207	25,38310896	43,6570386	45,9510102	46,13338171	80,85850552	67,39209824	47,29330592

Appendix F

MATLAB Scripts

F.1 MAIN.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% MAIN SCRIPT - This script calculates the 6 first steps of the RSC method
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
clear all
format long

%Create design space of feasible vessels
[Design_Space,Design] = Create_Design_Space_Patrol();

[Fleet_Space_Infeasible] = Create_Fleet_Space_infeasible();

%Create feasible fleet space
[Fleet_Space] = Create_Fleet_Space(Fleet_Space_Infeasible);

%Create attributes
[Attribute_Nr_PatDays,Attribute_Nr_Vessels,Attribute_Range,...
    Attribute_Endurance,Attribute_Speed,Attribute_Helicopter,...
    Attribute_Smallboat,Attribute_Sensors, Attribute_Arctic,...
    Attribute_Crew,Attribute_Oil_Rec,Attribute_Bollard_Pull] =...
    Performance_Attributes();

%Calculate normalized performance score for each vessel
[Vessel_Score_Range,Vessel_Score_Speed,Vessel_Score_Crew,...
 Vessel_Score_Helicopter,Vessel_Score_Smallboat,Vessel_Score_Sensor,...
 Vessel_Score_Ice,Vessel_Score_OilRec,Vessel_Score_Tugging] =...
 Normalization_Score_Vessel(Design_Space,Attribute_Range,...
 Attribute_Speed,Attribute_Crew,Attribute_Helicopter,...
```

```
 Attribute_Smallboat,Attribute_Sensors,...
 Attribute_Arctic,Attribute_Oil_Rec,Attribute_Bollard_Pull);

%Calculate single-attribute utilities for each fleet
[Range_Utility_Fleet,Speed_Utility_Fleet,Crew_Utility_Fleet,...
    Helicopter_Utility_Fleet,Smallboat_Utility_Fleet,...
    Sensor_Utility_Fleet,Ice_Utility_Fleet,...
    OilRec_Utility_Fleet,Tugging_Utility_Fleet] = SAU(Fleet_Space,...
    Vessel_Score_Range,Vessel_Score_Speed,Vessel_Score_Crew,...
    Vessel_Score_Helicopter,Vessel_Score_Smallboat,Vessel_Score_Sensor,...
    Vessel_Score_Ice,Vessel_Score_OilRec,Vessel_Score_Tugging);

%Calculate CAPEX for all fleet alternatives
[Fleet_Cost_CAPEX] = Calculate_Fleet_CAPEX(Fleet_Space);

%Calculate yearly OPEX for all fleet alternatives
[Fleet_Cost_OPEX] = Calculate_Fleet_OPEX(Fleet_Space);

%Calculate fleet patrol days
[Patrol_Days_Fleet] = Create_Patrol_Days(Fleet_Space);

%Create epoch space
[Epoch_Space] = Create_Epoch_Space();

%Create weights for the MAU function
 [Weights] = Create_Weights_MAU(Epoch_Space);

%Utility of each fleet in each epoch
[Epoch_Fleet_Utility] = Utility_Epoch(Range_Utility_Fleet,...
    Speed_Utility_Fleet,Crew_Utility_Fleet,Helicopter_Utility_Fleet,...
    Smallboat_Utility_Fleet,Sensor_Utility_Fleet,Ice_Utility_Fleet,...
    OilRec_Utility_Fleet,Tugging_Utility_Fleet,Weights,Fleet_Space,...
    Patrol_Days_Fleet);

%Calculate average utility over all epochs
 Find_Average_Utility;

% Find the pareto fleets in all epochs
[Pareto_Set]...
     = Pareto_Solutions_All_Epochs(Epoch_Fleet_Utility,Fleet_Space,...
                                   Fleet_Cost_CAPEX);

% Plot pareto
Create_Pareto_Plots;

```

```
% Find pareto trace
 Find_Pareto_Trace;

%Calculate NPV for all fleets
[NPV_Fleets,Flow] = Calculate_NPV(Fleet_Cost_CAPEX,Fleet_Cost_OPEX);
```

F.2 Create_Design Space_Patrol.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% THIS FUNCTION CREATES THE INITIAL DESGINSPACE OF FEASIBLE VESSELS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [Design_Space,Design] =...
    Create_Design_Space_Patrol()

%Create designspace
Design_Space =...
 [5000 20 1 1 0 1 1 40 0 50;
  5000 21 0 1 0 2 2 45 200 50;
  6500 23 1 1 0 2 2 50 500 70;
  7000 25 1 2 0 2 2 65 0 70;
  6500 18 0 1 0 2 2 24 1000 150;
  10000 28 1 3 0 3 2 100 0 70;
  10000 22 1 2 0 2 2 85 500 100;
  9000 16 1 2 0 2 3 50 500 100];

%Write designspace
[Design_Number, Design_Variable] = size(Design_Space);
Design = ones(Design_Number,1);
end
```

F.3 Create_Fleetspace_Infeasible.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function creates the infeasible fleet space
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function[Fleet_Space_Infeasible] = Create_Fleet_Space_infeasible()

%Create number of each vessel that can be mapped into fleets
Vessel_1 = [0:1:8];
Vessel_2 = [0:1:8];
Vessel_3 = [0:1:8];
Vessel_4 = [0:1:8];
Vessel_5 = [0:1:8];
```

```
Vessel_6 = [0:1:8];
Vessel_7 = [0:1:8];
Vessel_8 = [0:1:1];

%Create array 0 and 1 for fleet mapping
 Vessel_Array = {Vessel_1,Vessel_2,Vessel_3,...
     Vessel_4,Vessel_5,Vessel_6,Vessel_7,Vessel_8};

 %Generate variable location for vessel to mapping
 [a b c d e f g h  ] = ndgrid(Vessel_Array{:});


 %Map all possible fleet configurations, also infeasible
 Fleet_Space_Infeasible = [a(:) b(:) c(:) d(:) e(:) f(:) g(:) h(:)
     ];

end
```

F.4 Create_Fleet_Space.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% THIS FUNCTION MAPS ALL FEASIBLE FLEET COMBINATIONS BASED ON THE
%% FEASIBLE DESIGN SPACE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function[Fleet_Space] = Create_Fleet_Space(Fleet_Space_Infeasible)

%Refernce to fleet number and vessel number
[fleet_number,vessel_number]=size(Fleet_Space_Infeasible);

%Total number of fleet compositions
Fleet = ones(fleet_number,1);

%Remove all fleet compositions that are not feasible
%A fleet must consists of more than 3 vessel
for i = 1:fleet_number

    %Remove all empty rows.
     if sum(Fleet_Space_Infeasible(i,:)) == 0
         Fleet(i) = 0;
     end

    %The total number of vessel in a fleet can be at most 9
    if sum(Fleet_Space_Infeasible(i,:)) >=9
        Fleet(i) = 0;
```

```
    end

    %A fleet must consist of at least 5 vessels
    if sum(Fleet_Space_Infeasible(i,:)) <= 4
        Fleet(i) = 0;
    end

        %A fleet must consist of at least 1 ice-breaking vessels
    if (Fleet_Space_Infeasible(i,8)) == 0
        Fleet(i) = 0;
    end

        %Remove all fleets that involves fleet without heli capacity
        if ((Fleet_Space_Infeasible(i,1)) ~= 0 ) &&...
           ((Fleet_Space_Infeasible(i,3) < 3) &&...
            (Fleet_Space_Infeasible(i,4) < 3) &&...
            (Fleet_Space_Infeasible(i,6) < 3) &&...
            (Fleet_Space_Infeasible(i,7) < 3) &&...
            (Fleet_Space_Infeasible(i,8) < 3))
           Fleet(i) = 0;
        end

        if ((Fleet_Space_Infeasible(i,2)) ~= 0 ) &&...
           ((Fleet_Space_Infeasible(i,3) < 3) &&...
            (Fleet_Space_Infeasible(i,4) < 3) &&...
            (Fleet_Space_Infeasible(i,6) < 3) &&...
            (Fleet_Space_Infeasible(i,7) < 3) &&...
            (Fleet_Space_Infeasible(i,8) < 3))
           Fleet(i) = 0;
        end


        if ((Fleet_Space_Infeasible(i,5)) ~= 0 ) &&...
           ((Fleet_Space_Infeasible(i,3) < 3) &&...
            (Fleet_Space_Infeasible(i,4) < 3) &&...
            (Fleet_Space_Infeasible(i,6) < 3) &&...
            (Fleet_Space_Infeasible(i,7) < 3) &&...
            (Fleet_Space_Infeasible(i,8) < 3))
           Fleet(i) = 0;
        end

        %Remove all fleets that involves single vessels EXCEPT ice-breakers
        if (Fleet_Space_Infeasible(i,1) == 1) ||...
             (Fleet_Space_Infeasible(i,2) == 1) ||...
             (Fleet_Space_Infeasible(i,3) == 1) ||...
```

```
            (Fleet_Space_Infeasible(i,4) == 1) ||...
            (Fleet_Space_Infeasible(i,5) == 1) ||...
            (Fleet_Space_Infeasible(i,6) == 1) ||...
            (Fleet_Space_Infeasible(i,7) == 1)
         Fleet(i) = 0;
        end



end






% Create feasible fleet Space
 Fleet_Space=[];
   for i = 1:fleet_number
        if Fleet(i) == 1;
            Fleet_Space = [Fleet_Space_Infeasible(i,:); Fleet_Space];
        end
   end

%Create output variabel of all feasible fleets
Fleet_Space = Fleet_Space;

end
```

F.5 Performance_Attributes.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Create Performance Attributes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Attribute_Nr_PatDays,Attribute_Nr_Vessels,Attribute_Range,...
    Attribute_Endurance,Attribute_Speed,Attribute_Helicopter,...
    Attribute_Smallboat,Attribute_Sensors, Attribute_Arctic,...
    Attribute_Crew,Attribute_Oil_Rec,Attribute_Bollard_Pull] =...
    Performance_Attributes()

%Attribute Nr. of Patrol Days
Attribute_Nr_PatDays = [0 2400];

%Attribute Nr. of Vessels
Attribute_Nr_Vessels = [0 15];
```

```

%Attribute range:
Attribute_Range = [4000 10000];

%Attribute endurance:
Attribute_Endurance = [7 60];

%Attribute Speed:
Attribute_Speed = [10 28];

%Attribute Heli:
Attribute_Helicopter = [0 2];

%Attribute Smallboat:
Attribute_Smallboat = [0 2];

%Attribute Sensors:
Attribute_Sensors = [1 3];

%Attribute Arctic:
Attribute_Arctic = [1 3];

%Attribute Crew:
Attribute_Crew = [0 100];

%Attribute Oil rec
Attribute_Oil_Rec = [0 1000];

%Attribute Bollard Pull
Attribute_Bollard_Pull = [0 150];

end
```

F.6 Normalization_Score_Vessl.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function calculates normalized vessel score against each
%% performance attribute
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Vessel_Score_Range,Vessel_Score_Speed,Vessel_Score_Crew,...
 Vessel_Score_Helicopter,Vessel_Score_Smallboat,Vessel_Score_Sensor,...
 Vessel_Score_Ice,Vessel_Score_OilRec,Vessel_Score_Tugging] =...
 Normalization_Score_Vessel(Design_Space,Attribute_Range,...
 Attribute_Speed,Attribute_Crew,Attribute_Helicopter,...
 Attribute_Smallboat,Attribute_Sensors,...
```

```
 Attribute_Arctic,Attribute_Oil_Rec,Attribute_Bollard_Pull)

%% Initialize normalized utility leveles:
%Attribute 'range':
Utility_Range_min = min(Attribute_Range);
Utility_Range_max = max(Attribute_Range);

%Attribute 'speed':
Utility_Speed_min = min(Attribute_Speed);
Utility_Speed_max = max(Attribute_Speed);

%Attribute 'crew':
Utility_Crew_min = min(Attribute_Crew);
Utility_Crew_max = max(Attribute_Crew);

%Attribute 'Helicopter':
Utility_Helicopter_min = min(Attribute_Helicopter);
Utility_Helicopter_max = max(Attribute_Helicopter);

%Attribute 'Small boat'
Utility_Smallboat_min = min(Attribute_Smallboat);
Utility_Smallboat_max = max(Attribute_Smallboat);

%Attribute 'sensor capability':
Utility_Sensors_min = 0;
Utility_Sensors_max = max(Attribute_Sensors);

%Attribute 'ice capability'
Utility_Ice_min = 0;
Utility_Ice_max = max(Attribute_Arctic);

%Attribute 'Oil Recovery'
Utility_OilRec_min = min(Attribute_Oil_Rec);
Utility_OilRec_max = max(Attribute_Oil_Rec);

%Attribute 'Bollard Pull'
Utility_BollardPull_min = min(Attribute_Bollard_Pull);
Utility_BollardPull_max = max(Attribute_Bollard_Pull);

%Initialize vessel performance against attributes
[Vessel_type,b] = size(Design_Space);
Vessel_Score_Range = zeros(Vessel_type,1);
Vessel_Score_Speed = zeros(Vessel_type,1);
Vessel_Score_Crew = zeros(Vessel_type,1);
Vessel_Score_Helicopter = zeros(Vessel_type,1);
```

```
Vessel_Score_Smallboat = zeros(Vessel_type,1);
Vessel_Score_Sensor = zeros(Vessel_type,1);
Vessel_Score_Ice = zeros(Vessel_type,1);
Vessel_Score_OilRec = zeros(Vessel_type,1);,
Vessel_Score_Tugging = zeros(Vessel_type,1);

%Loop normalized range score pr vessel
for i = 1:Vessel_type
    Vessel_Score_Range(i) = (Design_Space(i)-Utility_Range_min)/...
        (Utility_Range_max-Utility_Range_min);
end %end loop i

%Loop normalized speed score pr vessel
for i = 1:Vessel_type
    Vessel_Score_Speed(i) = (Design_Space(i,2)-Utility_Speed_min)/...
        (Utility_Speed_max-Utility_Speed_min);
end %end loop i

%Loop normalized crew score pr vessel
for i = 1:Vessel_type
    Vessel_Score_Crew(i) = (Design_Space(i,8)-Utility_Crew_min)/...
        (Utility_Crew_max-Utility_Crew_min);
end %end loop i

%Loop normalized helictopter score pr vessel
for i = 1:Vessel_type
    Vessel_Score_Helicopter(i) = (Design_Space(i,3)-Utility_Helicopter_min)/...
        (Utility_Helicopter_max-Utility_Helicopter_min);
end %end loop i

%Loop normalized smallboat score pr vessel
for i = 1:Vessel_type
    Vessel_Score_Smallboat(i) = (Design_Space(i,4)-Utility_Smallboat_min)/...
        (Utility_Smallboat_max-Utility_Smallboat_min);
end %end loop i

%Loop normalized sensor score pr vessel
for i = 1:Vessel_type
    Vessel_Score_Sensor(i) = (Design_Space(i,6)-Utility_Sensors_min)/...
        (Utility_Sensors_max-Utility_Sensors_min);
end %end loop i

%Loop normalized ice score pr vessel
for i = 1:Vessel_type
    Vessel_Score_Ice(i) = (Design_Space(i,7)-Utility_Ice_min)/...
```

```
        (Utility_Ice_max-Utility_Ice_min);
end %end loop i

%Loop normalized oil recovery score pr vessel
for i = 1:Vessel_type
    Vessel_Score_OilRec(i) = (Design_Space(i,9)-Utility_OilRec_min)/...
        (Utility_OilRec_max-Utility_OilRec_min);
end %end loop i

%Loop normalized tugging score pr vessel
for i = 1:Vessel_type
    Vessel_Score_Tugging(i) = (Design_Space(i,10) -...
        Utility_BollardPull_min )/...
        (Utility_BollardPull_max -Utility_BollardPull_min );
end %end loop i

end
```

F.7 SAU.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function calculates all single-attribute utilities for each
%% performance attribute pr. fleet
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function[Range_Utility_Fleet,Speed_Utility_Fleet,Crew_Utility_Fleet,...
    Helicopter_Utility_Fleet,Smallboat_Utility_Fleet,...
    Sensor_Utility_Fleet,Ice_Utility_Fleet,...
    OilRec_Utility_Fleet,Tugging_Utility_Fleet] = SAU(Fleet_Space,...
    Vessel_Score_Range,Vessel_Score_Speed,Vessel_Score_Crew,...
    Vessel_Score_Helicopter,Vessel_Score_Smallboat,Vessel_Score_Sensor,...
    Vessel_Score_Ice,Vessel_Score_OilRec,Vessel_Score_Tugging)

%Initialize matrix dimmensions
[Fleet_number,Vessel_types] = size(Fleet_Space);

%Create multiple unit function to adjust performance if more than one unit
%of a system type is present
phi = [1];
for i = 2:20
    phi(i) = phi(i-1)+(1/(1*i));
end %end loop

%% Initialize range score adjusted pr fleet
Range_Score_Infeasible = zeros(Fleet_number,Vessel_types);
Range_Score_Fleet = zeros(Fleet_number,1);
```

```
Range_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;
for i = 1:Fleet_number
      for j = 1:Vessel_types
          for k = 1:length(C)
                if Fleet_Space(i,j) == k
                   Range_Score_Infeasible(i,j) =...
                       phi(k)*k*Vessel_Score_Range(j);
                   Range_Score_Fleet(i) = sum(Range_Score_Infeasible(i,:));
                end

          end % end loop k
      end %end loop j
end %end loop i

%Calculate range utility pr. fleet by linear normalization
%from best to worst score
Range_utility_min = 0;
Range_utility_max = max(Range_Score_Fleet);

for i = 1:Fleet_number
      Range_Utility_Fleet(i) = (Range_Score_Fleet(i)-Range_utility_min)/...
          (Range_utility_max-Range_utility_min);
end%end loop

%% Initialize speed score adjusted pr fleet
Speed_Score_Infeasible = zeros(Fleet_number,Vessel_types);
Speed_Score_Fleet = zeros(Fleet_number,1);
Speed_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;
for i = 1:Fleet_number
      for j = 1:Vessel_types
          for k = 1:length(C)
                if Fleet_Space(i,j) == k
                   Speed_Score_Infeasible(i,j) =...
                       phi(k)*k*Vessel_Score_Speed(j);
                   Speed_Score_Fleet(i) = sum(Speed_Score_Infeasible(i,:));
                end

          end % end loop k
      end %end loop j
end %end loop i

%Calculate speed utility pr. fleet by linear normalization
%from best to worst score
```

```
Speed_utility_min = 0;
Speed_utility_max = max(Speed_Score_Fleet);

for i = 1:Fleet_number
      Speed_Utility_Fleet(i) = (Speed_Score_Fleet(i)-Speed_utility_min)/...
          (Speed_utility_max-Speed_utility_min);
end%end loop


%% Initialize crew score adjusted pr fleet
Crew_Score_Infeasible = zeros(Fleet_number,Vessel_types);
Crew_Score_Fleet = zeros(Fleet_number,1);
Crew_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;
for i = 1:Fleet_number
      for j = 1:Vessel_types
          for k = 1:length(C)
                if Fleet_Space(i,j) == k
                   Crew_Score_Infeasible(i,j) =...
                       phi(k)*k*Vessel_Score_Crew(j);
                   Crew_Score_Fleet(i) = sum(Crew_Score_Infeasible(i,:));
                end

          end % end loop k
      end %end loop j
end% end loop i
%Calculate speed utility pr. fleet by linear normalization
%from best to worst score
Crew_utility_min = 0;
Crew_utility_max = max(Crew_Score_Fleet);

for i = 1:Fleet_number
Crew_Utility_Fleet(i) = (Crew_Score_Fleet(i)-Crew_utility_min)/...
(Crew_utility_max-Crew_utility_min);
end %end loop i

%% Initialize helicopter score adjusted pr fleet
Helicopter_Score_Infeasible = zeros(Fleet_number,Vessel_types);
Helicopter_Score_Fleet = zeros(Fleet_number,1);
Helicopter_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;
for i = 1:Fleet_number
      for j = 1:Vessel_types
          for k = 1:length(C)
                if Fleet_Space(i,j) == k
```

```
                   Helicopter_Score_Infeasible(i,j) =...
                       phi(k)*k*Vessel_Score_Helicopter(j);
                   Helicopter_Score_Fleet(i) =...
                       sum(Helicopter_Score_Infeasible(i,:));
                end

          end % end loop k
      end %end loop j
end % end loop i
%Calculate helicopter utility pr. fleet by linear normalization
%from best to worst score
Helicopter_utility_min = 0;
Helicopter_utility_max = max(Helicopter_Score_Fleet);

for i = 1:Fleet_number
      Helicopter_Utility_Fleet(i) = (Helicopter_Score_Fleet(i)-...
          Helicopter_utility_min)/...
          (Helicopter_utility_max-Helicopter_utility_min);
end %end loop i


%% Initialize smallboat score adjusted pr fleet
Smallboat_Score_Infeasible = zeros(Fleet_number,Vessel_types);
Smallboat_Score_Fleet = zeros(Fleet_number,1);
Smallboat_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;
for i = 1:Fleet_number
      for j = 1:Vessel_types
          for k = 1:length(C)
                if Fleet_Space(i,j) == k
                   Smallboat_Score_Infeasible(i,j) =...
                       phi(k)*k*Vessel_Score_Smallboat(j);
                   Smallboat_Score_Fleet(i) =...
                       sum(Smallboat_Score_Infeasible(i,:));
                end

          end % end loop k
      end %end loop j
end % end loop i
%Calculate helicopter utility pr. fleet by linear normalization
%from best to worst score
Smallboat_utility_min = 0;
Smallboat_utility_max = max(Smallboat_Score_Fleet);

for i = 1:Fleet_number
```

```
        Smallboat_Utility_Fleet(i) = (Smallboat_Score_Fleet(i)-...
            Smallboat_utility_min)/...
            (Smallboat_utility_max-Smallboat_utility_min);
end %end loop i


%% Initialize sensor score adjusted pr fleet
Sensor_Score_Infeasible = zeros(Fleet_number,Vessel_types);
Sensor_Score_Fleet = zeros(Fleet_number,1);
Sensor_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;
for i = 1:Fleet_number
      for j = 1:Vessel_types
          for k = 1:length(C)
                if Fleet_Space(i,j) == k
                   Sensor_Score_Infeasible(i,j) =...
                       phi(k)*k*Vessel_Score_Sensor(j);
                   Sensor_Score_Fleet(i) =...
                       sum(Sensor_Score_Infeasible(i,:));
                end

          end % end loop k
      end %end loop j
end %end loop i

%Calculate sensor utility pr. fleet by linear normalization
%from best to worst score
Sensor_utility_min = 0;
Sensor_utility_max = max(Sensor_Score_Fleet);
for i = 1:Fleet_number
        Sensor_Utility_Fleet(i) = (Sensor_Score_Fleet(i)-...
            Sensor_utility_min)/...
            (Sensor_utility_max-Sensor_utility_min);
end %end loop

%% Initialize ice score adjusted pr fleet
Ice_Score_Infeasible = zeros(Fleet_number,Vessel_types);
Ice_Score_Fleet = zeros(Fleet_number,1);
Ice_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;
for i = 1:Fleet_number
      for j = 1:Vessel_types
          for k = 1:length(C)
                if Fleet_Space(i,j) == k
                   Ice_Score_Infeasible(i,j) =...
```

```
                        phi(k)*k*Vessel_Score_Ice(j);
                    Ice_Score_Fleet(i) =...
                        sum(Ice_Score_Infeasible(i,:));
                end

            end % end loop k
        end %end loop j
end %end loop i

%Calculate Ice utility pr. fleet by linear normalization
%from best to worst score
Ice_utility_min = 0;
Ice_utility_max = max(Ice_Score_Fleet);
for i = 1:Fleet_number
        Ice_Utility_Fleet(i) = (Ice_Score_Fleet(i)-...
            Ice_utility_min)/...
            (Ice_utility_max-Ice_utility_min);
end %end loop

%% Initialize oil recovery score adjusted pr fleet
OilRec_Infeasible = zeros(Fleet_number,Vessel_types);
OilRec_Score_Fleet = zeros(Fleet_number,1);
OilRec_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;
for i = 1:Fleet_number
        for j = 1:Vessel_types
            for k = 1:length(C)
                if Fleet_Space(i,j) == k
                    OilRec_Infeasible(i,j) =...
                        phi(k)*k*Vessel_Score_OilRec(j);
                    OilRec_Score_Fleet(i) =...
                        sum(OilRec_Infeasible(i,:));
                end

            end % end loop k
        end %end loop j
end %end loop i

% Calculate oil recovery utility pr. fleet by linear normalization
% from best to worst score
OilRec_utility_min = 0;
OilRec_utility_max = max(OilRec_Score_Fleet);
for i = 1:Fleet_number
        OilRec_Utility_Fleet(i) = (OilRec_Score_Fleet(i)-...
            OilRec_utility_min)/...
```

```
          (OilRec_utility_max-OilRec_utility_min);
end %end loop

%% Initialize tugging score adjusted pr fleet
Tugging_Infeasible = zeros(Fleet_number,Vessel_types);
Tugging_Score_Fleet = zeros(Fleet_number,1);
Tugging_Utility_Fleet = zeros(Fleet_number,1);
C = 1:10;%number of vessels that can be mapped in a fleet
for i = 1:Fleet_number
      for j = 1:Vessel_types
          for k = 1:length(C)
                if Fleet_Space(i,j) == k
                   Tugging_Infeasible(i,j) =...
                       phi(k)*k*Vessel_Score_Tugging(j);
                   Tugging_Score_Fleet(i) =...
                       sum(Tugging_Infeasible(i,:));
                end

          end % end loop k
      end %end loop j
end %end loop i

% Calculate tugging utility pr. fleet by linear normalization
% from best to worst score
Tugging_utility_min = 0;
Tugging_utility_max = max(Tugging_Score_Fleet);
for i = 1:Fleet_number
      Tugging_Utility_Fleet(i) = (Tugging_Score_Fleet(i)-...
          Tugging_utility_min)/...
          (Tugging_utility_max-Tugging_utility_min);
end %end loop

end
```

F.8 Calculate_Fleet_CAPEX.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function calculates the CAPEX for each fleet
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [Fleet_Cost_CAPEX] = Calculate_Fleet_CAPEX(Fleet_Space)

%Initialize vessel cost:
Cost_Vessel1 = 220;
Cost_Vessel2 = 294;
```

```
Cost_Vessel3 = 277;
Cost_Vessel4 = 310;
Cost_Vessel5 = 298;
Cost_Vessel6 = 623;
Cost_Vessel7 = 446;
Cost_Vessel8 = 419;

%Initialize matrix
Cost_Matrix = [Cost_Vessel1;Cost_Vessel2;Cost_Vessel3;Cost_Vessel4;...
               Cost_Vessel5;Cost_Vessel6;Cost_Vessel7;Cost_Vessel8];

%Initialize loop
[Fleet_number, Vessel_types] = size(Fleet_Space);
C = 1:10;
Fleet_Cost_inf = zeros(Fleet_number,Vessel_types);
Fleet_Cost_CAPEX = zeros(Fleet_number,1);
%Calculate CAPEX Cost
 for i = 1:Fleet_number
         for j = 1:length(Cost_Matrix)
             for k = 1:length(C)
                   if Fleet_Space(i,j) == k
                     Fleet_Cost_inf(i,j) = k*Cost_Matrix(j);
                   end %if

             end% k
         end %j
         Fleet_Cost_CAPEX(i) = sum(Fleet_Cost_inf(i,:));
 end %i
Fleet_Cost_CAPEX = Fleet_Cost_CAPEX; %Write results
end
```

F.9 Calculate_Fleet_OPEX.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function calculates the yearly OPEX for each fleet
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [Fleet_Cost_OPEX] = Calculate_Fleet_OPEX(Fleet_Space)

%Initialize vessel cost:
Cost_Vessel1 = 36;
Cost_Vessel2 = 25;
Cost_Vessel3 = 44;
Cost_Vessel4 = 45;
Cost_Vessel5 = 46;
```

```
Cost_Vessel6 = 80;
Cost_Vessel7 = 67;
Cost_Vessel8 = 47;

%Initilaize matrix
Cost_Matrix = [Cost_Vessel1;Cost_Vessel2;Cost_Vessel3;Cost_Vessel4;...
               Cost_Vessel5;Cost_Vessel6;Cost_Vessel7;Cost_Vessel8];

%Initialize loop
[Fleet_number, Vessel_types] = size(Fleet_Space);
C = 1:10;
Fleet_Cost_inf = zeros(Fleet_number,Vessel_types);
Fleet_Cost_OPEX = zeros(Fleet_number,1);
%Calculate OPEX Costs
 for i = 1:Fleet_number
        for j = 1:length(Cost_Matrix)
            for k = 1:length(C)
                  if Fleet_Space(i,j) == k
                    Fleet_Cost_inf(i,j) = k*Cost_Matrix(j);
                  end %if

            end %k
        end %j
        Fleet_Cost_OPEX(i) = sum(Fleet_Cost_inf(i,:));
 end %i
Fleet_Cost_OPEX = Fleet_Cost_OPEX;%Write results
end
```

F.10 Create_Epoch_Space.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function creates all epochs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 function [Epoch_Space] = Create_Epoch_Space()

%Create geographic development epoch variables
%Fishery development
Fishery_Activity = [0,1];
Geographic_Spread = [0,1];

%Create mission priorities epoch variables based on activity development
Mission_Arctic = [0,1];
Mission_Environmental = [0,1];
Mission_Tugging = [0,1];
```

```matlab

%Create all possible epochs
Epoch_Vars = {Fishery_Activity,Geographic_Spread,Mission_Arctic,...
              Mission_Environmental,Mission_Tugging};
[a b c d e  ] = ndgrid(Epoch_Vars{:});

%Create epoch space
Epoch_Space_infeasible = [a(:) b(:) c(:) d(:) e(:)];

%Refernce to Epoch number and epoch variable
[Epoch_number,Epoch_variabels]=size(Epoch_Space_infeasible);
%Total number of epoch varialbes
Epoch = ones(Epoch_number,1);
%
%Create feasible epoch space
 Epoch_Space=[];
    for i = 1:Epoch_number
        if Epoch(i) == 1
             Epoch_Space = [Epoch_Space_infeasible(i,:); Epoch_Space];
        end %if


    end %i

 end
```

F.11 Create_Weights_MAU.m

```matlab
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function creates the weights for the MAU function
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [Weights] = Create_Weights_MAU(Epoch_Space);
%Initialize array for weights
[Epoch_number,Epoch_variable] = size(Epoch_Space);
[Weights] = zeros(Epoch_number,9);

%Create weights
for i = 1:Epoch_number
    for j = 1:Epoch_variable
 %% All epoch variables equal 1
    if ((Epoch_Space(i,(1:5)) == 1))
        Weights(i,1) = 0.2;  %Range
        Weights(i,2) = 1/15;  %Speed
        Weights(i,3) = 1/15;  %Crew
```

```
        Weights(i,4) = 0.2;  %Helicopter
        Weights(i,5) = 1/15; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0.1;  %Ice
        Weights(i,8) = 0.1;  %Oil recovery
        Weights(i,9) = 0.1;  %Tugging
    end

    %Fishery acticty low and geo spread high, high ice, oil.rec and tugging
    if ((Epoch_Space(i,1) == 0)& (Epoch_Space(i,2)== 1) &...
             (Epoch_Space(i,3)== 1)& (Epoch_Space(i,4)==1)&...
             (Epoch_Space(i,5)==1))
        Weights(i,1) = 0.1;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0;  %Crew
        Weights(i,4) = 0.1;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0.2;  %Ice
        Weights(i,8) = 0.2;  %Oil recovery
        Weights(i,9) = 0.2;  %Tugging

    end

    %Fishery acticty high and geo spread low, high ice, oil.rec and tugging
    if ((Epoch_Space(i,1) == 1)& (Epoch_Space(i,2)== 0) &...
             (Epoch_Space(i,3)== 1)& (Epoch_Space(i,4)==1)&...
             (Epoch_Space(i,5)==1))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.1;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.15;  %Sensors
        Weights(i,7) = 0.2;  %Ice
        Weights(i,8) = 0.2;  %Oil recovery
        Weights(i,9) = 0.2;  %Tugging

    end

    %Fishery acticty low and geo spread low, high ice, oil.rec and tugging
        if ((Epoch_Space(i,1) == 0)& (Epoch_Space(i,2)== 0) &...
             (Epoch_Space(i,3)== 1)& (Epoch_Space(i,4)==1)&...
             (Epoch_Space(i,5)==1))
        Weights(i,1) = 0;  %Range
```

```
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.05;  %Sensors
        Weights(i,7) = 0.3;  %Ice
        Weights(i,8) = 0.3;  %Oil recovery
        Weights(i,9) = 0.3;  %Tugging

    end
    %% Fishery activity weightings
    %If fischery activityis low, and geo. spread is low and all other
    %epoch variables are low (equal to 0) the following weightings are
    %given
    if ((Epoch_Space(i,1) == 0)& (Epoch_Space(i,2)== 0) &...
             (Epoch_Space(i,3)== 0)& (Epoch_Space(i,4)==0)&...
             (Epoch_Space(i,5)==0))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.2;  %Helicopter
        Weights(i,5) = 0.2; %Smallboat
        Weights(i,6) = 0.5;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
    end
%
    %If fischery activities high, and geo. spread is low and all other
    %epoch variables equal 0, the following weightings are given
    if  ((Epoch_Space(i,1) == 1)& (Epoch_Space(i,2)== 0) &...
             (Epoch_Space(i,3)== 0)& (Epoch_Space(i,4)==0)&...
             (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.1;  %Range
        Weights(i,2) = 0.1;  %Speed
        Weights(i,3) = 0.2;  %Crew
        Weights(i,4) = 0.25;  %Helicopter
        Weights(i,5) = 0.1; %Smallboat
        Weights(i,6) = 0.25;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
    end

    %If fischery activities low, and geo. spread is high
```

```
    %the following weightings are given
    if  ((Epoch_Space(i,1) == 0)& (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3)== 0)& (Epoch_Space(i,4)==0)&...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.3;  %Range
        Weights(i,2) = 0.1;  %Speed
        Weights(i,3) = 00.1;  %Crew
        Weights(i,4) = 0.2;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.25;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
    end

    %If fischery activities high, and geo. spread is high
    %the following weightings are given
    if  ((Epoch_Space(i,1) == 1)& (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3)== 0)& (Epoch_Space(i,4)==0)&...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.4;  %Range
        Weights(i,2) = 0.1;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.25;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.15;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
    end
%% 100
    %Arctic high = 1
    %Oil recovery low = 0
    %Tugging low = 0
    %If fischery activityis low, and geo. spread is low.
    if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 0) &...
        (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 0) &...
        (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.1;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0.4;  %Ice
```

```
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
     end

    %Arctic high = 1
    %Oil recovery low = 0
    %Tugging low = 0
    %If fischery activityis high, and geo. spread is low.
    if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 0) &...
        (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 0) &...
        (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.1;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.1;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0.4;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
    end

    %Arctic high = 1
    %Oil recovery low = 0
    %Tugging low = 0
    %If fischery activityis low, and geo. spread is high.
     if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 1) &...
        (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 0) &...
        (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.15;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0.4;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
      end

    %Arctic high = 1
    %Oil recovery low = 0
    %Tugging low = 0
    %If fischery activityis high, and geo. spread is high.
     if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 1) &...
```

```
        (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 0) &...
        (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.2;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.2;  %Helicopter
        Weights(i,5) = 0.; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0.4;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
     end

%% 110 00
    %Arctic high = 1
    %Oil recovery low = 1
    %Tugging low = 0
    %If fischery activityis low, and geo. spread is low.
    if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 0) &...
        (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 1) &...
        (Epoch_Space(i,5)==0))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0.4;  %Ice
        Weights(i,8) = 0.4;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
    end

    %Arctic high = 1
    %Oil recovery low = 1
    %Tugging low = 0
    %If fischery activityis high, and geo. spread is low.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.05;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.25;  %Sensors
```

```
        Weights(i,7) = 0.3;  %Ice
        Weights(i,8) = 0.3;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
        end

    %Arctic high = 1
    %Oil recovery low = 1
    %Tugging low = 0
    %If fischery activityis low, and geo. spread is high.
        if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.15;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0.25;  %Ice
        Weights(i,8) = 0.25;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
        end

    %Arctic high = 1
    %Oil recovery low = 1
    %Tugging low = 0
    %If fischery activityis high, and geo. spread is high.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.2;  %Range
        Weights(i,2) = 0.1;  %Speed
        Weights(i,3) = 0;  %Crew
        Weights(i,4) = 0.1;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0.25;  %Ice
        Weights(i,8) = 0.25;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
        end

%% 10100
    %Arctic high = 1
    %Oil recovery low = 0
    %Tugging low = 1
```

```
    %If fischery activityis low, and geo. spread is low.
    if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 0) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0.4;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0.4;  %Tugging
    end

    %Arctic high = 1
    %Oil recovery low = 0
    %Tugging low = 1
    %If fischery activityis high, and geo. spread is low.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 0) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.05;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.25;  %Sensors
        Weights(i,7) = 0.3;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0.3;  %Tugging
        end

     %Arctic high = 1
     %Oil recovery low = 0
     %Tugging low = 1
     %If fischery activityis low, and geo. spread is high.
        if  ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 0) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0.15;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0; %Smallboat
```

```
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0.25;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0.25;  %Tugging
        end


    %Arctic high = 1
    %Oil recovery low = 0
    %Tugging low = 1
    %If fischery activityis high, and geo. spread is high.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 1) & (Epoch_Space(i,4)== 0) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0.2;  %Range
        Weights(i,2) = 0.1;  %Speed
        Weights(i,3) = 0;  %Crew
        Weights(i,4) = 0.1;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0.25;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0.25;  %Tugging
        end
%
%% 01100

    %Arctic high = 0
    %Oil recovery low = 1
    %Tugging low = 1
    %If fischery activityis low, and geo. spread is low.
    if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0.4;  %Oil recovery
        Weights(i,9) = 0.4;  %Tugging

    end
```

```

    %Arctic high = 0
    %Oil recovery low = 1
    %Tugging low = 1
    %If fischery activityis high, and geo. spread is low.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.05;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.25;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0.3;  %Oil recovery
        Weights(i,9) = 0.3;  %Tugging
        end

    %Arctic high = 0
    %Oil recovery low = 1
    %Tugging low = 1
    %If fischery activityis low, and geo. spread is high.
        if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0.15;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0.25;  %Oil recovery
        Weights(i,9) = 0.25;  %Tugging
        end

    %Arctic high = 0
    %Oil recovery low = 1
    %Tugging low = 1
    %If fischery activityis high, and geo. spread is high.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0.2;  %Range
```

```
        Weights(i,2) = 0.1;  %Speed
        Weights(i,3) = 0;  %Crew
        Weights(i,4) = 0.1;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0.25;  %Oil recovery
        Weights(i,9) = 0.25;  %Tugging
        end

%% 01000
    %Arctic high = 0
    %Oil recovery low = 1
    %Tugging low = 0
    %If fischery activityis low, and geo. spread is low.
    if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0.5;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
    end

    %Arctic high = 0
    %Oil recovery low = 1
    %Tugging low = 0
    %If fischery activityis high, and geo. spread is low.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.1;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.25;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0.45;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
```

```
        end

    %Arctic high = 0
    %Oil recovery low = 1
    %Tugging low = 0
    %If fischery activityis low, and geo. spread is high.
        if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.15;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0.4;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
        end

    %Arctic high = 0
    %Oil recovery low = 1
    %Tugging low = 0
    %If fischery activityis high, and geo. spread is high.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 1) &...
            (Epoch_Space(i,5)==0))
        Weights(i,1) = 0.2;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.2;  %Helicopter
        Weights(i,5) = 0.; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0.4;  %Oil recovery
        Weights(i,9) = 0;  %Tugging
        end

%% 00100
    %Arctic high = 0
    %Oil recovery low = 0
    %Tugging low = 1
    %If fischery activityis low, and geo. spread is low.
     if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 0) &...
```

```
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0.5;  %Tugging
     end

    %Arctic high = 0
    %Oil recovery low = 0
    %Tugging low = 1
    %If fischery activityis high, and geo. spread is low.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 0) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 0) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.1;  %Helicopter
        Weights(i,5) = 0.05; %Smallboat
        Weights(i,6) = 0.25;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0.45;  %Tugging
     end

    %Arctic high = 0
    %Oil recovery low = 0
    %Tugging low = 1
    %If fischery activityis low, and geo. spread is high.
        if ((Epoch_Space(i,1) == 0) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 0) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0.15;  %Range
        Weights(i,2) = 0.05;  %Speed
        Weights(i,3) = 0.05;  %Crew
        Weights(i,4) = 0.15;  %Helicopter
        Weights(i,5) = 0; %Smallboat
        Weights(i,6) = 0.2;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0;  %Oil recovery
```

```
        Weights(i,9) = 0.4;  %Tugging
        end

    %Arctic high = 0
    %Oil recovery low = 0
    %Tugging low = 1
    %If fischery activityis high, and geo. spread is high.
        if ((Epoch_Space(i,1) == 1) & (Epoch_Space(i,2)== 1) &...
            (Epoch_Space(i,3) == 0) & (Epoch_Space(i,4)== 0) &...
            (Epoch_Space(i,5)==1))
        Weights(i,1) = 0.2;  %Range
        Weights(i,2) = 0;  %Speed
        Weights(i,3) = 0.1;  %Crew
        Weights(i,4) = 0.2;  %Helicopter
        Weights(i,5) = 0.; %Smallboat
        Weights(i,6) = 0.1;  %Sensors
        Weights(i,7) = 0;  %Ice
        Weights(i,8) = 0;  %Oil recovery
        Weights(i,9) = 0.4;  %Tugging
        end
     end %end j
end %end i

end %end function
```

F.12 Utility_Epoch.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function calculates the Multi-Attribute Utility Score for each
%% Fleet alternative
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function[Epoch_Fleet_Utility] = Utility_Epoch(Range_Utility_Fleet,...
    Speed_Utility_Fleet,Crew_Utility_Fleet,Helicopter_Utility_Fleet,...
    Smallboat_Utility_Fleet,Sensor_Utility_Fleet,Ice_Utility_Fleet,...
    OilRec_Utility_Fleet,Tugging_Utility_Fleet,Weights,Fleet_Space,...
    Patrol_Days_Fleet)

%Initialize loop
[Epoch_number,Weight_constant] = size(Weights);
[Fleet_number,Vessel_number]= size(Fleet_Space);
 Epoch_Fleet_Utility = zeros(Epoch_number,Fleet_number);
 Fleet = ones(Fleet_number,1);

 %Caculate utility for each fleet in each epoch
for i = 1:Epoch_number
```

```
    for j = 1:Fleet_number

      %Fleet feasibility for epoch 1
        if i == 1
            %if %((Fleet_Space(j,5) == 0))
                Epoch_Fleet_Utility(i,j) = 0;
           % else
                R = Weights(i,1);     %Range
                S = Weights(i,2);     %Speed
                C = Weights(i,3);     %Crew
                H = Weights(i,4);     %Helicopter
               SB = Weights(i,5);     %Small Boat capability
               SE = Weights(i,6);   %Sensor capability
                I = Weights(i,7);     %Ice capability
               OR = Weights(i,8);      %Oil recovery capability
               TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
           % end
        end
      %Fleet feasibility for epoch 2
        if i == 2
            %if %((Fleet_Space(j,5) == 0))
            %   Epoch_Fleet_Utility(i,j) = 0;
           % else
                R = Weights(i,1);     %Range
                S = Weights(i,2);     %Speed
                C = Weights(i,3);     %Crew
                H = Weights(i,4);     %Helicopter
               SB = Weights(i,5);     %Small Boat capability
               SE = Weights(i,6);   %Sensor capability
                I = Weights(i,7);     %Ice capability
               OR = Weights(i,8);      %Oil recovery capability
               TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
           % end
```

```
       end
      %Fleet feasibility for epoch 3
       if i == 3
         % if % ((Fleet_Space(j,5) == 0))
           %  Epoch_Fleet_Utility(i,j) = 0;
         % else
              R = Weights(i,1);     %Range
              S = Weights(i,2);     %Speed
              C = Weights(i,3);     %Crew
              H = Weights(i,4);     %Helicopter
             SB = Weights(i,5);     %Small Boat capability
             SE = Weights(i,6);   %Sensor capability
              I = Weights(i,7);     %Ice capability
             OR = Weights(i,8);      %Oil recovery capability
             TG = Weights(i,9);      %Tugging capability
        Epoch_Fleet_Utility(i,j) =...
       (R*Range_Utility_Fleet(j))+...
       (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
       (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
       (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
       (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
        %  end
       end
      %Fleet feasibility for epoch 4
       if i == 4
         % if %((Fleet_Space(j,5) == 0))
          %   Epoch_Fleet_Utility(i,j) = 0;
         % else
              R = Weights(i,1);     %Range
              S = Weights(i,2);     %Speed
              C = Weights(i,3);     %Crew
              H = Weights(i,4);     %Helicopter
             SB = Weights(i,5);     %Small Boat capability
             SE = Weights(i,6);   %Sensor capability
              I = Weights(i,7);     %Ice capability
             OR = Weights(i,8);      %Oil recovery capability
             TG = Weights(i,9);      %Tugging capability
        Epoch_Fleet_Utility(i,j) =...
       (R*Range_Utility_Fleet(j))+...
       (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
       (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
       (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
       (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
         % end
       end
```

```

    %Fleet feasibility for epoch
     if i == 5
         if Patrol_Days_Fleet(j) < 0
            Epoch_Fleet_Utility(i,j) = 0;
         else
             R = Weights(i,1);     %Range
             S = Weights(i,2);     %Speed
             C = Weights(i,3);     %Crew
             H = Weights(i,4);     %Helicopter
            SB = Weights(i,5);     %Small Boat capability
            SE = Weights(i,6);   %Sensor capability
             I = Weights(i,7);     %Ice capability
            OR = Weights(i,8);      %Oil recovery capability
            TG = Weights(i,9);      %Tugging capability
      Epoch_Fleet_Utility(i,j) =...
     (R*Range_Utility_Fleet(j))+...
     (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
     (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
     (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
     (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
         end
     end

    %Fleet feasibility for epoch
     if i == 6
         if Patrol_Days_Fleet(j) < 0
            Epoch_Fleet_Utility(i,j) = 0;
         else
             R = Weights(i,1);     %Range
             S = Weights(i,2);     %Speed
             C = Weights(i,3);     %Crew
             H = Weights(i,4);     %Helicopter
            SB = Weights(i,5);     %Small Boat capability
            SE = Weights(i,6);   %Sensor capability
             I = Weights(i,7);     %Ice capability
            OR = Weights(i,8);      %Oil recovery capability
            TG = Weights(i,9);      %Tugging capability
      Epoch_Fleet_Utility(i,j) =...
     (R*Range_Utility_Fleet(j))+...
     (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
     (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
     (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
     (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
         end
```

```
     end

    %Fleet feasibility for epoch
     if i == 7
        if Patrol_Days_Fleet(j) < 0
          Epoch_Fleet_Utility(i,j) = 0;
        else
          R = Weights(i,1);    %Range
          S = Weights(i,2);    %Speed
          C = Weights(i,3);    %Crew
          H = Weights(i,4);    %Helicopter
         SB = Weights(i,5);    %Small Boat capability
         SE = Weights(i,6);   %Sensor capability
          I = Weights(i,7);    %Ice capability
         OR = Weights(i,8);     %Oil recovery capability
         TG = Weights(i,9);     %Tugging capability
      Epoch_Fleet_Utility(i,j) =...
     (R*Range_Utility_Fleet(j))+...
     (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
     (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
     (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
     (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
        end
     end

    %Fleet feasibility for epoch 8
     if i == 8
        if Patrol_Days_Fleet(j) < 0
          Epoch_Fleet_Utility(i,j) = 0;
        else
          R = Weights(i,1);    %Range
          S = Weights(i,2);    %Speed
          C = Weights(i,3);    %Crew
          H = Weights(i,4);    %Helicopter
         SB = Weights(i,5);    %Small Boat capability
         SE = Weights(i,6);   %Sensor capability
          I = Weights(i,7);    %Ice capability
         OR = Weights(i,8);     %Oil recovery capability
         TG = Weights(i,9);     %Tugging capability
      Epoch_Fleet_Utility(i,j) =...
     (R*Range_Utility_Fleet(j))+...
     (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
     (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
     (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
     (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
```

```
            end
        end

       %Fleet feasibility for epoch 9
        if i == 9
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
              SB = Weights(i,5);    %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 10
        if i == 10
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
              SB = Weights(i,5);    %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
```

```
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 11
        if i == 11
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
              R = Weights(i,1);     %Range
              S = Weights(i,2);     %Speed
              C = Weights(i,3);     %Crew
              H = Weights(i,4);     %Helicopter
             SB = Weights(i,5);     %Small Boat capability
             SE = Weights(i,6);    %Sensor capability
              I = Weights(i,7);     %Ice capability
             OR = Weights(i,8);      %Oil recovery capability
             TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 12
        if i == 12
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
              R = Weights(i,1);     %Range
              S = Weights(i,2);     %Speed
              C = Weights(i,3);     %Crew
              H = Weights(i,4);     %Helicopter
             SB = Weights(i,5);     %Small Boat capability
             SE = Weights(i,6);    %Sensor capability
              I = Weights(i,7);     %Ice capability
             OR = Weights(i,8);      %Oil recovery capability
             TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
```

```
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 13
        if i == 13
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 14
        if i == 14
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
```

```
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 15
        if i == 15
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 16
        if i == 16
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
```

```
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 17
        if i == 17
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 18
        if i == 18
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
```

```
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 19
        if i == 19
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 20
        if i == 20
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
```

```
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 21
        if i == 21
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
              SB = Weights(i,5);    %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 22
        if i == 22
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
              SB = Weights(i,5);    %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
```

```
                TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 23
        if i == 23
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
                R = Weights(i,1);     %Range
                S = Weights(i,2);     %Speed
                C = Weights(i,3);     %Crew
                H = Weights(i,4);     %Helicopter
               SB = Weights(i,5);     %Small Boat capability
               SE = Weights(i,6);   %Sensor capability
                I = Weights(i,7);     %Ice capability
               OR = Weights(i,8);      %Oil recovery capability
               TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 24
        if i == 24
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
                R = Weights(i,1);     %Range
                S = Weights(i,2);     %Speed
                C = Weights(i,3);     %Crew
                H = Weights(i,4);     %Helicopter
               SB = Weights(i,5);     %Small Boat capability
               SE = Weights(i,6);   %Sensor capability
                I = Weights(i,7);     %Ice capability
```

```
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 25
        if i == 25
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);     %Ice capability
              OR = Weights(i,8);      %Oil recovery capability
              TG = Weights(i,9);      %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 26
        if i == 26
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);     %Range
               S = Weights(i,2);     %Speed
               C = Weights(i,3);     %Crew
               H = Weights(i,4);     %Helicopter
              SB = Weights(i,5);     %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
```

```
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 27
        if i == 27
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
              SB = Weights(i,5);    %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 28
        if i == 28
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
              SB = Weights(i,5);    %Small Boat capability
```

```
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 29
        if i == 29
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
              SB = Weights(i,5);    %Small Boat capability
              SE = Weights(i,6);   %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 30
        if i == 30
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
```

```
              SB = Weights(i,5);    %Small Boat capability
              SE = Weights(i,6);  %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 31
        if i == 31
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
               H = Weights(i,4);    %Helicopter
              SB = Weights(i,5);    %Small Boat capability
              SE = Weights(i,6);  %Sensor capability
               I = Weights(i,7);    %Ice capability
              OR = Weights(i,8);     %Oil recovery capability
              TG = Weights(i,9);     %Tugging capability
         Epoch_Fleet_Utility(i,j) =...
        (R*Range_Utility_Fleet(j))+...
        (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
        (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
        (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
        (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end

%Fleet feasibility for epoch 32
        if i == 32
            if Patrol_Days_Fleet(j) < 0
               Epoch_Fleet_Utility(i,j) = 0;
            else
               R = Weights(i,1);    %Range
               S = Weights(i,2);    %Speed
               C = Weights(i,3);    %Crew
```

```
                 H = Weights(i,4);    %Helicopter
                SB = Weights(i,5);    %Small Boat capability
                SE = Weights(i,6);   %Sensor capability
                 I = Weights(i,7);    %Ice capability
                OR = Weights(i,8);     %Oil recovery capability
                TG = Weights(i,9);     %Tugging capability
          Epoch_Fleet_Utility(i,j) =...
         (R*Range_Utility_Fleet(j))+...
         (S*Speed_Utility_Fleet(j))+(C*Crew_Utility_Fleet(j))+...
         (SB*Smallboat_Utility_Fleet(j))+(H*Helicopter_Utility_Fleet(j))+...
         (I*Ice_Utility_Fleet(j))+(OR*OilRec_Utility_Fleet(j))+...
         (TG*Tugging_Utility_Fleet(j))+(SE*Sensor_Utility_Fleet(j));
            end
        end
    end

end
end
```

F.13 Find_Average_Utility.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This script finds the average utility of each fleet alternative
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Initialize
[epoch_number,fleet_number] = size(Epoch_Fleet_Utility)
Average_Utility_Fleet = zeros(fleet_number,1);
%Calculate average utility of each fleet alternative
for i = 1:fleet_number

    Average_Utility_Fleet(i) = sum(Epoch_Fleet_Utility(:,i))/(length(
     Epoch_Fleet_Utility(:,i)));

end
```

F.14 Pareto_Solutions_All_Epochs.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% FIND Pareto Fleets for all Epochs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 function[Pareto_Set]...
     = Pareto_Solutions_All_Epochs(Epoch_Fleet_Utility,Fleet_Space,...
                                     Fleet_Cost_CAPEX)
%Initialize
```

```
Cm = Fleet_Cost_CAPEX;
Um = Epoch_Fleet_Utility;
[num_epochs,num_fleets] = size(Epoch_Fleet_Utility);

%For each epoch
for e = 1:num_epochs
    %While loop condition
    i = 0;
    %The first element in the pareto array
    k = 1;
    while i == 0
        %Find the maximum utility for each epoch
        [a,b] = max(Epoch_Fleet_Utility(e,:));
        %Adding fleet nr. to the pareto array
        Pareto_Set(e,k) = b;
        %Setting current maximum utility to -1 to avoid rechecking
        Epoch_Fleet_Utility(e,b) = -1;
        %Setting utility of all elements wit a larger cost to -1
        for j = 1:num_fleets
            if Fleet_Cost_CAPEX(j) >= Fleet_Cost_CAPEX(b)
                Epoch_Fleet_Utility(e,j) = -1;
            end
        end
        %Exit while loop when the lowest cost is reached or the max
        %utility is 0
        if (Fleet_Cost_CAPEX(b) == min(Fleet_Cost_CAPEX(:))) || (max(Epoch_Fleet_Utility(e,:)) == 0)
            i = 1;
        end
        %Find the next element inthe pareto array
        k = k+1;
    end
end

Pareto_Set;%Write results

end
```

F.15 Find_Pareto_Trace.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function performs the pareto trace through all epochs
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Input
```

```
Epoch_Space;
Pareto_Set;

%Initialize
[num_epochs,num_fleets] = size(Epoch_Space);
trace = unique(Pareto_Set);
Pareto_Trace_temp_infeasible = [trace,histc(Pareto_Set(:),trace)];
Pareto_Trace  =...
    [Pareto_Trace_temp_infeasible(:,1) ,...
    Pareto_Trace_temp_infeasible(:,2)/num_epochs];

%Initialize loop
[a,b] = size(Pareto_Trace_temp_infeasible);
C = ones(a,1);
for i = 1:a
    if Pareto_Trace_temp_infeasible(i,1) == 0
        C(i) = 0;
    end
end

%Initialize the Pareto trace
Pareto_Trace_temp=[];
%Calculate the Pareto trace
for i = 1:a
        if C(i) == 1;
            Pareto_Trace_temp  =...
                [Pareto_Trace_temp_infeasible(i,:); Pareto_Trace_temp];
        end
end
```

F.16 Calculate_NPV.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% This function calculates the NPV value of each fleet alternative
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [NPV_Fleets,Flow] = Calculate_NPV(Fleet_Cost_CAPEX,Fleet_Cost_OPEX)

%Discount rate
discount_rate = 0.04;
%Time horizon
t = 20;

%Initialize
[A,B] = size(Fleet_Cost_CAPEX);
Flow = zeros(A,t);
```

```
Cash_flow = zeros(A,1);
NPV_Fleets = zeros(A,1);

%Calculate NPV for all fleets
for i = 1:A
    for j = 1:t
        Flow(i,j) = ((Fleet_Cost_OPEX(i))/....
                  (1+discount_rate)^j);
        Cash_flow(i,1) = sum(Flow(i,:));
        NPV_Fleets(i,1) = (-Fleet_Cost_CAPEX(i,1) + Cash_flow(i,1));
    end %end j
end %end i
```