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# Design of an Offshore Standby Base for Remote Regions

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# Abstract

In this Master's thesis an optimization model for finding the optimal design of a standby base operating in remote regions is presented. The research and development within optimization of standby vessel design is limited. The objective of this thesis has been to utilize the state of the art within the areas of maritime fleet optimization, ship design optimization and the analytical hierarchy process in the development of a working model. Application of emergency preparedness assessment processes in the North Sea as quantifiable mathematical restrictions is also addressed.

By developing a linear optimization model, and implementing it into optimization software, a possible solution in finding the optimal design of a standby base has been approached. The scope of the thesis has been to find the basic design of the standby base, its attributes and the fleet of cooperating standby vessels with the minimum total cost and satisfactory emergency preparedness. As an addition, the model has also been extended with a weighted objective function considering the trade-off between cost and emergency preparedness.

In order to investigate the behavior of the model in producing the optimal design and functionality of a standby base, it was tested on a case study for future petroleum development near Jan Mayen. The results revealed a significant cost reduction when the standby base was implemented as apposed to only standby vessels. It also revealed that different design options proved more appropriate as a standby base when the data was run for the original model and the weighted objective function extension.

Because of the limited state of the art connected to optimizing the design of standby vessels, the model in this thesis is a version of what I consider to be a possible way of developing a tool in aiding naval architects. Because of the model's use of expert judgments, obtaining applicable results demands extensive work connected to data pre-processing.

**NTNU Trondheim**
**Norwegian University of Science and Technology**
*Department of Marine Technology*

# MASTER THESIS IN MARINE TECHNOLOGY

## SPRING 2013

## FOR

## Even Sunde Andresen

## Design of an Offshore Standby Base for Remote Regions

**Background**
As petroleum exploration moves into remote areas, the introduction of a standby base could be a valuable asset when there is a lack of onshore support. The motivation of this thesis is to develop a tool aiding naval architects in finding preliminary design and functionality of the standby base in an early phase of the design process.

The current state of the art connected to optimizing the design of standby and support vessels is limited. Most research and development is aimed at optimizing the design of cargo vessels. This thesis will utilize the state of the art within the areas of ship design, maritime fleet size and mix, expert judgement methods and emergency preparedness assessment to approach a solution.

**Objective:**
The objective of the thesis is to develop a method for deciding the design and functionality of a standby base with optimal trade-off between cost and emergency preparedness requirements. The method of logical approach should be based on operations research.

**Tasks**
a) Identify the current state of the art in ship design optimization and other relevant areas of research

b) Utilize the findings from the literature study to develop an optimization model reflecting the problem

c) Solve the optimization model using the optimization software FICO™ Xpress

d) Interpret the results and compare them to state of the art

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**General**

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, discussion of results and conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

**Supervision:**
Main supervisor:
Bjørn Egil Asbjørnslett
**Deadline: 10.06.2013**

# Summary

The main purpose of this thesis has been to develop a tool assisting naval architects in finding the optimal design and functionality of a standby base as a supplement to ordinary standby vessel. As petroleum exploration moves into remote areas, the introduction of a standby base could be a valuable asset when there is a lack of onshore support. The problem is to decide the design and functionality of the standby base with optimal trade-off between cost and emergency preparedness requirements.

The method for solving the problem has been mathematical optimization. Even though there are extensive research and methods within the area of optimizing cargo vessel design, there is a gap in the research of optimizing the design of standby vessels. This thesis proposes a linear optimization model by utilizing the state of the art within the areas of ship design, maritime fleet size and mix, the analytical hierarchy process and emergency preparedness assessment.

Two models have been developed, each subjected to the same set of restrictions. One model minimizes the total cost of the standby base and the fleet of standby vessel, while the extension of this model implements a weighted objective function considering the trade-of between cost and the capability for emergency preparedness. The behaviours of the two models are tested on a case study for future petroleum development near Jan Mayen. Two different sized second-hand tank vessels (DWT: 149 999 MT and 299 998 MT) were assessed as possible standby base designs. Different cost factors connected to each design option is discussed, including how the functionality of the standby bases changes throughout the scenario.

For both design options the optimal time of implementation of the standby base is four years after petroleum production initiates in the region. As the activity level in region increases so does the fleet size of standby vessels and the capabilities of the standby bases. For the instance when cost is minimized in the objective function, the total cost of the smaller tanker as a standby base is lower (NOK 5,828,600,000) than the bigger tanker (NOK 5,913,770,000). This difference arises from the later implementation of emergency preparedness equipment on the bigger tanker including higher operating expenses. In addition to a lower total cost, a larger fleet of standby vessels support the smaller tanker throughout the scenario.

The case study is also tested on the weighted objective function. The trade-off situation between total cost and the total capacity of recovered oil is investigated. By decreasing the weight of cost while increasing the weight of recovered oil capacity, a relationship between the two are made. The total cost and the total capacity increase with decreasing weight on cost. The bigger tank ship produces both a lower total cost and a higher recovered oil capacity compared to the smaller tanker as the weight of cost decreases.

The optimization model, including its extended objective function, presented in this thesis propose one method of optimizing the design of a standby base. Because of the lack of literature concerning optimizing standby vessel design, confirming the validity of the results has been difficult. It should also be noted that some of the data in the case study is based on assumptions. However, the model presented in this thesis proposes a unique addition to ship optimization in an area dominated by cargo vessels.

# Sammendrag

Hovedformålet med denne avhandlingen har vært å utvikle et verktøy som skal bistå skipsingeniører i å finne det optimale designet til en framskutt standby base inkludert i en beredskapsplan bestående av andre standby skip. Ettersom petroleumsvirksomheten beveger seg inn i avsidesliggende områder, kan innføring av en standby base være et verdifullt tillegg når det en mangel på støtte fra land og andre felt. Problemet er å bestemme utformingen og funksjonaliteten til basen med optimal avveining mellom kostnader og krav til beredskap.

Metoden for å løse problemet i denne avhandlingen har vært matematisk optimering. Selv om det finnes omfattende forskning og metoder innen optimering av designet til lasteskip, finnes det lite forskning innenfor optimering av standby fartøy design. I denne avhandlingen blir en lineær optimeringsmodell forslått ved å utnytte gjeldende kunnskap og løsninger innenfor skipsdesignoptimering, flåteoptimering, AHP-metoden og kjente vurderingsmetoder innen beredskap.

To modeller er blitt utviklet, som begge er utsatt for de samme matematiske begrensningene. En modell reduserer den totale kostnaden for standby basen og flåten av standby fartøy, mens en forlengelse av denne modellen implementerer en vektet målfunksjonen som vurderer sammenhengen mellom kostnad og beredskapskapasitet. Oppførselen til de to modellene er blitt testet på en tilfellestudie for framtidig petroleumsvirksomhet nær Jan Mayen. To forskjellige tankskip (Dødvekt: 149 999 tonn og 299 998 tonn) ble vurdert som mulig standby baser. De ulike kostnadsfaktorene knyttet til de to designene er blitt vurdert, i tillegg til hvordan funksjonaliteten til basen har endret seg gjennom scenariet.

For begge designmulighetene har det optimale tidspunkt for implementering av standby basen vært fire år etter at petroleumsproduksjonen har startet i regionen. Ettersom aktivitetsnivået i regionen øker, øker også størrelsen på flåten av standby fartøyer i tillegg til funksjonaliteten til standby basene. Den optimale løsningen i den minimerte kostnadsfunksjonen produserer et resultat der det mindre tankskipet og standby fartøyene har en total kostnad på 5,828,600,000 kr, mens det større tankskipet er knyttet til en totalkostnad på 5,913,770,000 kr. Kostnadsforskjellen kommer av at beredskapsutstyr blir implementert senere på det større tankskipet i tillegg til at det større tankskipet er knyttet til en høyere driftskostnad. Det mindre tankskipet er også støttet av en større flåte av standby fartøy gjennom scenarioet.

Dataverdiene fra tilfellestudiet er også testet på den vektede målfunksjon. Avveiningen mellom totalkostnad og den totale kapasiteten til oljeoppsamling er undersøkt. Ved å redusere vekten knyttet til kostnader og samtidig øke vekten knyttet til oljeoppsamlingskapasitet er det mulig å undersøke hvordan de to målene påvirker hverandre. Den totale kostnaden og den totale kapasiteten for oljeoppsamling øker i takt med synkende vekt på kostnader. Det større tankskipet er knyttet til både en lavere totalkostnad og høyere oljeoppsamlingskapasitet sammenliknet med det mindre tankskipet ettersom vekten knyttet til kostnader reduseres.

Optimeringsmodellen presentert i denne avhandlingen er en mulig metode for å optimalisere designet til en standby base. På grunn av mangelen på litteratur knyttet til optimering av standby fartøy design, har vurderingen av nøyaktigheten til resultatene vært vanskelig. Det bør også bemerkes at noe av dataen i tilfellestudiet er basert på antagelser. Uansett, så representerer modellen i denne avhandling en unik metode for å optimere designet til en stand-by base i et område dominert av lasteskip.

# Preface

This Master's thesis was prepared during spring of 2013 at the Norwegian University of Science and Technology (NTNU), Department of Marine Technology.

The solutions presented have been developed through use of state of the art within different areas of operations research. The strategy of my work has been to iteratively approach a model by verifying and evaluating possible solutions. The model presented in this thesis is the final result from a process of trial and error.

I would like to thank my supervisor at NTNU, Professor Bjørn Egil Asbjørnslett for invaluable help and guidance. I also want to thank Professor Kjetil Fagerholt for advice and support during the work with my thesis.

Trondheim, 10 June 2013

Even Sunde Andresen

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## List of Abbreviations

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| CR | Consistency Ratio |
| DNV | Det Norske Veritas |
| EP | Emergency Preparedness |
| ERRV | Emergency Response & Rescue Vessel |
| FSMVRP | Fleet Size and Mix Vehicle Routing Problem |
| LCC | Life Cycle Cost |
| LP | Linear Programming |
| MADM | Multi Attribute Decision Making |
| MFSMP | Maritime Fleet Size and Mix Problems |
| MOB | Man Over Board |
| MS | Microsoft |
| NCS | Norwegian Continental Shelf |
| NOFO | Norwegian Clean Seas Association For Operating Companies |
| NTNU | Norwegian University of Science and Technology |
| ORO | Oil Response Operation |
| SAR | Search And Rescue |
| SDDP | Ship Design and Deployment Problem |
| VRP | Vehicle Routing Problem |

Chapter 1

# Introduction

Area-based emergency preparedness was introduced on the Norwegian Continental Shelf ten years ago. The reason is that a greater extent of common air and maritime resources will lead to more cooperation thus improve the emergency preparedness readiness. For field development in remote regions, where there is greater vulnerability and minimal infrastructure, the best solutions for safety and emergency preparedness should be implemented. As an addition to a fleet of ordinary standby vessels, especially for remote regions with lacking infrastructure to rely upon, implementing an advanced standby base as a part of the contingency plan[1] might be a valuable asset increasing both human- and environmental safety. However, what is considered the optimal design and functionality for a standby base?

The standby base can in essence take the design of every floating structure as long as it possesses attributes that strengthen the emergency preparedness for the region. The term “standby base” or “advanced standby base” is not commonly used, and its definition in this thesis is a bigger standby vessel located strategically in a region supplementing ordinary standby vessels ready to give assistance in the event of an emergency on or near the installation. Another purpose of the name “standby base” is to distinguish it from a standby vessel/Emergency Response & Rescue Vessel (ERRV).

**The purpose of this thesis is to develop an optimization tool aiding naval architects in finding preliminary design and functionality of the standby base in an early phase of the design process**.

[1] Definition; a plan designed to take account of a possible future event or circumstance. In this thesis, contingency plan is referred to as the combined emergency preparedness readiness/capability of standby vessels and the standby base safeguarding the lives and environment in the region they are operating.

Many different problems arise when considering implementing a standby base as a part of an emergency preparedness plan. On a macro level, the two most important questions are; what should be the basic design of the standby base and its attributes, and how will it operate. The answers to these questions can be generated using a mix between marine technological assessments and logistical and operational tools. Mathematically it is possible to consider them either both at the same time or as individual problems. Both approaches have their benefits and drawbacks. When assessing them individually it is possible to include more details. However, the decision variables included in ship design, functionality and operation are difficult to merge, while at the same time have an optimization model that realistically reflects the problem. In Ray, Gokarn and Sha (1995) the optimal design specifications of a vessel is decided using a combination of empirical formulas related to ship parameters and an expert judgment method for weighting the attributes connected to the vessel. However, this model finds the optimal design for a cargo vessel transferring commodities between ports. A standby base will spend most of its time at one location. Connecting its attributes directly to ship parameters is therefore unrealistic. In relation to the state of the art connected to the problem of finding the optimal design of standby vessels, the information found during the literature study in this thesis is limited. However, the state of the art connected to optimal design of cargo vessels has come a long way. The scope of this thesis will therefore be to utilize the state of the art connected to optimal ship design, and develop it into a mathematical optimization model reflecting the problem of finding the optimal design of a standby base.

This thesis is organized as follows. Chapter 2 discusses the background of the problem and how the restrictions and regulations concerning emergency preparedness can be incorporated into the model. Chapter 3 is the literature study where state of the art is investigated and discussed. Chapter 4 discusses all the relevant parts of the model developed (objective function, sets, parameters and variables). Chapter 5 presents the mathematical optimization model while in Chapter 6 the model is tested for a scenario developed near Jan Mayen. In Chapter 7 a multi-objective model extension is explained while in Chapter 8 the results from the case study is presented. Chapter 9 and Chapter 10 consist of the discussion and the conclusion.

# Chapter 2

# Background

This chapter discusses the problem background, the development of the model and why optimization might be a valuable tool within ship design. It also describes the real problem and how it can be reflected as a mathematical optimization model. The last subchapter is the problem description. The problem description is an independent and concrete description of the problem, valuable for readers needing to understand the basics of the mathematical model without having read the background.

## 2.1 The Phases of the Model Development

During the process of developing a model reflecting the problem of finding the optimal design and functionality of a standby base, a special working approach has been utilized (Lundgren, Ronnqvist, & Varbrand, 2010). This approach includes a number of phases as illustrated in Figure 1. After generating the actual decision problem, the first phase was to identify the optimization problem. The next phase was to formulate the problem by describing it mathematically as an optimization model. The model was eventually solved using the optimization software FICO™ Xpress. Finally the model and its results were evaluated.

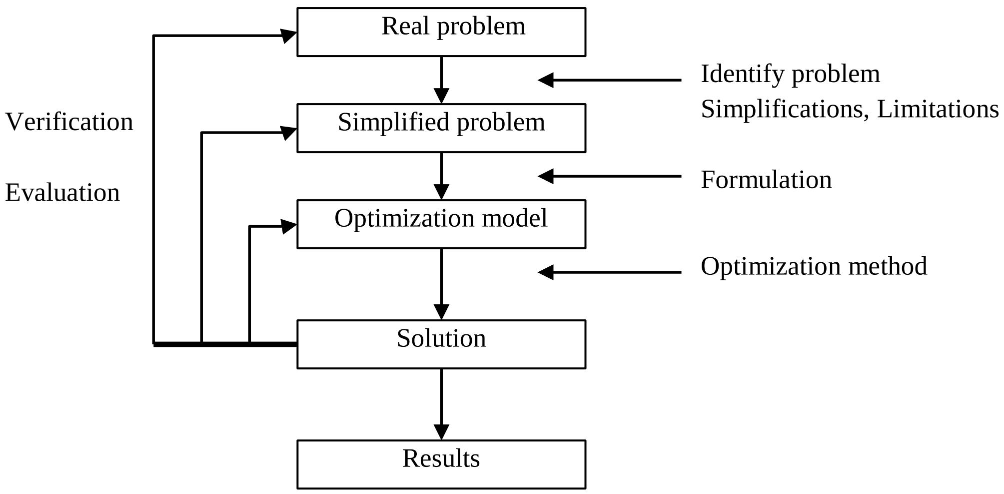



Figure 1: The process connected to the development of the optimization model

## 2.2 Motivation for Using Optimization

The first introductory course to marine design at NTNU included a chapter in Amdahl and Fuglerud (2003) regarding naval architecture. In this chapter the importance of finding the right balance between performance, stability, cost, functionality, etc. was highlighted. The way to illustrate the nature of the design phase was the spiral model. This is an iterative and sequential process where you first prepare the general terms and customer demands, before dimensions, stability and costs are calculated. The results from these calculations are checked against the requirements, and divergences and possible improvements are localized. The process is then repeated and the results are improved. In the end you hopefully have a design that satisfies all of the general terms. By exploiting optimization as a decision tool in the early design phase the number of iterations will drop and you will have a better starting point when initiating the broad investigation at the beginning of the spiral.

In Erikstad S (2012) the motivation for using optimization when modelling preliminary ship design is discussed. A drawback of the iterative process in the spiral model is that you typically get locked to your first assumptions. The iterative process is time consuming, and you are often only able to explore a limited part of the first design assumption. An alternative approach to iterative improvement and interaction with the ship designer is a mathematical process. The literature study will discuss different ways of optimizing ship design. Mathematical optimization represents a very powerful design tool because of its ability to make a direct mapping between the design problem in the performance space and a superior solution in the decision space. However, in order to use optimization techniques all aspects of the problem needs to be expressed in mathematical terms. The overall design problem of an advanced standby base is not easily transformed into the restricted format required by most mathematical optimization algorithms.

## 2.3 Real Problem

Chapter 2.4 -2.6 will try to identify all the relevant components influencing the problem. Chapter 2.4 introduces the basics of emergency preparedness. Chapter 2.5 discusses the regulatory requirements connected to offshore emergency preparedness and how they affect the design and functionality of the standby base. Chapter 2.6 discusses the relevant attributes of standby vessels, while Chapter 2.7 reviews the design and functionality of the standby base.

## 2.4 Area-based Emergency Preparedness in Remote Regions

From *Area-based Emergency Preparedness on the Norwegian Continental Shelf* (2012, pp. 6-8) some information about area based preparedness and ERRV/standby vessel capabilities can be extracted. It is stated that including the minimum requirements for standby vessels according to Sjøfartsdirektoratet (1992), requirements from preparedness analyses for individual installations, fields and regions will occur. However, there should be a long-term intention towards as many standby vessels as possible having high transit speed and a slide or similar to collect MOB boats or lifeboats.

In terms of remote areas, the guidelines only state that for installations far away from the coast or other petroleum activities it would be possible to impose extended requirements for the preparedness vessel. The intention is that by expanding the required attributes on board, the preparedness vessel will be able to cover more preparedness functions and be able to compensate for the lack of infrastructure. It is therefor sensible to assume that the parameters connected to the regulatory restrictions in the optimization model needs to have a stricter value compared to standard restrictions implemented in the North Sea.

Area-based preparedness is in essence the ability to share the capabilities of standby vessels among installations. There are some emergency preparedness groups that require vessels and equipment in close proximity, and others that do not.

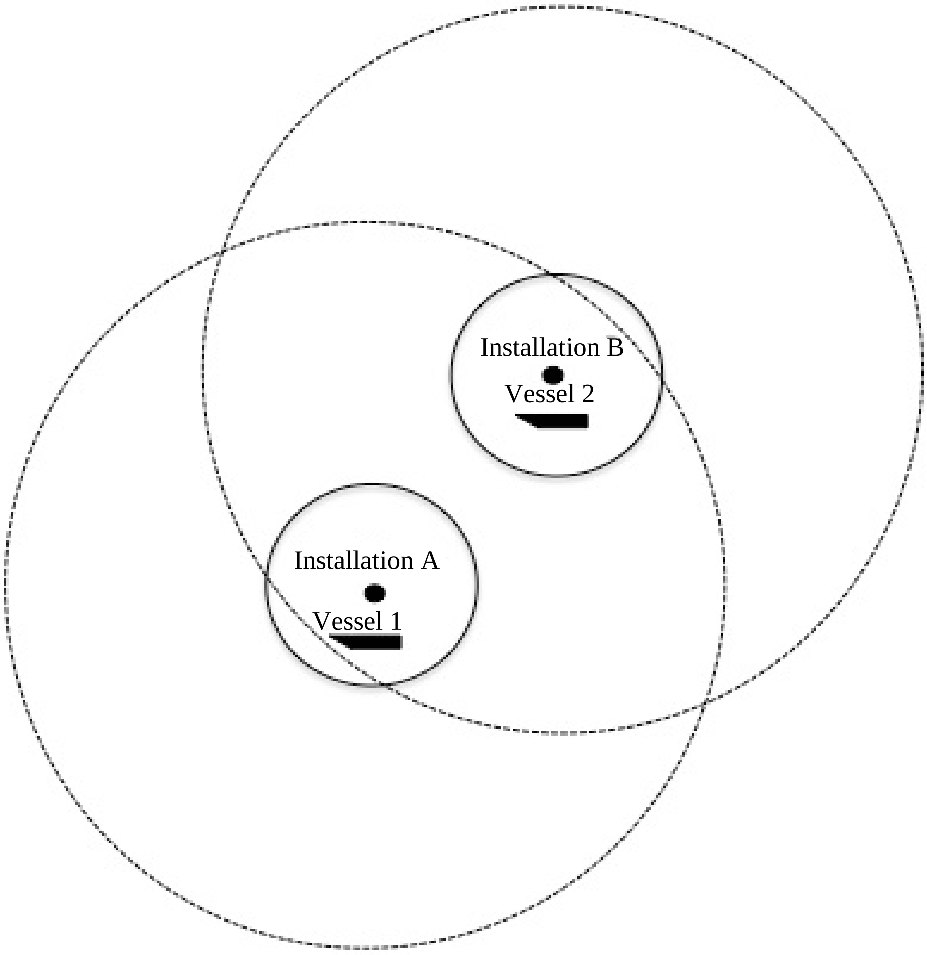



Figure 2: Area-based emergency preparedness for two installations

Figure 2 illustrates the basics of area-based emergency preparedness. The solid circles around installation A and installation B represent an emergency preparedness group, e.g. fire fighting, requiring standby vessels to be close to the installation. The dotted circles represent an emergency preparedness group, e.g. oil recovery, having a response time requirement high enough to cover both installations. The "solid line" category will impose a requirement equal to two standby vessels needing to have fire-fighting attributes (a requirement later referred to as a "Unit Requirement"). The "dotted line" requirement connected to installation A and B falls under the category of shared preparedness, because each vessel can cover both installations. Emergency preparedness groups with shared preparedness characteristics may be imposed to a requirement later referred to as "Total Requirement".

## 2.5 Emergency Preparedness Assessment

Today there are guidelines and standards to ensure adequate preparedness in the North Sea. The *NORSOK-standard Z-013N* has been developed in order to secure satisfactory safety, appreciation and cost efficiency for existing and developing projects in the petroleum industry *(NORSOK Standard*, 2010). The standard is structured around three elements; use of risk and emergency preparedness assessment as a basis for decision making, specific requirements for planning and execution of risk and preparedness for different activities and the relation between the risk and emergency preparedness assessments. Elements included in the *NORSOK-standard Z-013N* will be of importance when considering the restrictions the optimization model is subjected to.

The process of performing a risk and emergency preparedness assessment is divided into a risk assessment process and an emergency preparedness assessment process. The two processes can be performed separately, but preferably simultaneously. Input data used and the results obtained from one process will in many cases be used as input in the other process. Appendix Figure I in Appendix A from *NORSOK Standard* (2010) describes the process of performing a risk assessment.

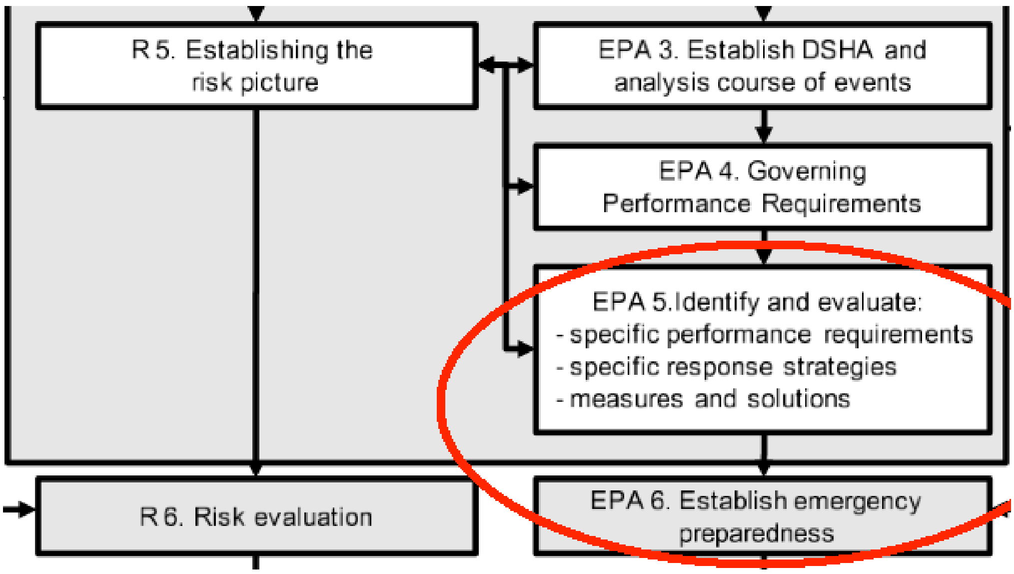



Figure 3: Process of performing a risk and emergency preparedness assessment

Figure 3 is a clipping from Appendix Figure I in Appendix A. The red circle highlights the area where optimization can be used as a decision support tool. The specific performance requirements represent the limitations and restrictions in the optimization model, and the specific response strategies would be the different standby vessels combined with the introduction of a standby base possessing a set of attributes. The measures and solutions will be the output from the model including post optimizing the results in order to determine the optimal design of the standby base. From the information regarding emergency preparedness assessment in *NORSOK Standard* (2010), it is evident that pre-processing information in order to get quantifiable and valid parameters and restrictions will be a major part of the pre-optimization process for the problem. However, because of the extent of work connected to this pre-processing of information, the parametric values for the processes R 5 and EPA 4 leading up to EPA 5 will not be emphasized in this thesis. For the case study in Chapter 6, many of the values connected to them are based on assumptions.

In chapter 5.2.2 in *NORSOK Standard* (2010) the objective when establishing the context for a risk assessment process is highlighted. It is important to include parameters related to both external and internal context in order to ensure that all activities in the risk assessment are covered. Apart from the establishment of the objective, the process shall also involve defining methods and models to be used, system boundaries and the system basis and risk acceptance criteria for the model. When defining the model it is important that the methods and models to be used in the process are suitable with respect to the decisions to be made and the availability of the required input data for the model. It is also stated that the use of alternative approaches, like expert judgments, to compensate for lack of relevant and required input data, shall be clearly stated and documented.

ALARP is short for as low as reasonably practicable. The term reasonably practicable implies that risk-reducing measures shall be implemented until the cost (in a wide sense, including time, capital costs or other resources/assets) of further risk reduction is grossly disproportional to the potential risk reducing effect achieved by implementing any additional measure. Based on the requirements concerning the risk assessment according to *NORSOK Standard* (2010) when considering implementing a standby base in a contingency plan for a petroleum field in remote areas it is possible to develop a rough layout of the optimization model.

The optimization model should reflect the contingency plan for the remote field, divided into a set of standby vessels and the standby base. The set of standby vessels and the standby base are linked to a set of cost parameters and a set of attribute parameters determined by what is considered adequate in terms of reflecting the capabilities of a standby vessel. The attributes connected to the fleet of standby vessels and the standby base should be able to maintain a satisfactory emergency preparedness level. The literature study in Chapter 3 reviews various methods that might be used to find the optimal design of the standby base, however a simplified linear model reflecting the emergency preparedness assessment is illustrated in Figure 4. The model illustrates how the capabilities of the standby vessels and the standby base combined need to be higher than the requirements. The objective of the model is to find the least expensive combination that satisfies these requirements.

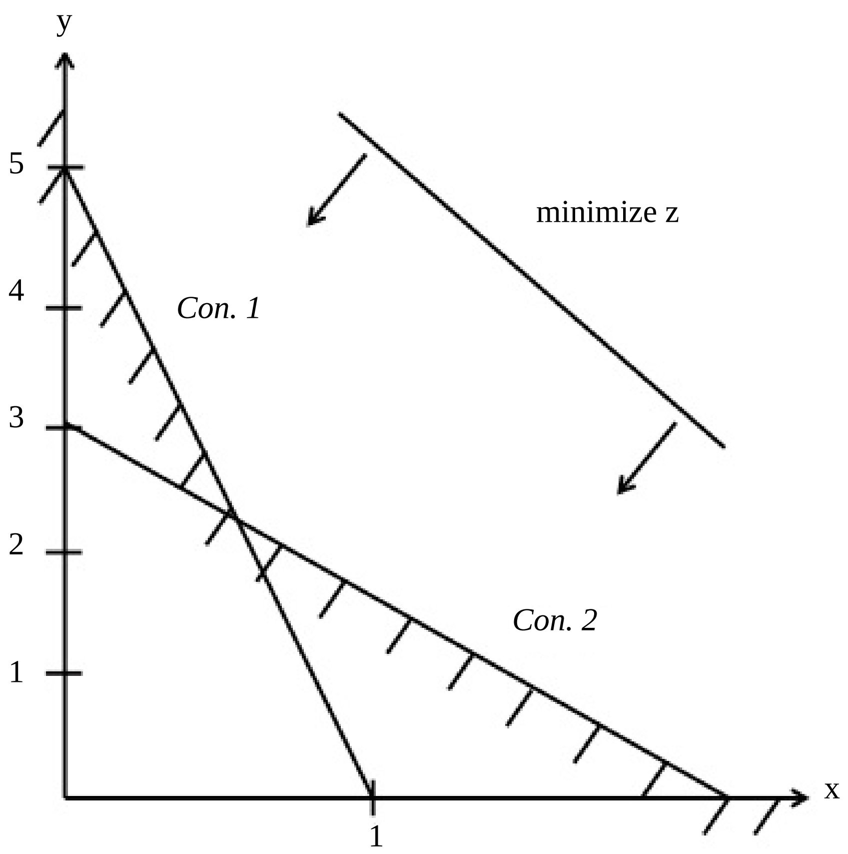



Figure 4: Graphical illustration of the emergency preparedness assessment

$$\begin{aligned} \min z \; = \; & C^X x + C^Y y && (Objective\ function) \\ s.t. \quad & A_1 x + A_1 y \geq R_1 && (Con. 1) \\ & A_2 x + A_2 y \geq R_2 && (Con. 2) \\ & x \in \{0,1\}, y \in integer && \end{aligned}$$

The binary variable *x* represents the standby base, and the integer variable *y* represents the number of standby vessels. The two constraints *Con. 1* and *Con. 2* reflect the minimum requirement for two different attributes in the contingency plan of the petroleum field. The standby vessel and the standby base have different capabilities when it comes to satisfying these requirements, expressed through the parameters $A_1$ and $A_2$. The cost of the contingency plan is expressed through the objective function and the cost parameters $C^X$ and $C^Y$ connected to the standby base and standby vessel. A significant and difficult part of the modelling is to develop a working connection between these parameters. Chapter 2.6 discusses the most relevant attributes in a contingency plan for a petroleum field.

## 2.6 Attributes Relevant in Offshore Contingency Planning

The attributes of a standby vessel are closely connected to the emergency equipment installed. Emergency equipment of similar types might have different functionality levels in order to perform a higher or lower degree of emergency preparedness support. For this thesis the emergency preparedness attributes of a possible standby base has been divided into three sub groups corresponding to those suggested by *Area-based Emergency Preparedness on the Norwegian Continental Shelf* (2012). The first group involves oil recovery operations, the second group is standby duties, rescue from sea and medical evacuation and the third group involves Search and Rescue (SAR) helicopter operations.

Based on the attributes of the two reference ships Stril Herkules and Stril Mariner, and a conversation with the finance manager of Møkster Shipping, Alf Møkster, the most relevant equipment (also referred to as attributes) implemented on a standby vessel will be discussed further in this chapter.

Stril Mariner is equipped and fitted for the following services: platform supply, fire fighting, standby/rescue duties and oil recovery operations. Stril Herkules is equipped and fitted for the following services: support and rescue, helideck, fire fighting, capable of retrieving FRDC/Lifeboats, first line oil recovery and emergency towing.

| Stril Herkules | Stril Mariner |
|---|---|
|  |  |
| Length (LOA): 97,5 m<br>Breadth Moulded: 19,2 m | Length (LOA): 78,6 m<br>Breadth Moulded: 17,6 m |
| **Oil Recovery Attributes** | |
| ORO Tank[2]: 1366 m$^2$ | ORO Tank: 1550 m$^3$ |
| Trans Rec skimmer[3] | Trans Rec skimmer |
| Two oil booms[4] | Oil boom |
| Dispersant system[5] | Dispersant system |
| - | Oil Detector Radar System |
| **Standby, rescue from sea and medical evacuation** | |
| Two MOBs[6] | Two MOBs |
| Radar | Radar |
| Safe haven: 370 persons | Safe haven: 300 persons |
| Hospital unit | Hospital unit |
| Retrieval of rescue vessels | Fire Fighter |
| **SAR Helicopter Operations** | |
| Helipad | - |
| Helicopter fuel | - |

Figure 5: Reference ships: Standby vessels

[2] ORO-tanks store oil spill recovered from the surface and must be equipped with permanent heating systems. A system must be able to raise the temperature of 1000 m$^3$ oil 15 degrees within 12 hours. Every tank needs to be equipped with a pump for unloading. The vessel's unloading system must satisfy a minimum of 500 m$^3$ per hour to 3 bar at 3000 cSt viscosity and a minimum of 300 m$^3$ per hour to 7 bar at 300 cSt viscosity. The pumps must be screw-driven and have a capacity of no less than 100 m$^3$/hour (NOFO, 2012).

[3] The Transrec Skimmers are used to transfer oil spill from the surface into the ORO-tanks through an umbilical. The pump capacity is between 200 and 400 m$^3$/h.

[4] An oil boom is a (usually 400 m long) tube deployed on a strategically chosen location in order to contain and control the oil spill (NOFO, 2012).

[5] A dispersant system is used to dissipate oil slicks. Dispersants cause the oil slick to break up and the oil is effectively spread throughout a larger volume of water than the surface from where the oil was dispersed (NOFO, 2012).

[6] MOBs (also referred to as Rescue boats) is intended for man over board situations. The MOB boat is required to be able to launched and retrieved quickly (Dokkum, 2007).

Figure 5 displays the most important attributes of the two reference standby vessels. Even though they both have attributes within each category, their functionality level and capability are different. These differences within the same attribute are transferrable to the functionality and design of the standby base and need to be incorporated into the optimization model.

### 2.6.1 Oil Recovery Attributes

Oil recovery requirements are closely connected to an organization called the Norwegian Clean Seas for Operating Companies (NOFO). NOFO is responsible for maintaining the operating companies' oil spill protection services. The preparedness is associated with exploration and production of oil and gas on the Norwegian Continental Shelf (NCS). Their main objective is to maintain the preparedness, which includes personnel, equipment and vessels. NOFO has developed a method for finding the required oil recovery capability for a field. The output of this method is referred to as number of NOFO systems (see Appendix D for NOFO calculations connected to the case study in Chapter 6). One NOFO system consists of:

- One oil recovery vessel
- One 400 m seagoing boom
- One oil skimmer
- The capacity to hold 1500 $m^3$ oil emulsion
- NOFO personnel.

### 2.6.2 Standby, Rescue, Hospital and Helicopter Attributes

Standardized regulation methods, like NOFO calculations, connected to attributes within the categories standby, rescue from sea, medical evacuation and SAR helicopter operations are not common. The requirements connected to these categories are usually decided using impact studies and expert judgments. However, some standards have been developed and must be taken into consideration when developing the optimization model.

In 1992 the Ministry of Trade and Industry in Norway introduced a regulation concerning preparedness vessels (Sjøfartsdirektoratet, 1992). This regulation is divided into eight chapters containing vital information that needs to be taken into consideration when designing an advanced standby base and incorporating it into a fleet of standby vessels. Many of the regulations deal with elements that are impossible to incorporate into an optimization model. Elements regarding crew training, maintenance and other unquantifiable elements have purposely been omitted as parameters. These details will be of importance when calculating cost estimates for operations, however when constructing the optimization model they are omitted for the sake of simplicity. Another important factor for deciding whether a regulation can be included in the model is the possibility to convert it into a working restriction. A restriction, like *Con. 1* in Figure 4, includes both parameters and variables. In order for the regulation to work in the model, it needs to have a numerical connection to a parameter, and must in some way or other influence the decision variables in the model. Based on these principles, the paragraphs relevant for the design of the standby base are listed in Appendix A. Table 1 summarizes these restrictions and categorizes them into what attribute they influence, which restriction they will impose on the optimization problem and whether they influence the standby vessels, the standby base or both.

| Chapter | Paragraph | Attribute | Restriction | Influences |
|---|---|---|---|---|
| IV | § 15 (1) | Speed | Min 13 knots | Vessels |
| | § 16 (1) | Ship design | Min freeboard | Base |
| | § 19 (1) | Safe haven | Bunks 10% rescued | Vessels and Base |
| | § 19 (2) | Safe haven | 0,75 $m^2$ /person | Base |
| | § 19 (4) | Hospital unit | Min 15 $m^2$/person | Base |
| | § 19 (7) | Safe haven | Room for deceased | Base |

Table 1: Regulations concerning preparedness vessels

## 2.7 Design and Functionality of the Standby Base

The basic design of the standby base is an important aspect of this thesis. The basic design is the vessel/standby base without any added functionality or attributes. The basic design can either be specified during a new build, or be a second-hand converted vessel. When considering investing in a ship, there are numerous factors to consider. These factors are discussed in Branch (1998). The most relevant factors for this thesis are capital cost, maintenance costs, resale value, adaptability, discounted cash flow generated annually by the new vessel, and depreciation of the vessel over its estimated useful life. Various vessel designs will provide different factors.

During the design process of a vessel there are different elements to consider. In terms of a new build, the shipyard cost of building the vessel is basically divided into labour cost and material costs. These will be directly connected to the size, capacity and functionality level of a vessel. A vessel will have a high investment cost if the design requires more/expensive materials. It can also be more expensive to build due to its complexity demanding more labour hours. There needs to be a reward for investing in a more expensive vessel. The reward can either be lower operating expenses or higher revenue. Either of them might be evident immediately after the vessel starts operations, or they can become evident far later. When considering the design of a standby base the future demand for a higher level of emergency preparedness must be taken into account. A complex vessel design with the ability to adapt to different activity levels in a cost efficient manner could easily prove less expensive in the long run compared to a simple design.

The ability to adapt when there is a slight mismatch between required attributes in the fleet of preparedness vessels could make the introduction of a versatile standby base valuable. If the required functionality level of search and rescue attributes are to low and the number of oil recovery attributes are redundant, having an adaptive standby base makes it possible to shift the recourses of the standby base to other areas consequently increasing the total emergency preparedness capacity and lowering the costs. However, different regulations will impose limitations on the attributes allowed on a standby base. Since there are a wide variety of design options to choose from when considering implementing a standby base, the detailed review of the cost parameters, performance indicators and capacity restrictions will be discussed further in the case study in Chapter 6.

## 2.8 Problem Description

The problem description is a very important part when utilizing optimization as a decision tool because it is a reflection of the optimization model, and should allow for the reader to understand the problem without having read the background. This subchapter is a definite and independent description of the problem.

**Problem Description**

*The problem in this thesis is to develop an optimization program that can be used as a tool by ship designers to decide the optimal design and functionality of a standby base operating in remote regions.*

The term "standby vessel" involves various designs of ships outfitted with many different types of equipment. Every vessel and its outfit serves the purpose of safe guarding the lives of the people working offshore and protecting the environment from the hazards of offshore oil drilling. When faced with the option of implementing a larger standby base in remote regions, the effect of its design and attributes needs to be considered. The considerations should be its ability to fulfil the required need for preparedness in the most cost efficient manner. In contingency planning the term As Low As Reasonably Possible (ALARP) is used in assessing safety-involved systems. This implies that risk reducing measures, like the functionalities of a standby base, shall be implemented until the cost of additional attributes are grossly disproportional to the potential risk reducing effect. A more quantifiable way of interpreting the ALARP principle is to impose requirements on different emergency preparedness attributes fulfilling a tolerable level of safety, and find the fleet of standby vessels and the design of the standby base able to cover it at the lowest cost (the objective function minimizes the total cost of the preparedness plan subjected to a set of emergency preparedness requirements).

During the life span of a petroleum field the activity levels will vary. Consequently, the requirements regarding level of functionality of different attributes serving emergency preparedness purposes will need to be covered by the fleet of vessels in the region. Examples of attributes on a standard support vessel are fire fighting, radar, oil recovery equipment, MOB boat etc. Every standby vessel, including the standby base, will possess different attributes. The functionality level of these attributes can vary between the vessels. A smaller standby vessel will most likely not have the same capabilities in terms of number of attributes and functionality level as a bigger and/or technologically advanced vessel.

When a region is assessed for future petroleum activity, scenarios for the level of activity will be established. Based on this scenario it is possible to develop a demand for future emergency preparedness. This scenario provides a possibility to find the optimal design of the standby base for this region. The operators in the region will have to accept that the chartered standby vessels have a specific set of attributes with a fixed functionality level. One way to assess the most cost efficient mix of standby vessels and the design of the standby base is by using optimization as decision support. Even though the attributes and functionality levels of the standby vessels are fixed, the implementation of a standby base with the ability to adapt to the increasing activity level in the region could prove beneficial. This way the operators can implement a base in an earlier phase of the development and keep operating costs low until a higher functionality level is demanded. However, the distribution of attributes on the standby base cannot be altered without a cost connected to the alteration. Lowering the functionality level of oil recovery equipment in order to increase the number of MOB boats, results in an interruption of regular operation as well as installation cost. One design might have the ability to do this transformation more seamlessly and cost efficient than another, however this design might require a higher investment cost. A design might have the ability for many attributes, however some attributes will occupy functionality sections of the vessel, either area or volume. Every design will have a pre-set capacity constraint when it comes to available sections for the installation of attributes. On the contrary, the attributes will utilize a pre-set area and/or volume of these sections.

The attributes connected to emergency preparedness are divided into two groups: one where the functionality levels are proportional and another where they are not. A proportional attribute is one where the values connected to the level of functionality can be added together. These attributes need to have quantifiable functionality characteristics, like the number of oil booms, room for rescued personnel in a safe have, MOB boats etc. An attribute that is not proportional is one where the level of functionality represents the ability to deliver a higher standard of emergency preparedness. Examples of such attributes are qualitative attributes like radar functions and fire fighting. For the region where the standby vessel is considered implemented, there might be required that at least three vessels have fire fighter capabilities with level one functionality characteristics. A vessel with level two fire fighter functionality will also cover the level one requirement. A proportional attribute can also have the characteristics of one that is not proportional. It might be required that at least two vessels have three oil booms on board. During one time period of the scenario the standby base can only utilize one level of functionality for each attribute and there will be an operating cost connected to it. Because of the difference in operations and design of the standby base compared to the other standby vessels, a decision method using expert judgment will be used to decide the increase or decrease in efficiency resulting from having an attribute on the standby base compared to a standby vessel.

Chapter 3

# Literature Study

There are different ways of solving the problem of optimal ship design. Some can be detail oriented where the model includes a wide variety of complex design parameters. Others might simplify the parameters in order to end up with a model that is easier to solve. Every model reviewed in this thesis has its advantages, and the goal of the literature study is to, when possible, utilize these advantages in describing the problem mathematically as an optimization model

In Ray et al. (1995) and Bertram and Schneekluth (1998) the use of empirical equations and detailed calculations is implemented into optimization models in order to decide optimal ship design for different scenarios. In the model developed by Ray et al. (1995) the following variables have been included: length, breadth, draft, depth, block coefficient, midship area coefficient and waterplane area coefficient. In the context of ship design, the listing of all variables and independent equations is a cumbersome method. There are many detailed estimations involved, hence Ray et al. (1995) has used a unit approach to identify the design parameters. The units included in the model are resistance, power, weight, freeboard, building cost and stability. The introduction of these variables and equations will when solved to global optimum produce a detailed cost efficient ship design for a given scenario. However, it is obvious that these variables will cause a nonlinear model. Nonlinearity in optimization complicates the solution method enormously compared to a linear model. There exits methods of solving nonlinear models, but unlike that of Linear Programming (LP) problems, there is no single method that can solve a general nonlinear model. When solving a non-linear problem it is very important to know if the problem is convex or not. Ray et al. (1995) makes the connection between ship design optimization, convexity characteristics and global versus local optimization. A problem is convex if the objective function is minimized and convex, and the feasible region defined by the constraints is a convex set. A problem is also convex if it is a maximization problem and the objective function is a concave function. When a problem is convex the local optimum is also the global optimum. In a nonconvex problem a local optimum might not be the global optimum. This fact ensures that if you want to find the real optimal solution to a nonconvex problem you have to check every possible local optimal solution. This will most likely demand a very long computational time. Most practical engineering problems, including ship optimization, can be formulated with nonconvex objective function, i.e. there are many local optimal solutions.

In Ray et al. (1995) two different methods have been applied to the ship design optimization problem in order bring down computational time and still produce an acceptable solution. One method is the multistart method. Because a local optimum generated with a local search heuristic might not be a very good solution, a multistart method is a simple approach of improving the performance of the local search. By restarting the heuristic from many selected or randomly generated solutions you obtain several local optima, from which you can choose the best.

The multistart methods applied on the ship optimization problem presented in Ray et al. (1995) are the Hook and Jeeves method and the Rosenbrock method. In order to perform a global optimization on the problem the article also investigated a method used in finding the minimum energy consumption when annealing solids. The procedure is called simulated annealing and is a stochastic optimization method based on iterative improvements of the objective function in order to escape the local minima. The advantage of this method is that results obtained will arrive at a near optimal solution with the same computational time as the multistart methods. The drawback is that the mathematical modelling is more complex. Ray et al. (1995) also discusses the possibility of combining the two methods where a multistart method is performed on the results from the simulation.

$$\min F = \sum_{i=1}^{N} W_i d_i \tag{3.1}$$

Equation (3.1) is the objective function in the nonlinear constrained optimization problem in Ray et al. (1995). The objectives *i* are concerned with minimizing building cost, power requirement and steel weight.

The ship design optimization method performed in Ray et al. (1995) concerns the main dimensions and is directed towards cargo vessels. The same can be said about similar articles presenting methods of solving the nonlinearity when optimizing ship design. Mistree, Smith, Kamal and Bras (1991) and Bertram and Schneekluth (1998) use a container ship in their case studies, and examples where focus is on machinery and hull design. A standby base will have to perform transits from shore to its location of standby duty. During this transit it is favourable to have a design that minimizes the economical costs. However, for the majority of its operations the standby base will not be moving, and it is questionable whether the best solution method is one that emphasizes the design of the hull and cargo handling.

When modelling an optimization problem for a specialized vessel it is important to consider how it operates. A standardized cargo vessel transports cargo between ports. A supply vessel also transports cargo between shore and offshore installations. Standby vessels provide emergency preparedness readiness to the offshore installation in order to maintain a required safety standard. Even though standby vessels transport little cargo, there might be a possibility to model the functionality and design of an advanced standby base as a routing problem. In routing problems the fleet of vessels visiting the customers are optimized for lowest possible cost. The optimal operation of one vessel is affected by the capabilities of the vessels in the fleet. Similarly the optimal design of an advanced standby base is affected by the customers (offshore installations) and the standby vessels operating in the region.

In a literature survey concerning fleet composition and routing the difference between tactical and strategic fleet composition is discussed (Hoff, Andersson, Christiansen, Hasle, & Løkketangen, 2008). At a strategic level focus is on the capacity of a fleet of ships used in a particular trade. The duration the operators want to acquire capacity for is typically long, say 20 years, and the fleet might not be acquired yet. This involves huge amounts of capital. The report also highlights the uncertainty in demand, costs, and revenues related to fleet operation over a period of time. The investment in an advanced standby base will also require a large amount of capital, and the remote region it is serving will as mentioned be dynamic (the activity level in the region will be changing). There will be series of exploratory drilling wells, and the combined uncertainty of finding hydrocarbons and initiating production will make the market as volatile as a shipping market. When considering a tactical setting Hoff et al. (2008) mention that the problem is more one of capacity adjustment, given an existing fleet. The period is shorter and the uncertainty lower. The Vehicle Routing Problem (VRP) has been extended in order to include a heterogeneous fleet, vehicle acquisition and/or depreciation costs. The extension is called Fleet Size and Mix Vehicle Routing Problem (FSMVRP). In Fagerholt and Lindstad (1999) the problem consists of optimizing operations for supply vessels involving one onshore service depot and seven offshore installations located in the Norwegian Sea. The capacities for the vessels in the pool vary between approximately 500 and 1100 $m^2$. The optimal solution was found by solving a set partition problem of pre-generated feasible routes. For a standby base, the problem and model need to be modified. Instead of an onshore depot, the depot would be represented by the standby base. There are a few functions of the standby base that could fit into a routing problem. ORO requires the standby vessels with ORO capabilities to collect and offload oil spill. This operation would be the reverse of the one described in Fagerholt and Lindstad (1999) because there would be a demand for transporting cargo from a rig to the depot. VRP could also include the distribution of supply products from the advanced standby base to the rigs. This supply would include ORO equipment like oil booms and skimmers. The variables of transported products when the problem is solved to optimality would represent the optimal functionality of the standby base. In case of oil spill there would be a series of events between detection and the leak being stopped: deployment of the first barrier, gathering oil using skimmers, transit to standby base, offloading oil and loading new equipment. The entire operation is considered time sensitive, and the need to include time in the model is essential. Many articles have extended the VRP to include time as a parameter. Salhi and Rand (1993) extend a MIP formulation by including time parameters as the maximum time a vehicle can spend traveling an arc. Osman and Salhi (1996) use a different formulation and introduces a time factor per distance unit for each vessel and a service time for the customers. These models are suitable for some of the attributes that could be implemented on a standby base. However, emergency preparedness attributes cannot all be compared at the same level, and introducing all of them with detailed accuracy in one model is very difficult.

$$\min M \sum_{k \in K} C^k \delta^k + m \sum_{k \in K} \sum_{r \in R_k} D_r^k x_r^k \tag{3.2}$$

Equation (3.2) is the objective function in Fagerholt and Lindstad (1999). The first term is the main objective and corresponds to minimizing the total cost of using the vessels. The binary variable $\delta^k$ is equal to *one* if vessel *k* is used in the optimal solution and *zero* otherwise.

Patricksson, Erikstad and Asbjørnslett (2013) investigate the possibility of using optimization to decide the functional capabilities of a vessel. A set of attributes is represented as requirements in available contracts. The optimal design of the vessel might have all or some of these attributes. The function types (attributes) are divided into levels of capabilities. By formulating a binary integer programming model the profit is maximized. Compared to ship optimization models like Ray et al. (1995) the complexity of the programming is lower. There are no local optimums and there are four parameters and two variables. However, there will be more uncertainties regarding the values of the parameters and the connection between them. For an attribute, like MOB boats, it will require a lot of initial analyses to determine the correct cost for a set of functionality levels, including the functional requirement connected to it. As highlighted in Patricksson et al. (2013), the model does not adjust for correlation between the attributes. For instance, by installing one functional level of crane capabilities, one would assume that the necessary level of MOB capabilities would be lower since there is then no need for installing a secondary crane for lowering the MOB boat. Or a vessel with helipad capabilities will not be able to have heavy crane functionalities because of available deck area complications. As mentioned in the paper, the solution needs a post-optimization evaluation to confirm the validity of the chosen functionality level.

In order to avoid this correlation effect and improve the validity of results Patricksson et al. (2013) presents a model extension based on the solution method of the Ship Design and Deployment Problem (SDDP) presented in Erikstad, Fagerholt and Solem (2011). Similarly to the FSMVRP, the SDDP uses a set of pre-generated vessels as a parameter in the model. However, by combining a base cost for the pre-generated designs and the same cost parameter for the attributes as the old model you are able to produce a more unique vessel. One parameter decides whether an attribute of a certain level is available for the vessel design. The model finds the optimal combination of attributes that is feasible for the vessel. This model solution ensures that the level of realism is higher in terms of vessel design.

How can this model be implemented as a tool for finding optimal functionality of an advanced standby base? In the model a set of pre generated contracts are available at different times, with varying durations, requirements and revenues. These contracts could represent one remote field, and the objective was for the investor to maximize total profit from the standby base design. However, the problem description in this thesis is to minimize the costs of preparedness for one remote field. Extensions and alterations of the model are needed in order to reflect the problem description.

In the concluding remarks of Patricksson et al. (2013) it is mentioned that a natural follow-up would be to make the deterministic model stochastic. When considering the uncertainty of whether production is actually initiated after an exploratory drilling, this could be a way of improving a model of finding optimal design of a standby base. In a literary survey regarding fleet size and mix problems, a model extension suitable for Maritime Fleet Size and Mix Problems (MFSMP) is presented (Pantuso, Fagerholt, & Hvattum, n.d.). The extension uses a multistage stochastic program with recourse. By dividing the lifespan of the advanced standby base into different periods, where each period represents new information regarding whether production is initiated in the remote region, it is possible to generate the optimal design of the standby base according to a stochastic scenario.

The diversity of functions (attributes) needed to maintain a sustainable contingency plan in remote regions will, as mentioned, generate issues when implementing them into the same optimization model. The functions are not easy to compare against each other and it is difficult to evaluate their impact on the design. Not all attributes are possible to implement on an advanced standby base and when there are several features to choose between you are faced with a decision problem. Choices where several incomparable attributes need to be considered on a single scale are not necessarily trivial. In the course "TMR 4115- Design Methods" the lecture note Erikstad S. (2012) discusses how to evaluate a design solution. The lecture presents a structured method that systematically analyses and evaluates complex selection problems. The decision maker in the method faces several alternatives, which are described by a set of attributes. Each alternative has specific values for these attributes. In order to include all relevant aspects when evaluating the different alternatives against each other, the method splits the main objective into several sub-objectives. The sub-objectives may be split further until the appropriate level of detail is reached. In connection to the design of a standby base, this strategy could be useful when comparing the design of standby vessels against the design of a standby base.

Another technique available for organizing and analysing complex decisions is the Analytic Hierarchy Process (AHP). It can be used in a wide variety of decision situations, including comparing attributes against each other. In the same way as the decision method explained in Erikstad S (2012), the problem is decomposed into a hierarchy of sub problems. In Coyle (2004) the process of AHP is explained mathematically. The calculations are in essence aimed at constructing a matrix expressing the relative values of a set of attributes. Based on how the different attributes are valued, products that possess these attributes can be compared against each other. However, it is very much possible to combine the method of decision making techniques and mathematical optimization methods. In Ray et al. (1995) a method very similar to AHP is incorporated into the model. Multi Attribute Decision Making (MADM) was used in deciding the weighting of weight, building cost and power in the objective function (3.1).

Vaidya and Kumar (2004) present a literature review of the applications of AHP. A total of 150 application papers are referred to in the article. In Ghodsypour and O´Brien (1998) the combination of AHP and LP is used when deciding the best suppliers and the optimum order quantities among them. Similarly, Benjamin, Ehie and Omurtag (1992) used a multi-objective decision model in allocating space when planning the facilities in an academic environment.

## 3.1 Relevance

Most models mentioned in this study optimize ship design for transportation problems. Even though there are connections between the routing problem and some of the functionality demands of a standby vessel/standby base, there are to many attributes that cannot be expressed using the method. Using a routing model as a decision maker for the design will be very difficult and unrealistic because of the lack of demand of transportation of goods that is present in the shipping market. The fact that emergency preparedness involves many different parameters and standby support vessels will make the use of a routing model inconvenient.

The model presented in Ray et al. (1995) is essentially made for transportation problems. But in contrast to a routing model, the combination of decision methods and mathematical optimization makes it transformable to designing a standby base. The output will be specifications in terms of ship hull design and considers stability and ship dimension ratios. The key to using a similar model would be to incorporate functionalities as decision variables. Never the less the method will, because of its nonlinearity and complexity, be difficult to solve. Incorporating the attributes and their functionalities for the standby base in the contingency plan of the region will be impossible. This means that the functionality demand must be based on preparedness analysis involving a predetermined fleet of standby vessels for the given scenario. This is a very unrealistic approach to the operation of emergency preparedness, where the changing activity levels will make the fleet of standby vessels vary throughout the effective life of the scenario.

For a specialized standby base including many different attributes and supporting standby vessels, similar models as presented in Patricksson et al. (2013) would generate a model easier to formulate, calculate and evaluate. The AHP and MADM methods would also be useful for ranking the different attributes compared to its operation on either the standby base or standby vessels. In order to include both qualitative and quantitative factors, using integrated analytical hierarchy processes and linear programming as in Vaidya and Kumar (2004) would make it possible to consider both tangible and intangible factors when choosing optimal design of the standby base.

The state of the art in this chapter is utilized in the Chapter 4 and Chapter 5 where the optimization model deciding the optimal design of a standby base is presented.

Chapter 4

# Simplified Problem

Through the process of formulating the problem description, gathering literature from relevant problems and investigating the emergency preparedness standard in the North Sea, the extent of the real problem has been identified. The relevant components included in the complex process of finding a method for mathematically deciding the optimal design and functionality of a standby base in remote regions has been identified. The outcome from this identification phase is discussed in this chapter. During the optimization process as illustrated in Figure 1, the simplified problem has iteratively been approached. The first attempt of a model approach was based on a vehicle routing fleet size and mix method. However, because of the different functionalities of a preparedness vessel and the fact that they seldom include transportation of resources to a location with a demand, the model was discarded and a different approach was employed. The new approach included some elements from the discarded model. The binary decision variables in fleet size and mix methods and the capacity constraint restrictions connected to deck space and tank volume are incorporated in the model. By combining these elements with the base design and attribute functionality method in Patricksson et al. (2013) and the integrated LP and AHP techniques published in Vaidya and Kumar (2004), the model presented in this chapter could represent an applicable tool for deciding both the optimal design of an advanced standby base and the time to incorporate it as part of the contingency plan in an offshore region.

The model is run for each possible standby base design and the different results are compared. In Patricksson et al. (2013) the profit is maximized and all design possibilities are included in set *D*. This is omitted from the model in this thesis because it would leave out valuable information not concerning cost. For example when there are marginal differences between costs, it is preferable to have a design where the functionality levels of attributes are not altered a lot throughout the scenario. A design that is put into operation at a later stage is also preferred because it makes the standby base less dependent on future petroleum activity assessments. If it turns out that production on a field is not be commenced, the optimization model can be run over with the new data, and another design might prove more cost efficient. In essence, there will be a significant value of running the model for each design and compare the results.

When a vessel worth investigating further as a possible basic design has been decided on, different parameters associated with its characteristics and costs need to be developed. Each design has different abilities when it comes to attributes and functionality levels (Further explanation can be found in Chapter 4.2). The designs are regarded as stripped-down vessels like in Figure 6. In order to explain how the model works, Figure 6, Figure 7, and Figure 8 illustrate the methodology applied to the process of modelling when two possible designs are considered as possible standby bases in a hypothetical offshore region.

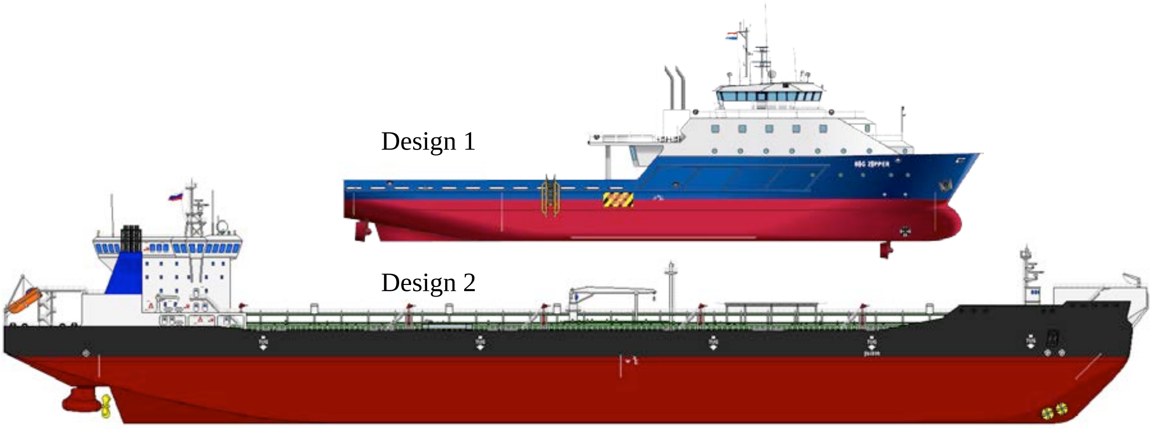



Figure 6: Possible basic standby base designs

Design one is a new and sophisticated standby vessel, while design two is a tanker bought on the second-hand market. Both have different advantages when it comes to emergency preparedness functions, however the level of these advantages might not outweigh the lower cost parameters of the other design. Additionally, the designs need to be able to fit into a contingency plan including other standby vessels.

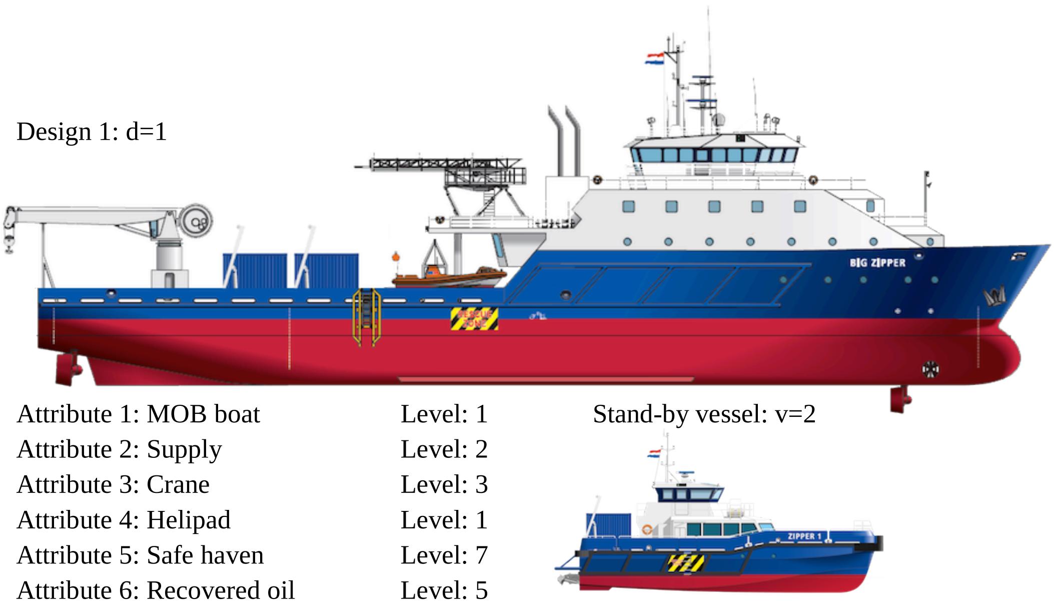



Figure 7: Example of emergency preparedness readiness for design one

In Figure 7 design one is paired up with a smaller standby vessel. This could be one configuration of the optimal contingency plan for the remote field in an early phase of the scenario. The smaller vessel would operate in proximity of an offshore installation for the purpose of fast rescue.

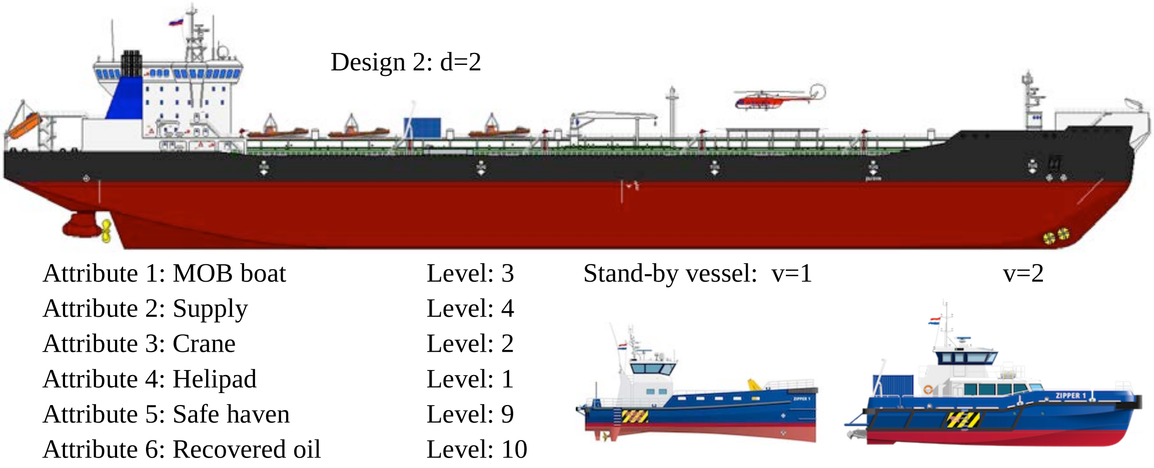



Figure 8: Example of emergency preparedness readiness for design two

Figure 8 shows the optimal configuration if design one was implemented in the same period. Even though design two has higher functionality levels for many attributes compared to design one, the need for an additional standby vessel could be required because of the loss of efficiency connected to the attributes. Because design one is a specialized rescue vessel, it has better efficiency when e.g. deploying MOB boats compared to design two, which essentially is a converted tanker. The efficiency level of having three MOB boats on design two could represent the same level of safety as having two MOB boats on design one. These gains or losses in safety in terms of moving an attribute from a standby vessel to the standby base will be assessed using the same AHP methods as reviewed in the literature study. The hierarchy in this model is discussed further in Chapter 4.3.

## 4.1 Objective Function

When defining the objective function it is important to make clear what it is you want to maximize or minimize. In Patricksson et al. (2013) profit was maximized, and the objective function split into two parts: revenue and cost. For the fleet sizing problem in Crary, Nozick and Whitaker (2002) the probability of winning the war is maximized using weights decided using AHP for the vessels' capabilities in the different phases of the war. Similarly, weights associated with power, steel weight and building costs were minimized in Ray et al. (1995). In Fagerholt and Lindstad (1999) the objective function is split into two separate terms. The first term corresponds to the cost of chartering the supply vessels, whilst the second term is the total sailing time for the fleet in case of alternative solutions to the main objective. In the case of an emergency preparedness scenario, there is no revenue involved as a factor to consider. However, considering the ability to utilize the standby base as a supply depot will have to be included in the model. Apart from this functionality, the objective of the model will be to minimize the total cost of maintaining required preparedness for an offshore petroleum field during its effective life. The cost parameters involved are the investment in the basic design for the standby base, cost of implementing an attribute during the first year of operation, cost of implementing an attribute later in the scenario, operating cost of the base considering its attributes, cost of altering the functionality level of an attribute, gain in shared operating expenses and the cost of chartering standby vessels. However, how should these parameters be interpreted? The terms highlighted in bold connect the paragraph to the terms of the objective function in Chapter 5.

**Term 1**

According to Branch (1998) the annual cost structures of shipping companies are divided into three main elements: capital, operating and voyage costs. Capital charges consisting of interest charges and principal repayments are fixed, while operating and voyage costs are variable. During the time span for petroleum activities in the remote field, the cost connected to the contingency plan can be regarded as a cash flow analyses or Life Cycle Cost (LCC). The capital cost in this model will be the one-time expense incurred when investing in the standby base. However, there will also be a capital cost connected to the acquirement and initial installation of an attribute on the basic design chosen for the standby base. The differences between the two costs are that the investment in a new attribute does not include depreciation or resale value. This is a fair assumption considering that the removal of an attribute will probably be connected to a low or non-existing resale value. A time index is included in the cost parameter for the investment in a new design. This is to adjust for the depreciation of the capital cost during its depreciable life. The present value of the depreciation cost from the time of investment and until the last time period of the scenario will be the one-time expense for the design in that specific time period. Equation (4.1) is a simplified calculation for the depreciation expense of the investment (Mankiw, 2009).

$$Depreciation\ Expense = Cost\ of\ Fixed\ Asset - Residual\ Value \qquad (4.1)$$

The residual value will be the estimated value of the standby base at the time it will be sold or disposed of. It is imperative that all costs are adjusted to the present value (e.g. 2013). Usually the company will divide the depreciation expense with the useful life of the asset in order to acquire the annual depreciation expense. In the optimization model this method will unnecessarily complicate the development of the parameters because the optimal results will be the same regardless.

$$PresentValue = \frac{Cost}{(1 + interest\ rate)^t} \qquad (4.2)$$

In equation (4.2) $t$ could represent the number of compounding periods between the first time period in the scenario and the time period of the investment in the standby base. The future investment cost will be adjusted to its present value.

**Term 5**

In terms of operating costs the parameter connected to the attributes has been simplified not to include discounted costs. The reason is the assumption that the real interest rates for operating expenses are close to zero. General operating expenses connected to the standby base like fuel, docking, maintenance, insurance, administration, spare parts etc. have been omitted from the model for simplification. It is possible to include them in the model by decreasing the residual value of the base when creating the investment cost parameter (which has been done in the case study). However, operating expenses for the attributes at each level of functionality is included as fixed present value cost parameters. It is reasonable to assume that a higher level of functionality e.g. three NOFO systems, will not generate three times the operating expenses of level one functionality. Also, a basic design that is specialized for oil recovery operations will generate lower operating expenses connected to NOFO systems than a basic design specialized for search and rescue operations. It is possible to include the cost savings in implementing supply services connected to the standby base by introducing a negative cost parameter connected to the functionality level of the supply attribute. The functionality level of the supply attribute corresponds to available deck area and the tanks capacity to hold cargo and bulk.

**Term 2, Term 3 and Term 4**

Apart from operating expenses connected to maintaining a specific level of functionality for each attribute, there are also costs connected to altering the level of functionality of an attribute. The cost connected to altering the level of functionality depends on the attribute type and how many levels of functionality the alteration consists of. The level of alteration is not symmetrical, and changing an attribute from level one to level four functionality might not generate the same cost as an opposite alteration. The cost of implementing an attribute for the first time depends on its functionality level. The cost of implementing an attribute after the standby base's first period of operation is assumed more expensive. The cost of implementing and altering an attribute are, in the same way as the operating costs, considered as constant present values throughout the scenario.

**Term 6**

It is not realistic to assume that operating expenses for every attribute can be summarized in order to find the total cost connected to the standby base. The same crew might operate different emergency preparedness attributes, and when these attributes are implemented on the standby base in the same time period, the objective function will subtract an amount from the total cost.

**Term 7**

The last term in the objective function is the cost of chartering additional standby vessels. This cost is dependent on the time period for which it is chartered. This assumption reflects the versatility of the shipping market and is transferable to standby vessels. By accounting for the time period the standby vessel is chartered, it is possible to implement information, like oil price predictions and new builds and scrapping, in order to make the model more realistic.

## 4.2 Sets

The model consists of six sets. Each set represents a category in the problem, and every variable is indexed in order to include the categories making the simplified problem reflect the real problem as realistically as possible. Two of the sets are also sets within one of the other sets. Included in the model are also five subset representing a collection of indexes within that set. Appendix C illustrates the use of the sets in the case study.

***V*** is the set of standby vessels that might be chartered for a period of time. The vessels are ordinary standby vessels and their design and functionality will be predetermined and might reflect the current collection of standby vessels in the North Sea.

***A*** is the set of attributes of the standby base and standby vessel. The set of attributes needs to extensive enough to reflect the area-based preparedness for the petroleum field. However, the attributes must be connected to the standby base or the standby vessel.

***$L_a$*** is the set of functionality levels for each attribute. An attribute might have different levels of functionality representing a higher or lower level of provided emergency preparedness support. This level of functionality might be quantitative, as the number of MOBs, or qualitative, as the vessel's fire fighting capabilities.

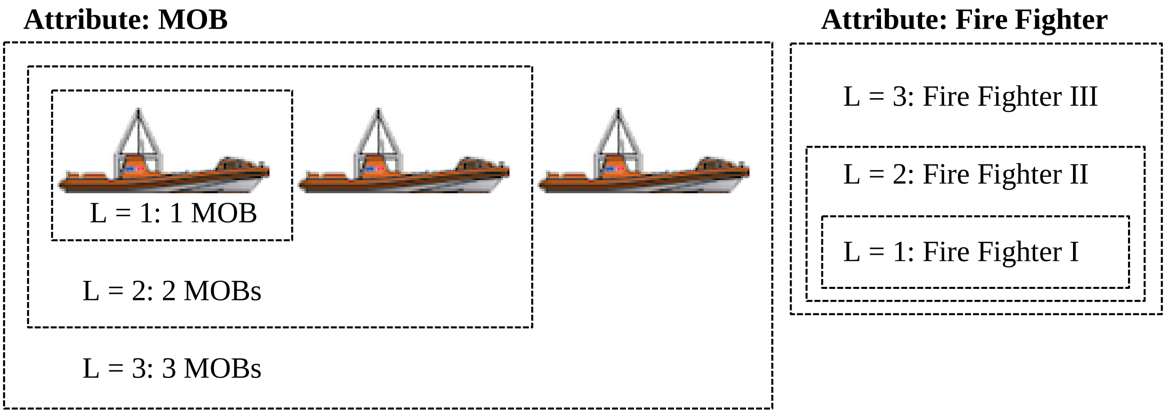



Figure 9: Functionality level of different attributes

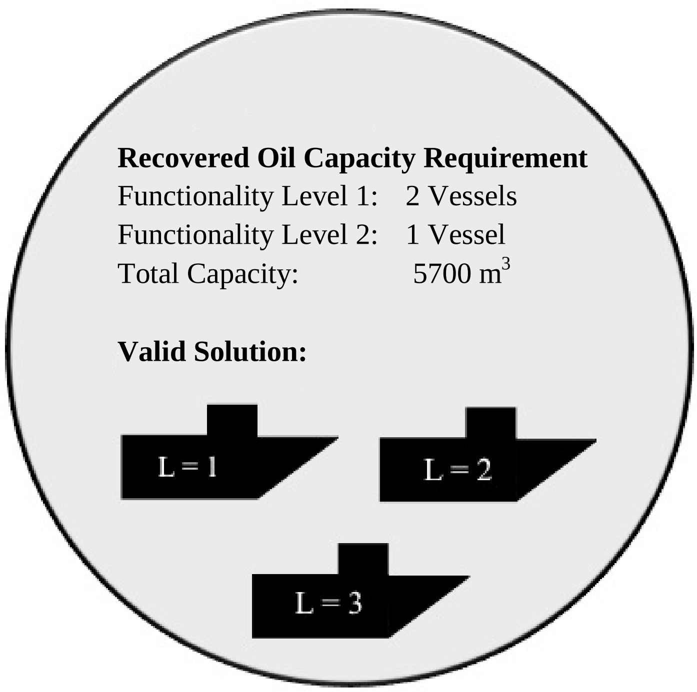
Figure 9 illustrates the functionality level of the two different attributes "MOB" and "Fire Fighter". For every increase in functionality level for the attribute "MOB", there is an additional MOB implemented on the vessel.

DNV divides the fire capabilities of a standby vessel into three different classes; Fire Fighter III, Fire Fighter II and Fire Fighter I (DNV, 2013). An increase in functionality level for the attribute "Fire Fighter" represents an increase in the vessels fire fighting classification. A vessel with Fire Fighter III capability will also be able to cover Fire Fighter II and Fire Fighter I requirements.

***E*** is the set of emergency preparedness groups. The purpose of this category is to unite the different attributes within emergency preparedness in order to exploit the shared operating expenses between them. Many oil recovery attributes require a permanent crew on board the vessels. However, this crew can operate a set of attributes, and with multiple oil recovery equipment on board the vessel it will not be realistic to summarize the operating expenses of each attribute individually. The level of detail in the problem and available data decides the size of the set. For the model in this thesis, the emergency preparedness is divided into the following groups: ORO (Oil Recovery Operations), RESC (Rescue from sea and medical evacuation) and HELI (SAR Helicopter). Each group reflects the preparedness groups presented in Vinnem (2012). It is possible for attributes to be present in multiple preparedness groups.

***$A^1$*** is a subset of the attributes *A*. The attributes in the subset are characterized by the property of their functionality level. An increase in the functionality level represents an increase in the capability of the attribute without an increase in the quantity of it. “Fire Fighter” belongs to the subset $A^1$.

***$A^2$*** is a subset of the attributes *A*. The attributes in the subset are similarly to $A^1$ characterized by the property of their functionality level. Unlike $A^1$, an increase in the functionality level does not alter the complexity of the attribute, but the quantity of it. However, an attribute can be present in both $A^1$ and $A^2$. This depends on whether there is a requirement for the total quantity of the attribute on the field and the number of vessels with a specific functionality level, e.g. quantity of the attribute. For remote regions, the attribute to store recovered oil is included in both $A^1$ and $A^2$. There will be requirements regarding the number of vessels with NOFO systems on board. This requirement is based upon the dispersant rate calculated for the field, where one system includes the capacity to store 2400 $m^3$/d (See Appendix B for detailed calculations). For a field in a remote area it needs to be a total capacity to store the recovered oil in the time period until a certified tank vessel is available. This total capacity represents the pessimistic period until the tank vessel is operable multiplied with the calculated dispersion rate. The parameter will be explained further in Chapter 4.4.




**Functionality Levels**
L=1: 1500 $m^3$
L=2: 2000 $m^3$
L=3: 2500 $m^3$

Figure 10: Valid solution to unit requirement and total requirement combined

In Figure 10 the reason for dividing the attributes into the different subsets is illustrated. Even though two vessels with level 1 oil recovery functionality (1500 $m^3$ ORO tanks) and one vessel with level 2 (2000 $m^3$) is required, the total amount of storing recovered oil being 5700 $m^3$ makes one valid solution an implementation of three standby vessels with level 1, level 2 and level 3 oil recovery functionality. The vessel to the right covers the level 2 functionality requirement and half of the level 1 functionality requirement. However, because of the total oil recovery requirement a third vessel with level 3 functionality must be included in order to obtain a valid solution.

In order to distinguish between the two subsets the attributes in $A^1$ are called non-proportional, while $A^2$ are called proportional. Even though $A^2$ is called a proportional attribute, there is no requirement concerning equal intervals of units between each functionality level. This means that for storing recovered oil, functionality level 1 might represent a tank capacity of 1500 $m^3$, however level 2 and 3 might respectively have capacities of 2000 $m^3$ and 3000 $m^3$.

The three remaining sub attributes, $\boldsymbol{A^{ORO}}$, $\boldsymbol{A^{RESC}}$ and $\boldsymbol{A^{HELI}}$ are directly connected to the shared operating expenses. This also means that they are linked to the emergency preparedness set $E$. The attributes included in each category will give a reduction in operating expenses determined by how many are implemented on the standby base. This way of modelling is fairly simplified compared to the real problem because it does not distinguish between different attributes within the set and the functionality level of the attribute. By implementing more sub attributes for different types of shared expenses, it is possible to develop a more realistic model. However, it is not possible to take into consideration the different functionality levels of each attribute.

$\boldsymbol{T}$ is the set of time periods during the life span of the petroleum field. The size of the set and the intervals of the time periods depend on the available data for the development of the field. For a field where production and exploration is assessed for a time period of 30 years, it will be sensible to include 30 time periods where each period represents one year. However, if the activity during the first ten years have a high degree of fluctuation because of extended exploratory drilling, it would be sensible to have a shorter interval during this period, e.g. six months. This means that the set $T$ will consist of 40 time periods, where the first 20 each represent six months, and the remaining 20 each represent one year.

$\boldsymbol{Q_e}$ is the set of units of attributes with shared operating expenses within each emergency preparedness group. This set consists of integer values from *one* to the number of attributes within each emergency preparedness group. If there are four attributes that have shared expenses in terms of oil recovery operations, this set is defined as: {1, 2, 3, 4}.

## 4.3 Analytical Hierarchy Process

From the discussion in the literature study it was evident that when dealing with elements in optimization regarding abstract data decided by expert judgments, the AHP method is frequently used. *NORSOK Standard* (2010, p. 37) also mentions expert judgement as a useful tool in acquiring quantifiable data. The method might be used in a variety of complex situations, however the basic principle of the method consists of a goal, criteria and alternatives. In this model the AHP method has been used when deciding the difference between the efficiency of an attribute implemented on a standby base compared to a standby vessel. The calculation method of the AHP values can be found in Appendix A.

The first step when using the AHP is to decompose the problem into a hierarchy of easily comprehended sub problems. There is no limit to the number of sub problems and size of the hierarchy three, however because the use of the AHP method in this thesis is not developed in cooperation with experts in the field of emergency planning, the hierarchy is kept simple. The main reason for including the AHP method in the model is to illustrate how intangible elements in the real problem concerning experience and evaluation can be transformed into numerical values in the optimization model.

The goal of the hierarchy is to obtain best possible safety. There are four criteria for each attribute: location, deployment time, speed and manoeuvrability. The standby base and the standby vessels are compared against each other for each of the criteria.

Location is chosen as a criterion because of the difference between how the standby base and the standby vessels are operating. The standby base will most likely be located in an area where its distance to the installations reflects the strategy for how the base is operating. If this strategy is to have an equal distance to each installation, and the strategy of the standby vessels are to be in close proximity of the installations, attributes that depend on this close proximity will have a loss of performance when implemented on the standby base.

Deployment time is chosen as a criterion because for many attributes the ability to be deployed fast will have an influence on its performance. The ability for fast deployment of MOB boats and SAR helicopter in the case of a helicopter crash is critical.

Speed of the standby vessel is chosen as a criterion because the ability to move to a location will be important for attributes involving for example oil recovery operations. The calculated drift path of the oil spill will influence the optimal location for deploying oil booms, and the ability to get to this location fast separates the standby base and the standby vessels.

The last criterion, manoeuvrability, is included because the ability to manoeuvre when transferring equipment, like oil skimmers or oil booms, onto the standby vessels, or recovered oil the other way, will influence the performance during an oil recovery operation. In high sea, low manoeuvrability will make the process slower or even impossible, thereby affecting the overall performance of the operation.

The importance of the criteria are evaluated against each other on a scale from one to nine, where one is defined as equal importance, three is somewhat more important, five is much more important, seven is very much more important and nine is absolutely more important. For every attribute in the contingency plan belonging to set $A^2$, a 4 x 4 matrix is constructed expressing the relative values of the criteria. 2 x 2 matrixes are constructed for each criterion, where the capabilities of the standby base relative to the standby vessels for the criterion are expressed. The eigenvectors of the criteria, the standby base and the standby vessels are calculated, and based on these values the overall vector giving the difference between the two when it comes to best possible safety for the specific attribute is produced (see Appendix H).

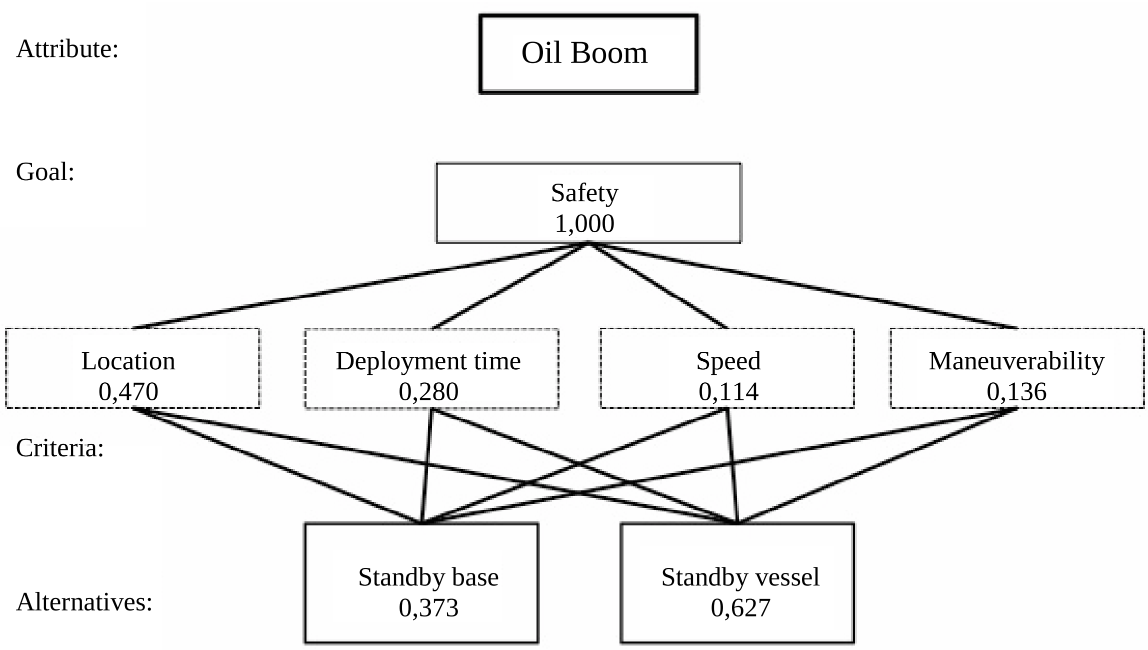



Figure 11 Analytical Hierarchy Process tree for the attribute "Oil Boom"

Figure 11 is an illustration of what the hierarchy tree for the attribute "Oil Boom" might look like. Based on the calculated eigenvectors for the criteria and the capability of the standby base and the standby vessel, their respective vectors are 0,373 and 0,627. For the optimization model in this thesis, it is assumed that the standby vessel is the benchmark in terms of the required functionality level from each attribute. This means that the factor for every attribute implemented on the standby vessel has a value of 100 %. In order to obtain the factor for implementing an attribute on the standby base, the vector for the standby base is divided by the vector for the standby vessel. For the instance in Figure 11, the performance of implementing an attribute on the standby base would equal 59 % of the performance the attribute would provide on a standby vessel. If the total requirement for oil booms in the region is eight, and there are four oil booms located on standby vessels, the minimum number of oil booms implemented on the standby base is seven.

The final stage of the AHP is to calculate the Consistency Ratio (CR). The CR gives an indication of how consistent the judgments have been relative to large samples of purely random judgments. The judgments are untrustworthy if their values are much in excess of 0,1. This will put the judgments to close to randomness and the effectiveness factors of the standby base are considered valueless.

## 4.4 Parameters

The parameters included in the model are divided into four groups: costs, required emergency preparedness, the characteristics of the attributes at different functionality levels and the characteristics of the standby base. Since the cost parameters are already explained in Chapter 4.1 the remaining three groups will be discussed in this subchapter. Each parameter is referred to as being arrays of different sets, meaning that they are tables of different dimensions. For a two-dimensional table the indexes belonging to the first set represents the rows, and the indexes in the second set represents the columns. For a three-dimensional parameter, there is a two dimensional table of the second and third set for each index in the first set. When the two-dimensional table is constructed for an index, a new two-dimensional table is created for the following index. When there is inconsistency in the size of the sets, e.g. $L_a$, the missing values are referred to as *-1*. Appendix C illustrates how the tables are constructed using MS Excel for the case study in Chapter 6.

$\boldsymbol{R^{UNITS}}$ **(array of $\boldsymbol{A}$, $\boldsymbol{L_a}$, $\boldsymbol{T}$)** is the requirement for the number of vessels with an attribute with a minimum functionality level implemented. This requirement includes the standby base and the standby vessels. The values in the parameter are binary. This requirement will grow in line with the activity on the field.

$\boldsymbol{R^{TOTAL}}$ **(array of $\boldsymbol{A}$, $\boldsymbol{T}$)** is the total requirement for the attributes in subset $A^2$ where the functionality levels represent the quantity of the attribute. The total requirement can be any real number and includes both the standby base and the standby vessels. However, there might be a difference between the efficiency of an attribute on the standby base compared to the standby vessels. This efficiency is determined using the AHP technique explained in Chapter 4.3.

***K* (array of *A*, $L_a$)** is the quantity of units represented at functionality level $l$ for each attribute $a$. The purpose of this parameter is to transfer the binary information regarding an attribute installed on either the standby base or the standby vessel into a real value that can be measured against the requirement $R^{TOTAL}$.

***P* (array of *A*)** is the factor representing the loss of performance for attributes on the standby base compared to standby vessels. The parameter is only relevant for $R^{TOTAL}$ requirements. For further explanation see Chapter 4.3.

**$F^{ERRV}$ (array of *V*, *A* and $L_a$)** are binary values describing the capabilities of the different standby vessels for an attribute $a$.

**$F^{BASE}$ (array of *A* and $L_a$)**. This parameter is essentially equal to $F^{ERRV}$, however it describes the capabilities of the design of the standby base. Because the capabilities of the standby base are dynamic, and functionality levels of attributes can be altered throughout the scenario, it is important to include binary values for all the possible functionality levels in $L_a$ for each attribute $a$.

$\boldsymbol{S^{DECK}}$ describes the available deck area at the standby base. $\boldsymbol{U^{DECK}}$ **(array of *A* and $\boldsymbol{L_a}$)** is the deck area utilized by attribute *a* at each functionality level *l*. The sum of utilization from the different attributes implemented cannot exceed $S^{DECK}$. The denomination of $S^{DECK}$ is $m^2$. $S^{VOL}$ [$m^3$], $S^{ACC}$ [$m^2$], $U^{VOL}$ [$m^3$] and $U^{ACC}$ [$m^2$] are similar parameters, but they describe different sections of the ship. The first parameter concerns the available tank volume of the standby base, while the second parameter concerns the accommodation section of the base. There is no limit to how many sections the standby base is divided into, but more sections requires more detailed information about the attributes and how they utilize different parts of the vessel.

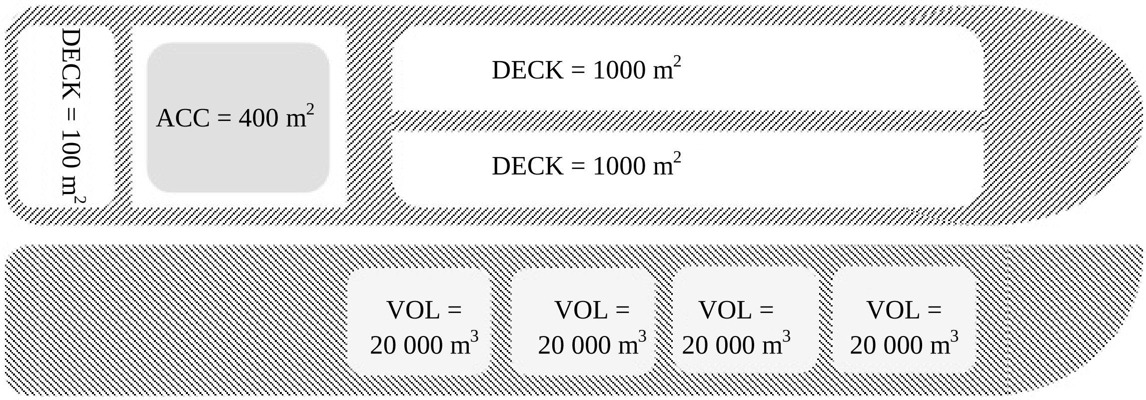



Figure 12: Possible outline for a tank vessel fitting the optimization model

In Figure 12 a simplified outline of a tank vessel is illustrated. For this design the *S* parameters for *DECK*, *VOL* and *ACC* are 2100 $m^2$, 80 000 $m^3$ and 400 $m^2$ respectively. The three categories can as mentioned be divided further to reflect the real problem more realistically, however for describing the model in this thesis the three categories are considered sufficient.

***I*** **(array of *Q*)** is a parameter that has the same value as its index *q*. This parameter is needed for finding the quantity of attributes within each emergency preparedness group for each time period and is included in restrictions (5.13), (5.14) and (5.15).

## 4.5 Variables

There are seven types of variables, each of them connected to a specific cost. Because they are connected to the objective function, their explanations in this subchapter will be limited. Extended explanation of their purpose in the model can be found in Chapter 4.1.

***x* (array of *T*)** is a binary variable that that will take a nonzero value only in the period the standby base is implemented in the scenario. Deciding if this variable would be nonzero for all periods in set *T* or a binary variable for the first period of implementation was an early problem to be addressed in the modelling phase. Modelling the variable with only one nonzero value for the period of implementation made the mathematical modelling a lot less complex, however this also forced the simplified assumption that the standby base is operating until the last period of the scenario.

***b* (array of *A* and *L*)** is a binary variable taking a nonzero value for the attributes in set *A* initially implemented on the standby base (when $x_t$ equals *one*). There is no need for time specific index *t*, because $b_{al}$ is only forced to take a nonzero value by restriction (5.10) for the period of implementation.

***m* (array of *A*, *L* and *T*)** is a binary variable taking a nonzero value for attributes being initially implemented on the standby base after the period where $x_t$ equals *one*.

***w* (array of *A*, *L*, *L´* and *T*)** is a binary variable taking a nonzero value for all attributes implemented on the standby base and its functionality level from the time period prior to *t* (indexed *l*) and the time period *t* (indexed *l´*).

***z* (array of *A*, *L* and *T*)** is a binary variable taking a nonzero value if the attribute *a* with functionality level *l* operates on the standby base in time period *t*.

***y* (array of *V* and *T*)** is an integer variable referring to the number of standby vessels *v* which are a part of the contingency plan in period *t*.

***h* (array of *E*, *T* and $Q_e$)** is a binary variable taking a nonzero value for the number of attributes, within emergency preparedness group *e* in time period *t*, matching the index value of *q*. If there are four attributes operating in preparedness group *e*, the index of *q* will be four.

Chapter 5

# Optimization Model

In this chapter the linear mathematical optimization model is presented. Even though the sets, parameters and variables have already been discussed in Chapter 4, they are given a very short description in this chapter as well. Following the objective function, the mathematical restrictions of the model are presented. Each equation is numbered, and the purposes of the equations are explained after the presentation of the mathematical model.

Sets:

| | |
|---|---|
| $V$ | Set of standby vessels, indexed by $v$ |
| $E$ | Set of emergency preparedness groups, indexed by e |
| $A$ | Set of attribute types, indexed by $a$ |
| $L_a$ | Set of levels for attribute $a$, indexed by $l$ |
| $A^1$ | Subset of attributes where level of functionality is not proportional |
| $A^2$ | Subset of attributes where level of functionality is proportional |
| $A^{ORO}$ | Subset of attributes where operating cost is a shared expense |
| $A^{RESC}$ | Subset of attributes where operating cost is a shared expense |
| $A^{HELI}$ | Subset of attributes where operating cost is a shared expense |
| $T$ | Set of time periods, indexed by $t$ |
| $Q_e$ | Set for the quantity of attributes for EP group $e$, indexed by $q$ |

Parameters:

| | |
|---|---|
| $C_t^{BASE}$ | Cost of acquiring standby base at time $t$ |
| $C_{al}^{F}$ | Cost of initial implementation of attribute $a$ to level $l$ |
| $C_{al}^{L}$ | Cost of later implementation of attribute $a$ to level $l$ |
| $C_{all'}^{A}$ | Cost of altering attribute $a$ from level $l$ to level $l'$ |
| $C_{al}^{O}$ | Cost per time period for operating attribute $a$ at level $l$ |
| $C_{eq}^{G}$ | Gain in operating expenses for EP group $e$, and attribute quantity $q$ |
| $C_{vt}^{ERRV}$ | Cost of chartering in standby vessel $v$ in time period $t$ |
| $R_{alt}^{UNITS}$ | Requirement for units of vessels with attribute $a$ at level $l$ in period $t$ |
| $R_{at}^{TOTAL}$ | Total requirement for proportional attribute $a$ in time period $t$ |
| $K_{al}$ | Number of units of proportional attributes $a$, at level $l$ |
| $P_a$ | Factor representing the loss/gain of utilizing attribute $a$ on standby base |
| $F_{val}^{ERRV}$ | Capability for attribute $a$, level $l$ using vessel $v$ |
| $F_{al}^{BASE}$ | Capability for attribute $a$, level $l$ for the standby base |
| $S^{DECK}$ | Deck capacity for the standby base |
| $S^{VOL}$ | Tank capacity for the standby base |
| $S^{ACC}$ | Accommodation capacity for the standby base |
| $U_{al}^{DECK}$ | Deck utilization factor for attribute $a$, level $l$ |
| $U_{al}^{VOL}$ | Tank utilization factor for attribute $a$, level $l$ |
| $U_{al}^{ACC}$ | Accommodation utilization factor for attribute $a$, level $l$ |
| $I_q$ | Quantity of attributes for quantity $q$ |

Variables:

| | |
|---|---|
| $x_t$ | Binary variable for investing in the standby base in time period $t$ |
| $b_{al}$ | Binary variable for whether attribute $a$, level $l$ was initially implemented |
| $m_{alt}$ | Binary variable for implementation of attribute $a$, level $l$ in time period $t$ |
| $w_{all't}$ | Binary variable for altering attribute $a$ from level $l$ to $l'$ in time period $t$ |
| $z_{alt}$ | Binary variable for utilizing attribute $a$, level $l$ in time period $t$ |
| $y_{vt}$ | Integer variable for number of standby vessels $v$ during time period $t$ |
| $h_{etq}$ | Binary variable for EP group $e$, in time period $t$, with $q$ attributes |

Objective function:

$$minimize \quad \sum_{t\in T} C_t^{BASE} x_t + \sum_{a\in A}\sum_{l\in L_a} C_{al}^{F} b_{al} + \sum_{a\in A}\sum_{l\in l_a}\sum_{t\in T} C_{al}^{L} m_{alt}$$
$$+ \sum_{a\in A}\sum_{l\in L_a}\sum_{l'\in L_a}\sum_{t\in T} C_{all'}^{A} w_{all't} + \sum_{a\in A}\sum_{l\in L_a}\sum_{t\in T} C_{al}^{O} z_{alt}$$
$$- \sum_{e\in E}\sum_{t\in T}\sum_{q\in Q} C_{eq}^{G} h_{etq} + \sum_{v\in V}\sum_{t\in T} C_{vt}^{ERRV} y_{vt} \qquad (5.1)$$

Subjected to:

$$\sum_{t\in T} x_t \leq 1 \qquad (5.2)$$

$$\sum_{v\in V}\sum_{l'\in L_a|l'\geq l} F_{val'}^{ERRV} y_{vt} + \sum_{l'\in L_a|l'\geq l} z_{al't} \geq R_{alt}^{UNITS} \qquad a\in A^1, l\in L_a, t\in T \qquad (5.3)$$

$$\sum_{v\in V}\sum_{l\in L_a} K_{al} F_{val}^{ERRV} y_{vt} + \sum_{l\in L_a} P_a K_{al} z_{alt} \geq R_{at}^{TOTAL} \qquad a\in A^2, t\in T \qquad (5.4)$$

$$\sum_{a\in A}\sum_{l\in L_a} U_{al}^{DECK} z_{alt} \leq S^{DECK} \sum_{t'=1}^{t} x_{t'} \qquad t\in T \qquad (5.5)$$

$$\sum_{a\in A}\sum_{l\in L_a} U_{al}^{VOL} z_{alt} \leq S^{VOL} \sum_{t'=1}^{t} x_{t'} \qquad t\in T \qquad (5.6)$$

$$\sum_{a\in A}\sum_{l\in L_a} U_{al}^{ACC} z_{alt} \leq S^{ACC} \sum_{t'=1}^{t} x_{t'} \qquad t\in T \qquad (5.7)$$

$$\sum_{l\in L_a} z_{alt} \leq \sum_{t'=1}^{t} x_{t'} \qquad a\in A \;\; t\in T \qquad (5.8)$$

$$z_{alt} \leq F_{al}^{BASE} \sum_{t'=1}^{t} x_{t'} \qquad a\in A, l\in L_a, t\in T \qquad (5.9)$$

$$b_{al} + 1 \geq x_t + z_{alt} \qquad a \in A, l \in L_a, t \in T \tag{5.10}$$

$$m_{alt} + \sum_{l \in L_a} z_{al(t-1)} + x_t \geq z_{alt} \qquad a \in A, l \in L_a, t \in T \setminus \{|1|\} \tag{5.11}$$

$$w_{all'(t+1)} + 1 \geq z_{alt} + z_{al'(t+1)} \qquad a \in A, l \in L_a, l' \in L_a, t \in T \setminus \{|T|\} \tag{5.12}$$

$$I_q h_{etq} \leq \sum_{a \in A^{ORO}} \sum_{l \in L_a} z_{alt} \qquad e = \{ORO\}, t \in T, q \in Q \tag{5.13}$$

$$I_q h_{etq} \leq \sum_{a \in A^{RESC}} \sum_{l \in L_a} z_{alt} \qquad e = \{RESC\}, t \in T, q \in Q \tag{5.14}$$

$$I_q h_{etq} \leq \sum_{a \in A^{HELI}} \sum_{l \in L_a} z_{alt} \qquad e = \{HELI\}, t \in T, q \in Q \tag{5.15}$$

$$\sum_{q \in Q_e} h_{etq} \leq \sum_{t'=1}^{t} x_{t'} \qquad e = E, t \in T \tag{5.16}$$

$$x_t \in \{0,1\} \qquad t \in T \tag{5.17}$$

$$b_{al} \in \{0,1\} \qquad a \in A, l \in L_a \tag{5.18}$$

$$z_{alt} \in \{0,1\} \qquad a \in A, l \in L_a, t \in T \tag{5.19}$$

$$m_{alt} \in \{0,1\} \qquad a \in A, l \in L_a, t \in T \setminus \{1\} \tag{5.20}$$

$$w_{all't} \in \{0,1\} \qquad a \in A, l \in L_a, l' \in L_a, t \in T \setminus \{1\} \tag{5.21}$$

$$y_{vt} \geq 0 \quad integer \qquad v \in V, t \in T \tag{5.22}$$

$$h_{etq} \in \{0,1\} \qquad e \in E, t \in T, q \in Q \tag{5.23}$$

(5.1) is the objective function that is minimized. The first term corresponds to the cost of utilizing the standby base during a time period. The second term is the cost of implementing an attribute in the first period of operations. The third term is the cost of adding an attribute with a certain level of functionality to the base at a later stage. The fourth term corresponds to the cost of altering the level of functionality for an attribute already installed on the base. The fifth term represents the cost of operating an attribute with a certain level of functionality during a time period. The sixth term is the reduction in operating expenses when attributes within the same category are implemented on the standby base. The last term is the cost of chartering a standby vessel during a time period

Constraint (5.2) in the model ensures that the implementation of the standby base can only take place in one time period.

Constraints (5.3) ensure that the fleet of standby vessels and the standby base cover the required number of vessels with an attribute having a certain level of functionality. The constraints ensure that a vessel with a functionality level required or higher will be included.

Constraints (5.4) ensure that the fleet of standby vessels and the standby base cover the required functionality level for the attributes where the levels of functionality are proportional. If the required level of functionality is e.g. ten oil booms, two vessels with four and six oil booms will cover the requirement. A factor $P_a$ for the standby base is also multiplied in order to adjust for the probable loss or gain in efficiency for an attribute on the base compared to standby vessels.

Constraints (5.5), (5.6) and (5.7) ensure that the implemented attributes do not exceed the standby base's maximum deck, tank and accommodation capacity. The term, $\sum_{t'=1}^{t} x_{t'}$, multiplied with the different capacities ensures that the restrictions are only valid for the periods where the standby base is a part of the contingency plan, reducing the computation time.

Constraints (5.8) ensure that only one level of functionality of an attribute for the base is utilized at the same time by ensuring that the summarization of all the functionality levels of each attribute has a value no higher than *one*.

Constraints (5.9) ensure that the level of functionality for the base is no higher than the capability of the design. The $z_{alt}$ variable may only take a nonzero value when the value of $F_{al}^{BASE}$ with equal indexations *(a* and *l)* is *one*.

Constraints (5.10) decide the attributes initially being implemented on the standby base and create a binary variable, $b_{al}$, for the level of functionality of the attribute. If it is the first period of implementation ($x_t$ equals *one*) and the $z_{alt}$ variable equals *one*, variable $b_{al}$ with the same index values ($a$ and $l$) as $z_{alt}$ will be forced to take a nonzero binary value. Because $b_{al}$ is connected to the positive parameter $C_{al}^{F}$ in the minimized objective function, $b_{al}$ will take *zero* values for all incidences where the restriction allows it.

Constraints (5.11) decide whether a new attribute has been equipped on the base in a later stage and create a binary variable for the level of functionality for the new attribute. If it is not the period where the standby base has been implemented ($x_t$ equals *zero*) and for the preceding period there has been no nonzero binary values for all functionality levels for attribute $a$, $m_{alt}$ is forced to take the value *one* if there is operations of this attribute on the standby base in this time period. Because $m_{alt}$ is connected to the positive parameter $C_{al}^{L}$ in the minimized objective function, $m_{alt}$ will take the value of *zero* for all incidences where the restriction allows it.

Constraints (5.12) decide whether the attribute has changed its level of functionality from one time period to the next, and creates a binary variable for the changes of the levels. If an attribute is operating in two consecutive periods, $w_{all'\mathrm{t}}$ is forced to take the value of *one*. Even though there has not been any alterations in the functionality level (*l*=*l´*) this will not affect the solution because the values in $C_{all'}^{A}$ for these incidents are equal to *zero*.

Constraints (5.13), (5.14) and (5.15) decide the number of attributes within each sub attribute where operating costs are a shared expense, and creates an integer variable for the number. Because the parameter in the objective function, $C_{eq}^{G}$, connected to the variable $h_{etq}$ is negative and inclining in correlation to the index $q$, $h_{etq}$ will take nonzero values for all incidents where (5.13), (5.14) and (5.15) allows it. These incidents are controlled by parameter $I_q$, which ensures that the value of index *s* cannot be higher than the number of attributes implemented on the standby base for emergency preparedness group *e*.

Constraints (5.16) ensure that for each emergency preparedness group in every period, there is only one binary variable for the number of attributes in that emergency preparedness group. Because the objective function decreases when the index value $q$ increases, $\mathrm{h}_{\mathrm{etq}}$ will take a nonzero value for the highest possible index $q$ allowed by constraints (5.13), (5.14) and (5.15).

Constraints (5.17) impose binary requirements on the variables deciding whether the standby base has been implemented in a time period. Constraints (5.18) impose binary requirements on the variables deciding the attributes initially implemented on the standby base. Constraints (5.19) impose binary requirements on attributes and their functionality level. Constraints (5.20) impose binary requirements on the variables deciding the implementation of a new attribute. Constraints (5.21) impose binary requirements on the variables deciding if an attribute has altered its level of functionality from one time period to the next. Constraints (5.22) impose integer requirements on the variables deciding whether a standby vessel is chartered. Constraints (5.23) impose binary requirements on the variables deciding the number of attributes within each preparedness group for each time period.

## 5.1 Implementation of the Model Into Computer Software

The mathematical model has been implemented into the optimization software FICO™ Xpress Optimization Suite. The programming language of the model is called MOSEL (Appendix G).

A step-by-step process was followed when the model was implemented in Xpress. The first step was to get the software to read all sets and parameters similarly to the mathematical model. In this process the input data was initialized from simple text files. The size of each set was kept as small as possible to promote easy troubleshooting. After the input values were implemented into the program, the variables and objective function were declared. The most time consuming part of the programming was the implementation of the restrictions. Each restriction was written individually and verified against independent hand calculations. Once the model was confirmed as being mathematically exact, the model was tested against a variety of different datasets to imitate possible emergency preparedness scenarios and basic standby base designs. In this process data was initialized from a Microsoft (MS) Excel file.

### 5.1.1 Merging Xpress and MS Excel

Using text files to initialize input values is a tedious procedure. By creating an MS Excel file from where Xpress could initialize input data, the testing of the model and the case study in Chapter 6 was made easier for me whilst providing the possibility for people without knowledge of Xpress to utilize the model. Additionally, second party calculations, like present value cost calculations and NOFO calculations, can easily be implemented into the model.

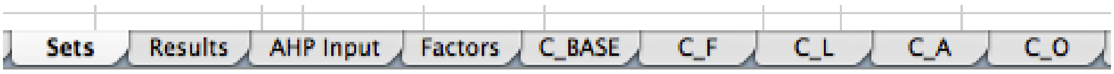



Figure 13: The implementation of Excel sheets to overview input values

The Excel file is divided into a series of sheets as illustrated in Figure 13. The first sheet is called *Sets* (Appendix H), and is where the information as mentioned in Chapter 4.2 is typed. This information will automatically be updated throughout the Excel file, making the input of the parameter values easier. The *Results* sheet extracts the value of the objective function from the Xpress calculations and it's seven components and displays them in individual cells. The sheet *AHP Input* displays the Analytical Hierarchy Tree, as discussed in Chapter 4.3, and gives the user the possibility to rate each attribute in set $A^2$ according to the four criteria: location, deployment time, speed and manoeuvrability. The user also has the possibility to rate the standby base against standby vessels for each criterion.

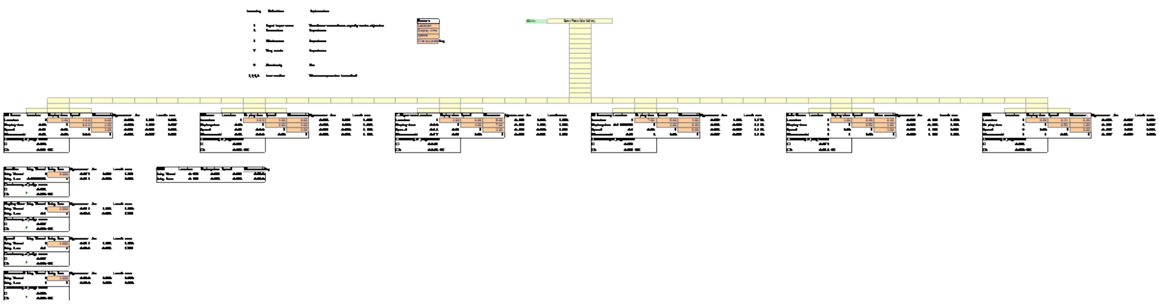


Figure 14: Overview of the AHP hierarchy tree in MS Excel

Figure 14 is a zoomed out illustration of the hierarchy tree for the attributes included in subset $A^2$ for the case study in Chapter 6. A larger version can be found in Appendix H.

| Oil Boom | Location | Deploy time | Speed | Maneuverability | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|---|---|
| Location | 1 | 2.00 | 4.00 | 3.00 | 0.470 | 1.894 | 4.026 |
| Deploy time | 0.50 | 1 | 3.00 | 2.00 | 0.280 | 1.129 | 4.037 |
| Speed | 0.25 | 0.33 | 1 | 1.00 | 0.114 | 0.461 | 4.036 |
| Maneuverability | 0.33 | 0.50 | 1.00 | 1 | 0.136 | 0.547 | 4.025 |
| Consistency of judgements | | | | | | | |
| CI | 0.010 | | | | | | |
| CR | 0.011 | OK | | | | | |

Figure 15: Example of implementing expert judgments into the optimization model

Figure 14 shows a section of the Excel sheet *AHP Input*, and Figure 15 illustrates how the ratings are implemented for the attribute "Oil Boom". The criterion on the left side is rated against the criterion on top. The weight of each criterion is listed in the column *Eigenvector*. Because the standby base and the standby vessels have different capabilities in relation to the criteria, the expert judgements from the AHP sheet can be converted into the factors of the parameter $P_a$ in the sheet *Factors*. The columns *Aw* and *Lambda max* are used to find the consistency of the expert judgements. The calculation method can be found in Appendix B. The remaining sheets in the Excel file is the data connected to the parameters in the model, as illustrated in Appendix C.

Chapter 6

# Case Study

The case study in this thesis is based on an impact study for petroleum activity near Jan Mayen developed by the Norwegian Petroleum Directorate *(Scenarioer for petroleumsvirksomhet i havområdene ved Jan Mayen*, 2012). Included in the impact study is a scenario for how the petroleum activity in the region might be developing in the future. The maritime zone on the Norwegian side of Jan Mayen covers an area of 100 000 $km^2$. In connection with the impact study, an analysis of emergency preparedness and support functionalities for petroleum activities in the area has been developed by Proactima (Hoell, Nilssen, Wale, Nødland, & Hoff, 2012). These two reports, together with the fact that the area around Jan Mayen is considered remote with little dependable infrastructure and onshore support, makes it an ideal case study for testing the model.

For this case study the two Frontline owned vessels, Front Brabant and Front Champion will be investigated as possible basic designs. From the results obtained, the applicability of the model as a decision tool will be discussed. Because of the lack of data connected to many parameters, running the model only once for a single set of data will not result in a robust solution. The cost parameters based on assumptions will be given a value according to MS Excel generated normal distribution. The sets and parameters of the case study can be found in Appendix C.

## 6.1 Converting a Tank Vessel Into a Standby Base

The first part of the case study is to determine the parameters connected to the two different designs. The cost and design parameters are rough estimates, using applicable sources where possible, and otherwise based upon assumptions. The source for the tank vessel design (Table 2) parameters is *Frontline* (2013), and the source for the standby vessels design and cost parameters are based on Møkster (2013). The second-hand prices for tank vessels are gathered from *Platou R.* (2013), while the operating costs are gathered from *Moore Stephens* (2013).

### 6.1.1 Basic Design Parameters and Costs Connected to the Tankers

| | **Front Brabant** | **Front Champion** |
|---|---|---|
| **Dimensions** |  |  |
| Length Over All | 269,19 m | 334,45 m |
| Beam | 46,00 m | 58,00 m |
| Moulded depth | 24,40 m | 31,05 m |
| DWT (summer) | 149 999 MT | 299 998 MT |
| **Parameters** | | |
| $S^{DECK}$ | 8000 $m^2$ | 13 000 $m^2$ |
| $S^{VOL}$ | 166 383 $m^3$ | 336 032 $m^3$ |
| $S^{ACC}$ | 500 $m^2$ | 700 $m^2$ |

Table 2: General characteristics for the two standby base designs

Investment cost is based upon second-hand prices of five-year-old suezmax and VLCC according to *Platou R.* (2013). The residual values of the vessels are considered not to be affected by the investment in attributes. The yearly depreciation rate is calculated using the average scrapping prices listed in *Platou* (2013) for 2011 and Equation (6.1). The depreciable life of the vessel is set to 20 years (Branch, 1998). The values of the one time investment cost, including depreciation costs and operating costs (operating costs independent of the attributes), are calculated under the assumption that there are no fluctuations in the second-hand and scrapping market, and that the real interest rate of operating costs is equal to zero. Calculations for $C_t^{BASE}$ can be found in Appendix Table I in Appendix C.

$$depreciation\ rate = 1 - \sqrt[N]{\frac{scrap\ value}{cost\ of\ vessel}} \tag{6.1}$$

*N* is the estimated life of the vessel. For this case study N will equal 20 years.

| | Front Brabant | Front Champion |
|---|---|---|
| Second-hand value (5 years old) | NOK 258,300,000 | NOK 355,880,000 |
| Operating costs (yearly) | NOK 35,713,250 | NOK 37,512,940 |
| Depreciation rate | 9% | 14% |
| Scrap value | NOK 5,740,000 | NOK 17,220,000 |

Table 3: Investment cost for Front Brabant and Front Champion

## 6.2 The Functionality and Cost of the Standby Vessels

| | Parameter | Stril Herkules | Stril Mariner |
|---|---|---|---|
| $F_{val}^{ERRV}$ | Attribute ($a$) | Functionality level ($l$) | |
| | Oil boom | 3 | 1 |
| | Skimmer | 2 | 1 |
| | Chemical Dispersants | 3 | 1 |
| | Oil Recovery | 3 | 1 |
| | Helipad | 2 | Not available |
| | Helifuel | 2 | Not available |
| | Hospital Unit | 3 | 1 |
| | Safe Haven | 3 | 2 |
| | MOB | 3 | 2 |
| | Radar | 3 | 2 |
| | Fire Fighting | 3 | 1 |
| | Supply | 1 | 1 |
| | | Chartering costs (yearly) | |
| | $C_{vt}^{ERRV}$ | NOK 98,000,000 | NOK 120,000,000 |

Table 4: Functionality level of attributes and cost connected to the standby vessels

Table 4 displays the functionality levels of the different attributes for the two standby vessel. Stril Herkules has higher emergency preparedness capability compared to Stril Mariner. The yearly chartering costs, $C_{vt}^{ERRV}$, are kept constant for all time periods in the scenario.

## 6.3 Cost Parameters

The cost parameters connected to $C_{al}^{F}$, $C_{al}^{L}$, $C_{all'}^{A}$, $C_{al}^{O}$, $C_{eq}^{G}$ are fictive, but assumed realistic. Because of the assumptions connected with these parameters they are given a random value. The random value is given using a function in MS Excel called *NORM.INV*. This function follows the normal continuous probability distribution, defined by Equation (6.2), and displays the $x$ value given $f(x)$, $\sigma$ and $\mu$.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (6.2)$$

The standard deviation ($\sigma$) is set to 10% of the mean value ($\mu$) of the cost parameter. The actual random cost parameters are decided by the $x$ value generated from *NORM.INV* where *f(x)* is a random value between zero and one.

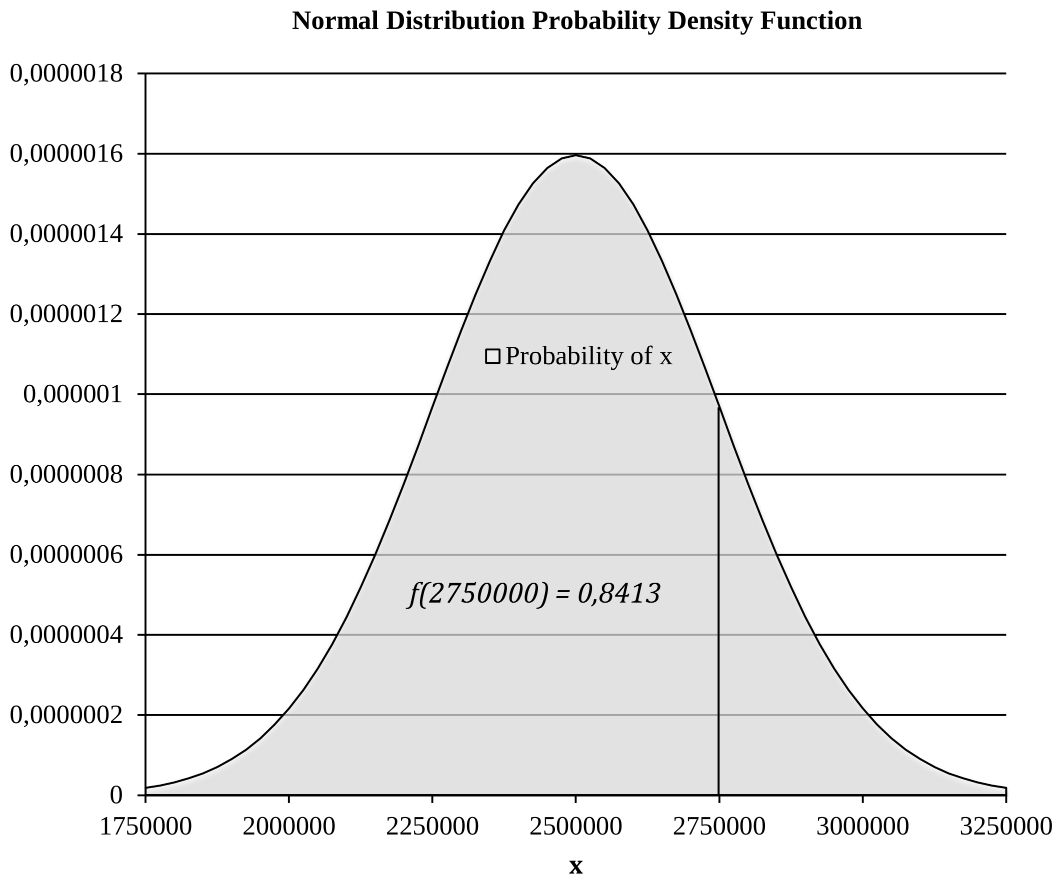



Figure 16: Normal Distribution Probability Density Function

Figure 16 illustrates how the cost value for an attribute is decided using Equation (6.2). A random value between zero and one, using MS Excel function *RAND()*, is generated for f(x) (f(x)=0,8413). The mean value for the cost is NOK 2,500,000, and its standard deviation NOK 250,000. The randomly generated value for these parameters is NOK 2,750,000. The mean value for the cost parameters can be found in Appendix C. It is important to only give the first functionality level of each attribute the random value. The remaining functionality levels are dependent on the value of the first functionality level by a predetermined fractional value. This prevents the unrealistic event that the cost of a higher functionality level is lower than its predecessors.

## 6.4 Scenario for Petroleum Development Near Jan Mayen

In the scenario the first exploration drilling is commenced in 2017. One exploration well is drilled every year. It is assumed that the exploration drilling ceases after four years with dry wells. It is also assumed that the period from discovery of a well until start of production is ten years, which corresponds to what is the average in the North Sea. The scenario with the highest probability for cost efficient implementation of a standby base is the “high scenario” where there eventually are five production wells. The initial period of exploration drilling is not considered in this thesis, and period one corresponds to the first year of production in 2027.

In Appendix D, Appendix Table XVIII illustrates the scenario generation for exploration drilling. Table 5 illustrates how the activity in the region is developing from year 2027. The years of no variation in activity in the area are not included in the table. As an assumption, each installation will be producing for ten years, meaning last year of production is 2047. This period (2027-2047) is the set *T* in the model, consisting of 20 indexes *t* where each index corresponds to a one-year duration.

| Year | Production initiation/termination | Location |
|---|---|---|
| 2027 | Floating LNG | 70°N, 08°E |
| 2030 | 2 FPSOs | 69°N, 08°E |
| 2033 | 1 FPSO | 71°N, 09°E |
| 2037 | 1 FPSO | 71°N, 09°E |
| 2037 | Floating LNG Production Terminated | 70°N, 08°E |
| 2040 | 2 FPOSs Production Terminated | 69°N, 08°E |
| 2043 | 1 FPSO Production Terminated | 71°N, 09°E |
| 2047 | 1 FPSO Production Terminated | 71°N, 09°E |

Table 5: Scenario Jan Mayen: Production initiation and location

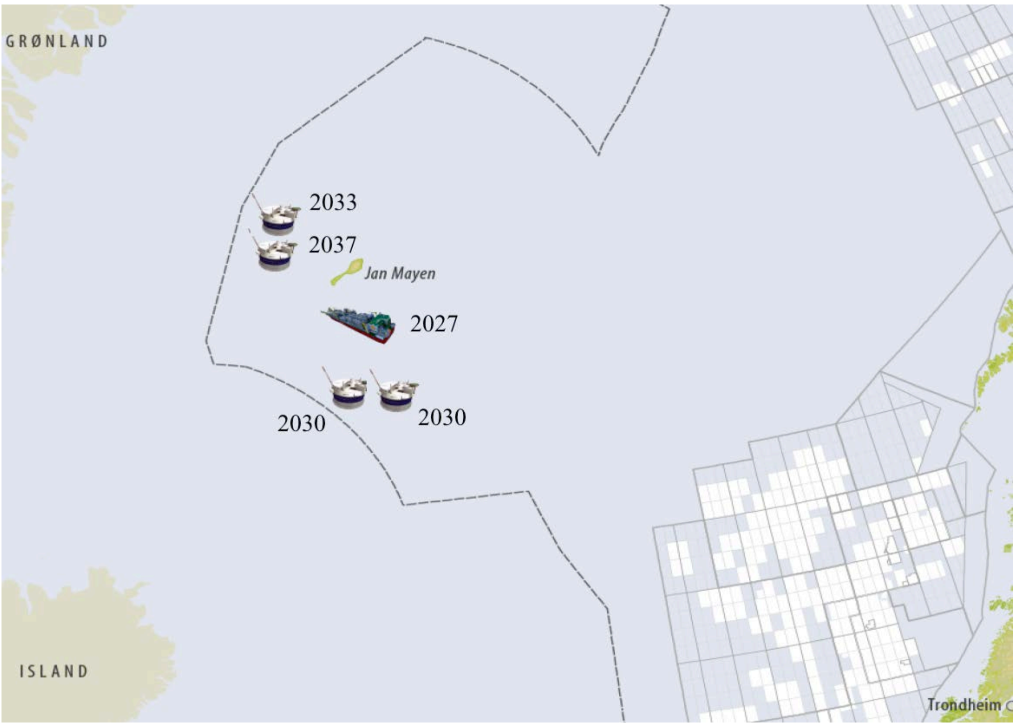



Figure 17: Scenario Jan Mayen: Map over locations

Figure 17 is a presentation of Table 5 where the locations of the installations are illustrated. In connection to the impact assessment, DNV has developed an oil drift analyses in the event of a blow out. The properties of the oil at the Norne field are used as a basis for developing an oil spill scenario for the five installations.

### 6.4.1 Oil Recovery Scenario

By using the NOFO calculator with the oil properties of the Norne field, and the most pessimistic blowout rates presented in *Åpningsprosess for petroleumsvirksomhet i havområdene ved Jan Mayen* (2012), the requirements in terms of oil recovery operations have been generated. The numbers imposing the strictest requirements will be used as values in the optimization model and are presented in Table 6. The NOFO calculations can be found in Appendix D.

| Location | Barrier 1 | Barrier 2 | Recovered Oil |
|---|---|---|---|
| 71°N, 09°E | 1 NOFO System | 1 NOFO System | >2881 $Sm^3/d$ |
| 69°N, 08°E | 1 NOFO System | 1 NOFO System | >2478 $Sm^3/d$ |

Table 6: ORO requirements for the case study

Based on how far away from shore the installations are located, the minimum response time for the two barriers have been developed as illustrated in Table 7. The closest area-based preparedness location is the Heidrun field, located approximately 480 nautical miles southeast of Jan Mayen (*Area-based Emergency Preparedness on the Norwegian Continental Shelf*, 2012). The vessels at Jan Mayen must be able to cope with 40 hours of

ORO before additional support arrives. The total requirement of recovered oil in $R^{TOTAL}$ is 4130 $m^3$ from year 2030, and 4800 $m^3$ from year 2033.

| Location | Barrier 1 | Barrier 2 |
|---|---|---|
| 71°N, 09°E | 3 hours | 9 hours |
| 69°N, 08°E | 9 hours | 12 hours |

Table 7: Response time requirements for the case study

### 6.4.2 Standby and Rescue Scenario

As mentioned in Chapter 2.5.2, finding standardized requirements connected to standby, rescue from sea, medical evacuation and SAR helicopter operations is difficult. These requirements in this scenario are based on regulations according to Appendix A and otherwise sensible assumptions. The AHP ratings of the attributes connected to $P_a$ are found in Appendix Figure V and the AHP ratings connected to the standby base and the standby vessels are found in Appendix Figure VI (Appendix H).

The requirements of $R_{at}^{UNIT}$ and $R_{at}^{TOTAL}$ can be found in Appendix Table VII and Appendix Table VIII.

The chart in Figure 18 illustrates how the activity in the region changes during the scenario in relation to the $R_{at}^{TOTAL}$ requirement (5.4). The percentage value (Activity) is the average value of the attributes in set $A^2$ in terms of their percentage value of maximum $R_{at}^{TOTAL}$.

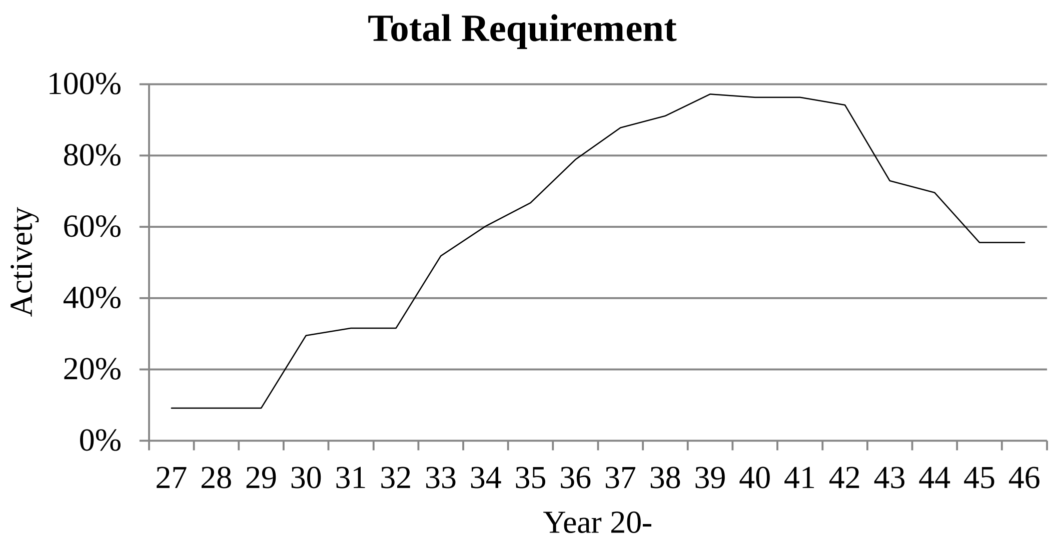



Figure 18: Development of total requirement throughout the scenario

Chapter 7

# Model Extension

## 7.1 Weighted Objective Function

The model presented in Chapter 5 minimizes the total cost so that emergency preparedness requirements are fulfilled. Indeed, the problem to find the fleet of standby vessels and design of standby base providing the lowest cost will keep the solution in the ALARP area (ALARP is explained in Chapter 2.5). However, the solution obtained from running the model will generate a result in the upper part of the ALARP area. The objective of emergency preparedness is not to minimize costs regardless. A trade-off between cost and safety will generate a solution further away from the unacceptable risk border in Figure 19. This trade-off is possible by introducing multi-objective optimization.

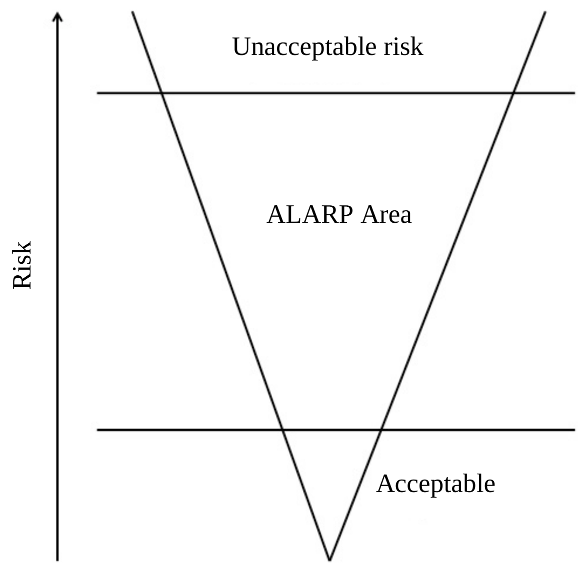



Figure 19: The ALARP principle expressed as a carrot diagram.

### 7.1.1 Multi-objective Optimization

A basic single-objective optimization problem can be formulated as follows (Caramia & DellÓlmo, 2008):

$$\min f(x) \\ x \in S, \tag{7.1}$$

Where *f* is a scalar function and *S* is the (implicit) set of constraints.

Multi-objective optimization can be described in mathematical terms as follows:

$$\min[f_1(x), f_2(x), \dots, f_n(x)] \\ x \in S, \tag{7.2}$$

Where *n* > 1 and *S* is the set of constraints defined as in (7.1). The concept of *optimality* does not apply directly to the multi-objective setting. Instead the notion of Pareto-optimality[7] has been introduced.

Multi-objective problems are often solved by combining the multiple objectives into one single-objective scalar function. This approach is generally known as the *weighted-sum* method.

$$\min \sum_{i=1}^{n} \gamma_n \cdot f_i(x) \\ \sum_{i=1}^{n} \gamma_n = 1 \\ \gamma_i > 0, i = 1, \dots, n \\ x \in S, \tag{7.3}$$

In (7.3) the weighted-sum method minimizes a positively weighted convex sum of the objectives. The objective function (3.1) is a version of (7.3) in a model optimizing ship design. There are different methods of deciding the weights $\gamma_n$, and it is up to the decision maker to choose appropriate weights. The same AHP method as described in Chapter 4.3 can be used to find appropriate weights using expert judgments. In Li and Guangwen (1990) the AHP method is used to take into account both quantitative and qualitative factors in multi-objective objective programming. The problem presented in the article is finding the optimal water quality management for rivers.

[7] A vector $x^* \in S$ is said to be Pareto-optimal for a multi-objective problem if all other vectors $x \in S$ have a higher value for at least one of the objective functions $f_i$, with $i = 1,\dots,n$, or have the same value for all the objective functions.

For the model extension in this thesis the weights of the objective function will not be given different values according to the AHP method. Instead the results when altering the weights will be investigated and discussed.

The model approach chosen when introducing the two conflicting factors of cost and safety is the trade-off of cost against the total capacity of a proportional attribute (set $A^2$). The total cost is the same as in the previous model, (5.1), and the total capacity of the attribute which is to be maximized is mathematically illustrated in objective function (7.4). In order to model the new weighted multi-objective function in Xpress, a new set has been introduced. This set consists of the attribute $a$ weighted against cost, and is called $A^3$.

.

$$maximize \quad \sum_{v \in V} \sum_{a \in A^3} \sum_{l \in L_a} \sum_{t \in T} K_{al} F_{val}^{ERRV} y_{vt} + \sum_{a \in A^3} \sum_{l \in L_a} \sum_{t \in T} K_{al} z_{alt} \tag{7.4}$$

Objective function (7.4) consists of two terms. The first summarizes the capacity of the standby base for each year, while the second term summarizes the capacity of the standby vessels for each year. It is important to bear in mind that the objective function (7.4) summarizes the capacity for all time periods.

The weighted multi-objective function for the model extension in this thesis will consist of the two objective functions (5.1) and (7.4). Because of the fact that they are implemented in one single-objective scalar function, and cost (5.1) is minimized while capacity (7.4) is maximized, one of the objective functions needs to be negative. If the single-objective function is minimized, the capacity term (7.4) needs to be negative. This makes sense because while you want to minimize cost, you still want the capacity to store for instance recovered oil to be high. For the model extension in Chapter 7.2, the cost term (5.1) is multiplied with the weight parameter $\alpha$ while the capacity term (7.4) is multiplied with the weight parameter $\beta$. It is important that the sum of the two weights always equals one as illustrated in (7.5).

$$\alpha + \beta = 1 \tag{7.5}$$

## 7.2 The Extended Optimization Model

New set

$A^3$ Set that includes the single attribute *a*, which is weighted against cost

New parameters

$\alpha$ The weight connected to cost

$\beta$ The weight connected to the attribute *a* in set $A^3$

New objective function

$$minimize \;\; \alpha \Bigg[ \sum_{t \in T} C_t^{BASE} x_t + \sum_{a \in A} \sum_{l \in L_a} C_{al}^F b_{al} + \sum_{a \in A} \sum_{l \in l_a} \sum_{t \in T} C_{al}^L m_{alt} + \sum_{a \in A} \sum_{l \in L_a} \sum_{l' \in L_a} \sum_{t \in T} C_{all'}^A w_{all't} + \sum_{a \in A} \sum_{l \in L_a} \sum_{t \in T} C_{al}^O z_{alt} - \sum_{e \in E} \sum_{t \in T} \sum_{q \in Q} C_{eq}^G h_{etq} + \sum_{v \in V} \sum_{t \in T} C_{vt}^{ERRV} y_{vt} \Bigg] - \beta \Bigg[ \sum_{v \in V} \sum_{a \in A^3} \sum_{l \in L_a} \sum_{t \in T} K_{al} F_{val}^{ERRV} y_{vt} + \sum_{a \in A^3} \sum_{l \in L_a} \sum_{t \in T} K_{al} z_{alt} \Bigg] \quad (7.6)$$

Since the model presented above is subjected to the same constraints as the model presented in Chapter 5, the same results will be generated when $\alpha$ equals one. As $\beta$ increases, total cost should start to increase together with the capacity of attribute *a* in set $A^3$. In Chapter 8 the model extension will be tested on the attribute “Oil Recovery” and the behaviour of the results as different weights are given to $\alpha$ and $\beta$ will be reviewed.

Chapter 8

# Results

In this chapter the results from the Jan Mayen scenario will be presented. Because of the similarity between the two basic designs, distinguished mostly by their size, it is important to investigate not only the cost, but also how the functionality level of the standby base changes throughout the scenario. The results presented in this chapter are based on the output from the Xpress model displayed in Appendix E. For simplicity, the behaviour of the results and how the results reflect the model will be discussed in this chapter. The results in relation to the problem description and state of the art will be discussed further in Chapter 9. Finding the standby base best suited for operation near Jan Mayen is not the most important part when discussing the results, but how the model reflects the problem description. Nevertheless, a conclusion regarding the standby base best suited will be made in Chapter 10.

| **Standby base** | | **Front Brabant** | **Front Champion** |
|---|---|---|---|
| **Total Cost** | **Objective function** | **NOK 5,828,600,000** | **NOK 5,913,770,000** |
| Year of implementation | | 2030 | 2030 |
| | | | |
| Investment cost in standby base | **1. term** | NOK 810,812,000 | NOK 966,478,000 |
| Initial costs of implementation | **2. term** | NOK 29,244,933 | NOK 39,459,800 |
| Costs of later implementation | **3. term** | NOK 116,008,000 | NOK 155,040,000 |
| Costs for altering functionality level | **4. term** | NOK 39,956,200 | NOK 59,580,000 |
| Operating costs | **5. term** | NOK 116,316,000 | NOK 227,825,000 |
| Savings from shared operation | **6. term** | NOK 17,736,000 | NOK 28,608,000 |
| Cost for chartering standby vessels | **7. term** | NOK 4,734,000,000 | NOK 4,499,000,000 |
| | | | |
| Total cost connected to standby base | | NOK 1,094,601,133 | NOK 1,419,774,800 |

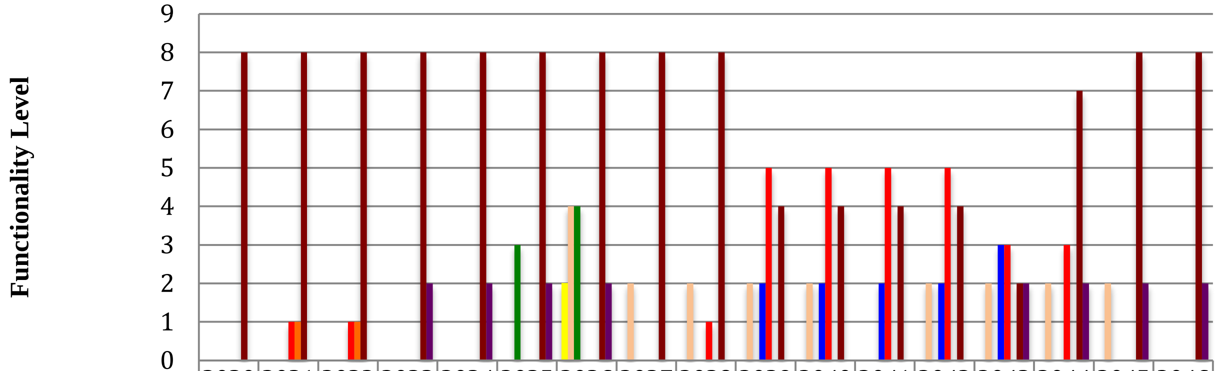
Table 8: Costs connected to the two different basic standby base designs

Table 8 lists the values of the seven terms in the objective function when it is solved to optimality. It also displays the year the standby base is implemented as a part of the contingency plan and the total cost related to the standby base. The total cost difference between the two designs is NOK 85,170,000. This difference is not considered significant enough to conclude that Front Brabant is better suited as a standby base compared to

Front Champion. The output from the model in Appendix Table XXI needs to be investigated further in order to draw any conclusions.

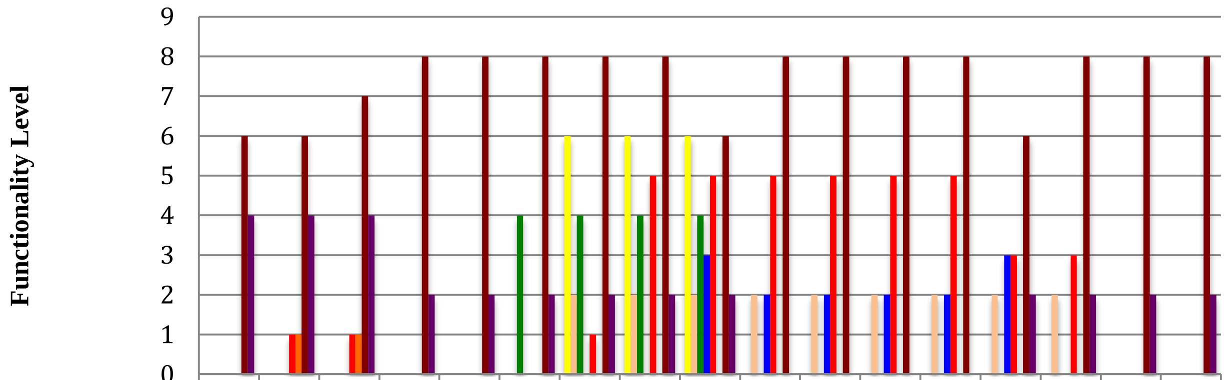
Before any further investigation is commenced concerning the design of the standby base, the cost when disregarding the possibility of implementing a standby base needs to be computed. By altering restriction (5.2) from $\sum_{t \in T} x_t \leq 1$ to $\sum_{t \in T} x_t \leq 0$ the model will refuse implementation of a standby base, and the output will be the standby vessels needed to maintain required preparedness (Appendix E, Appendix Table XXII). For this instance the total cost is NOK 6,848,000,000, approximately one billion higher than the total cost obtained with Front Brabant. This difference definitely makes the implementation of a standby base worth investigating further.

Figure 20 and Figure 21 illustrate how the functionality levels for attributes implemented at the standby base are altered from time of implementation in year 2030 until the end of the scenario in year 2046. It is evident that the "Supply" attribute reaches its maximum functionality level of eight for many time periods. Because of this it could be reasonable to extend the levels of functionality for this attribute in order to exploit the available deck area. Front Champion has a higher deck area capacity, and this might bring the total cost of the two basic designs closer. However, this also depends on how much more supply is needed for the region and how often the standby base takes trips to shore to resupply.




| | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 | 2046 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oil Boom | | | | | | | 2 | | | | | | | | | | |
| Skimmer | | | | | | | 4 | 2 | 2 | 2 | 2 | | 2 | 2 | 2 | 2 | |
| C.Dispersants | | | | | | 3 | 4 | | | | | | | | | | |
| Safe Haven | | | | | | | | | | 2 | 2 | 2 | 2 | 3 | | | |
| MOB | | 1 | 1 | | | | | | 1 | 5 | 5 | 5 | 5 | 3 | 3 | | |
| Radar | | 1 | 1 | | | | | | | | | | | | | | |
| Supply | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 4 | 4 | 4 | 4 | 2 | 7 | 8 | 8 |
| Oil Recovery | | | | 2 | 2 | 2 | 2 | | | | | | | 2 | 2 | 2 | 2 |

Figure 20: Functionality level for attributes at Front Brabant




| | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 | 2046 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oil Boom | | | | | | | 6 | 6 | 6 | | | | | | | | |
| Skimmer | | | | | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | |
| C.Dispersants | | | | | | 4 | 4 | 4 | 4 | | | | | | | | |
| Safe Haven | | | | | | | | | 3 | 2 | 2 | 2 | 2 | 3 | | | |
| MOB | | 1 | 1 | | | | 1 | 5 | 5 | 5 | 5 | 5 | 5 | 3 | 3 | | |
| Radar | | 1 | 1 | | | | | | | | | | | | | | |
| Supply | 6 | 6 | 7 | 8 | 8 | 8 | 8 | 8 | 6 | 8 | 8 | 8 | 8 | 6 | 8 | 8 | 8 |
| Oil Recovery | 4 | 4 | 4 | 2 | 2 | 2 | 2 | 2 | 2 | | | | | 2 | 2 | 2 | 2 |

Figure 21: Functionality level for attributes at Front Champion

Another important aspect of the result to investigate is how the attributes' functionality levels of the standby base are altered throughout the scenario. These alterations are connected to the cost parameters, $C_{al}^{L}$ (cost of later implementation) and $C_{all'}^{A}$ (cost of altering functionality level) in the optimization model, but because of the uncertainty of these costs and the fact that these alterations might impose complications and make the standby base not operational for a period, it is favourable to keep them to a minimum.

For both Front Brabant and Front Champion the two attributes implemented in period four are "Oil Recovery" and "Supply". The same is the case for attributes implemented later in the scenario; they are similar for both standby base designs. Table 9 displays the year of implementation for these attributes according to variable $m_{alt}$. MOB is removed as an attribute in year 2032, and implemted again in year 2038.

| **Attribute** | **Year** |
|---|---|
| Oil Boom | 2036 |
| Skimmer | 2036 |
| C. Dispersants | 2035 |
| Safe Haven | 2039 |
| MOB | 2031 and 2038 |
| Radar | 2031 |
| Oil Recovery | 2034 |

Table 9: Attributes implemented later in the scenario

In the area of altering functionality level for an attribute there are differences between the two standby base designs. The variable $w_{all't}$ displays how the functionality level is altered between two time periods. Table 10 and Table 11 display during which years the functionality levels are altered for the two standby base designs. The number to the left of the arrow is the functionality level for the attribute in the previous year while the number to the right of the arrow is the functionality level for the year in the same column.

| **Year**<br>**Attribute** | 2032 | 2033 | 2036 | 2037 | 2038 | 2039 | 2043 | 2045 | **SUM** |
|---|---|---|---|---|---|---|---|---|---|
| Oil Boom | | | | | | | | | 0 |
| Skimmer | | | | 4→2 | | | | | 1 |
| C.Dispersants | | | 3→4 | | | | | | 1 |
| Oil Recovery | | 4→2 | | | | | | | 1 |
| Safe Haven | | | | | | | 2→3 | | 1 |
| MOB | | | | | | 1→5 | 5→3 | | 2 |
| Radar | | | | | | | | | 0 |
| Supply | | | | | | 8→4 | | 7→8 | 2 |

Table 10: Alteration of functionality level for Front Brabant

| **Year**<br>**Attribute** | 2032 | 2033 | 2036 | 2037 | 2038 | 2039 | 2043 | 2045 | **SUM** |
|---|---|---|---|---|---|---|---|---|---|
| Oil Boom | | | | | | | | | 0 |
| Skimmer | | | | 5→6 | | 6→2 | | | 2 |
| C.Dispersants | | | | | | | | | 0 |
| Oil Recovery | | 4→2 | | | | | | | 1 |
| Safe Haven | | | | | | 3→2 | 2→3 | | 2 |
| MOB | | | | 1→5 | | | 5→3 | | 2 |
| Radar | | | | | | | | | 0 |
| Supply | 6→7 | 7→8 | | | 8→6 | 6→8 | 8→6 | | 5 |

Table 11: Alteration of functionality level for Front Champion

If Front Brabant was to be implemented as a standby base, the total number of alterations of the functionality levels would be eight throughout the scenario, while if Front Champion was implemented as a standby base the total number of alterations is twelve. This difference should give Front Brabant an advantage over Front Champion as a possible standby base design.

Because of the importance of standby vessels when it comes to emergency preparedness, it is vital to investigate how the fleet of standby vessels is altered throughout the scenario. The fleet of standby vessels for each time period is decided by the integer variable $y_{vt}$. Figure 22 illustrates how the two fleets for Front Brabant and Front Champion change throughout the scenario. Comparing these two results will need to be a part of the process of deciding the optimal basic design.

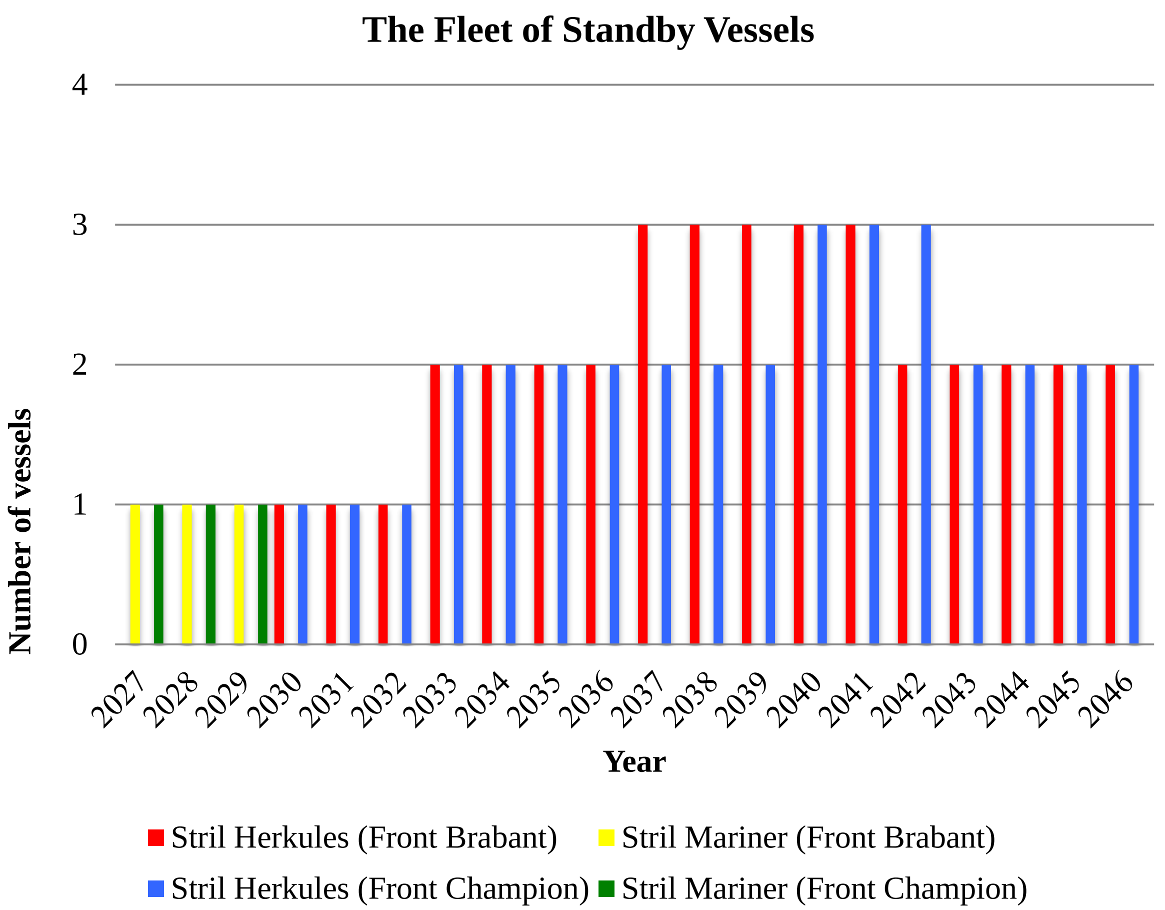



Figure 22: The fleet of standby vessels for the two standby base designs

From the results in Figure 22, it is obviously optimal to charter one standby vessel similar to Stril Mariner during the first three years of the scenario. For the remaining time periods, the optimal solution suggests a fleet of one, two or three standby vessels similar to Stril Herkules. In year 2037 and 2038 there are three standby vessels operating along with Front Brabant, compared to two standby vessels for Front Champion. The solution suggests the opposite for year 2042. Overall, throughout the scenario, implementing Front Brabant as a standby base generates a solution where there are two more standby vessels in total compared to Front Champion

## 8.1 Model Extension: Cost and Oil Recovery Trade-off

The purpose of the model extension was to develop a model generating results closer to what is considered the ALARP principle. In this chapter the data in Appendix C has been tested on the model extension in Chapter 7 including two factors: cost and capacity to store recovered oil. By running the weighted multi-objective model with different combinations of values for $\alpha$ (cost) and $\beta$ (oil recovery capacity) the results in Appendix Table XXIII were generated. The table includes total cost, cost of standby base, cost of standby vessels and the summarized capacity for recovered oil throughout the scenario. An interesting aspect of the multiple-objective function is that you can force the model to emphasize an attribute more without breaking the minimum requirements. This is especially interesting for activity in remote regions where the minimum requirements of the North Sea most likely will prove inadequate.

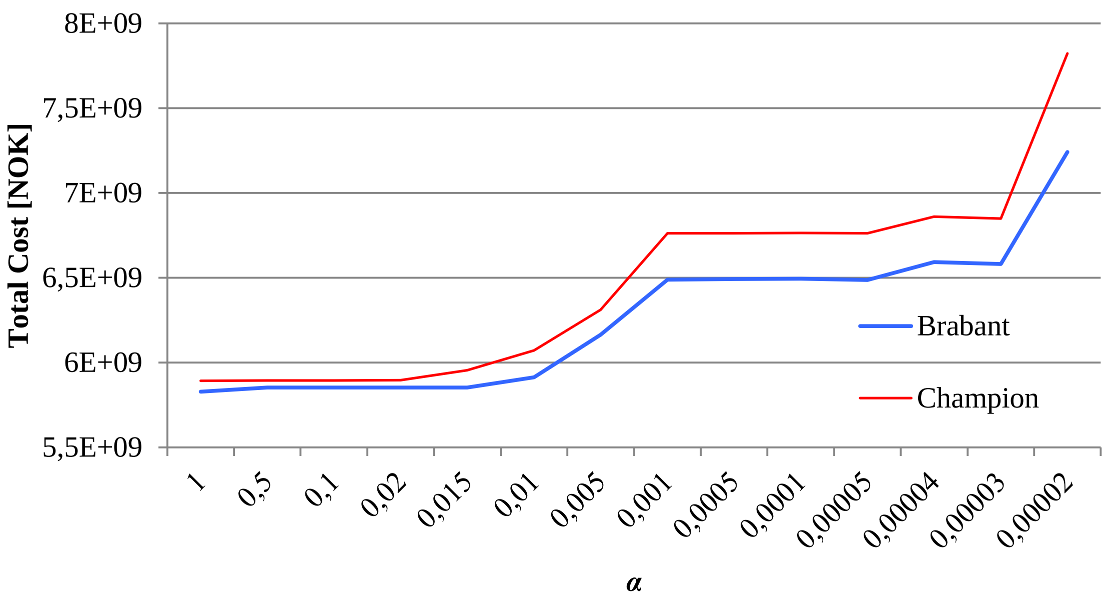



Figure 23: Total cost of preparedness relative to weight $\alpha$ in the objective function

After running the model for a series different weights the behaviour of the results was investigated against what was expected. The investigation process can be illustrated through Figure 23. Total cost is constant when $\alpha$ lies in the two intervals (1-0,015) and (0,001-0,00005). The behaviour in the first interval can be explained by the minimum requirements (5.4) forcing the reduction of cost before increase of oil recovery capacity. When $\alpha$ reaches 0,015 the relatively inexpensive surplus capacity available at the standby base increases both total capacity and total cost. When $\alpha$ reaches 0,001 the capacity of the standby base is maximized and extra capacity can only be obtained by chartering expensive standby vessels. This does not happen before $\alpha$ is 0,00005, and reducing the weight of cost will force extensive chartering of standby vessels consequently increasing the total cost drastically.

### 8.1.1 Trade-off Graph

From the results in Appendix F the set of efficient solutions have been used to create Figure 24 illustrating the trade-off between cost and oil recovery capacity. Drawing a graph with each objective function in (7.6) representing the axis of the chart makes for a good illustration of the trade-off situation.

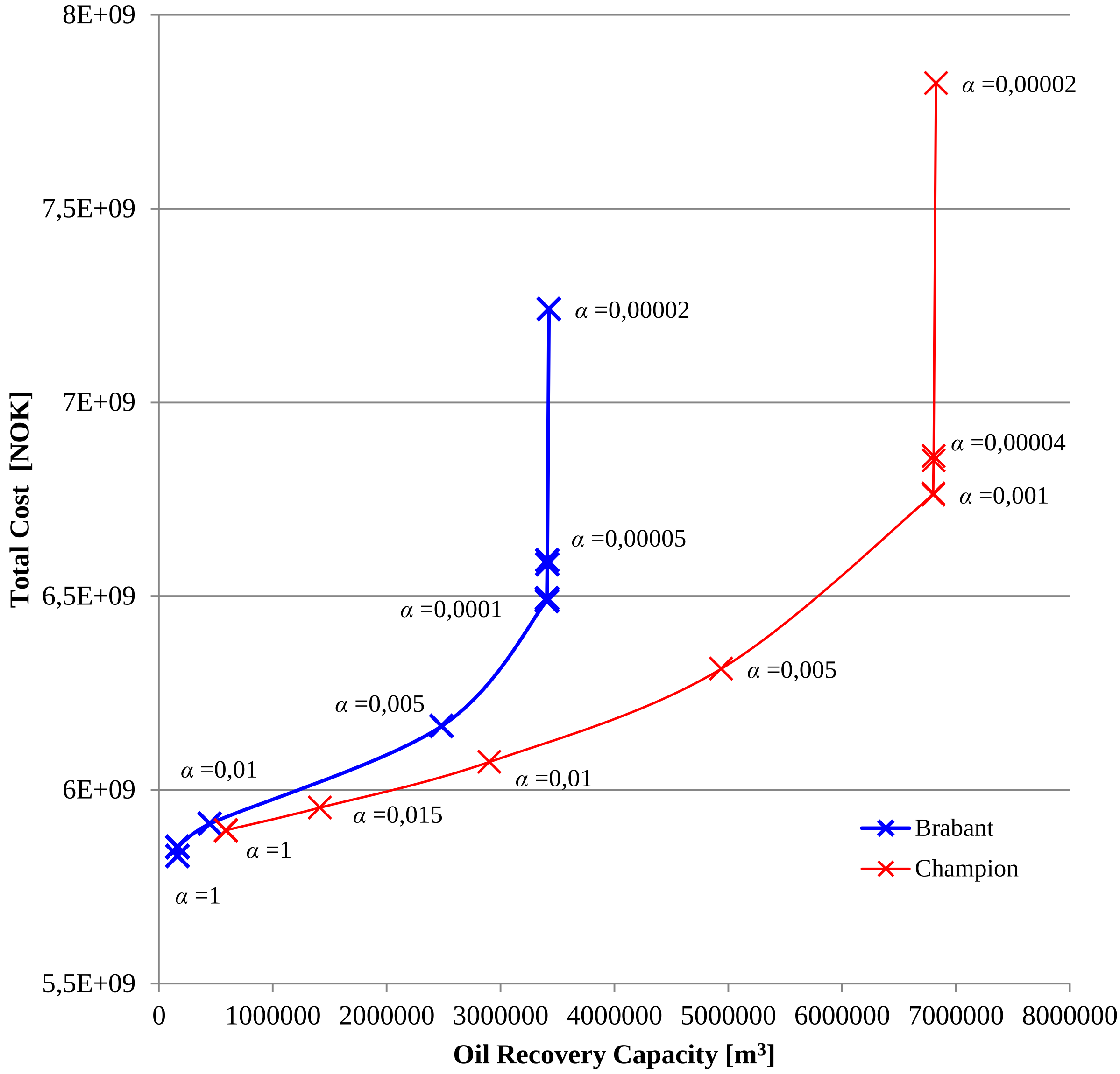



Figure 24: The trade-off between cost and oil recovery capacity

For the situation where only cost is minimized ($\alpha$=1) the total cost when utilizing Front Brabant as a standby base is lower than when using Front Champion. As the weight decreases and oil recovery capacity increases, the total cost for Front Brabant gets higher than for Front Champion. This is reasonable considering the higher capacity of Front Champion. The total cost for Front Brabant starts growing exponentially around 2500000 $m^3$ and when total capacity reaches 3400000 $m^3$ a marginal capacity increase leads to a substantial growth in costs. This is connected to the low capacity of the standby vessels relative to the standby base. The same behaviour of exponential growth of costs is starting around 3500000 $m^3$ for Front Champion and extreme marginal costs occur at 6800000 $m^3$.

# Chapter 9

# Discussion

In this chapter the model and the results from the case study will be discussed with regard to the problem description. Assumptions and simplifications will also be discussed including how the work performed compares to state of the art.

## 9.1 The Model as a Tool for Deciding Design and Functionality

In Chapter 2.8 the main problem is presented as *develop an optimization program that can be used as a tool by ship designers to decide the optimal design and functionality of a standby base operating in remote regions*.

The model developed only minimizing cost produced a result where the functionality of the standby base did not necessarily utilize its full capacity. This was according to the problem description and as expected because the model is subjected to minimum requirements when it comes to emergency preparedness. However, the effect of incorporating costs connected to later implementation of attributes, alteration of functionality level and gain in shared operating expenses did not have the effect as expected in advance (term 3, term 4 and term 6 in Table 7). By implementing these cost parameters, a standby base with overcapacity in terms of functionality versus requirements was expected from the year of implementation. For Front Brabant the "Supply" attribute was implemented in year 2030, while for Front Champion the "Supply" and "Oil Recovery" attributes were implemented in 2030. The reason for this might be unrealistic values of cost parameters, and if higher costs were associated with later implementation and alteration of functionality levels, and a higher reward was given to shared operating expenses, the model might have produced a result where the standby base has a more constant set of attributes and functionality levels.

The weighted multi-objective extension of the model considering the trade-off between cost and the total capacity of an attribute did accurately address the problem of the results obtained with the model only minimizing costs. By shifting the focus away from only minimizing cost to considering the total capacity of storing recovered oil as well, the standby base utilized its full capacity as a tanker without considerably increasing the total cost of the contingency plan. This also shifts the optimal basic design for the standby base from Front Brabant to Front Champion because of its higher capacity. The multi-objective weighting makes for a more robust solution for remote regions. It is possible to use the restrictions of the model to set requirements similar to the standard in the North Sea, and reduce the weight of cost *(α)* until the cost of further risk reduction is grossly disproportional to the potential risk reducing effect.

The most important part of the model for the ship designer will be to find the optimal basic design of the standby base. In this thesis only two basic designs are compared against each other. Introducing other designs besides tank vessels would generate greater variation in results. The attributes of the different designs should give the ship designers a basis for deciding the functionality of the standby base. The year of implementation will also help in planning the project concerned with converting the basic design into a standby base. The model also holds the possibility to be used as a means to find the design and functionality of a regular standby vessel. This is executed by excluding the AHP part of the model and giving the value *one* to all attributes $a$ in $P_a$.

## 9.2 Assumptions Made

The real problem reviewed in Chapter 2 was the basis for the simplified problem in Chapter 4. The transition from the real problem to the simplified one involves assumptions, which are important in the development of a working mathematical model reflecting the problem. Chapter 4 consists of a thorough review of the model and includes the reasons for the assumptions made. The most important assumptions will be highlighted in this subchapter.

**Partitioning of attributes into functionality levels.** The fact that each attribute is divided into a series of functionality levels forces the assumption that the attribute can only take a series a quantities. This is not a problem for attributes where each functionality level represents one unit, e.g. “MOB”, however for attributes with large quantities like “Oil Recovery” this will omit solutions in between two quantities (functionality levels). The consequence of this is that even though the optimal solution suggests that the oil recovery capacity of the standby base is 166383 $m^3$, 180000 $m^3$ might be the real optimal solution. Because this quantity is not represented as a functionality level, it cannot be a solution.

**Dividing attributes into three emergency preparedness groups.** In order to consider shared expenses between attributes, three emergency preparedness groups were created. If more than one attribute within one group is implemented on the standby base, there will be a preset reduction in operating expenses. This way of modeling the problem assumes no difference in reduction within the attributes in the group. However, by introducing more emergency preparedness groups the simplification can be made less significant.

**The model does not consider the transit from shore to location of standby operation.** The economical aspects of this simplification are possible to incorporate into the investment cost of the standby base ($C_t^{BASE}$), however the loss of safety when the standby base is "off location" is not part of the model. It is assumed that because both the standby vessels and the standby base have periods when not operational, the requirements in the model will consider this as a natural part of the contingency plan.

**There are no limitations in the number of standby vessels available for charter.** This means that the model assumes there are always standby vessels available and that the chartering contracts can be terminated in any time period *t* of the scenario.

**Assumptions are made in connection to data values.** The case study in this thesis is based on data developed from valid sources and own assumptions. The expert judgments connected to the AHP part of deciding the values of $P_a$ are based on assumption. The mean values of the cost parameters ($C_{al}^F$, $C_{al}^L$, $C_{all'}^A$, $C_{al}^O$, $C_{eq}^G$) and the requirements connected to the attributes not concerning oil recovery are also based on assumptions.

**The model extension does not differentiate between the capacity of the standby base and the standby vessels.** The term (7.4) in the weighted multi-objective function that maximizes total capacity for an attribute summarizes the capacity of the standby base and the fleet of standby vessels. If the use of standby vessels is considered superior compared to the standby base this will make the optimal solution unrealistically emphasize the capacity of the standby base.

## 9.3 Model Compared to State of the Art

I believe the model developed in this thesis can be divided into two parts: the maritime fleet size and mix problem (MFSMP) and the ship design problem. The level of knowledge and development within each part is high, and different versions of problems have been tested on countless scenarios. For both an offshore support fleet serving a region with installations, as discussed by Fagerholt and Lindstad (1999), and a fleet of cargo vessels transporting commodities between ports, as discussed by Hoff et al. (2008), the fleet composition is vital when minimizing the cost. The importance of the composition of the fleet of standby vessels is too high to exclude when the optimal design of a standby base is to be decided. In the same way as for traditional MFSMP, the fleet of standby vessels is decided by an integer variable indexed by its type $v$ and time period $t$. The difference is that its capabilities are not speed, cargo capacity, fuel consumption, etc. but attributes and functionality connected to emergency preparedness.

The second part of the model is the design of the standby base. Unlike the problem at hand in Ray et al. (1995), where the design variables are parameters like length, breadth, draft and block coefficient, the variables of the standby base are connected to its attributes. The design category of the model in this thesis is more comparable to Patricksson et al. (2013). The difference, apart from the independence from a fleet of vessels, is that the model only gives indication of a constant design and functionality, whereas the model in this thesis opens the possibility of altering functionality level and the implementation of attributes later in the scenario.

Connecting the fleet of standby vessels with the design of the standby base was an important part when developing the model in this thesis. The connection was done using the AHP method. In Crary et al. (2002) AHP was used to compare the fleet of destroyers in the US Navy. For the model in this thesis the same method was used to compare standby vessels with the standby base. The difference is that the weights obtained from the AHP calculations are used in the objective function in Crary et al. (2002), while the weights in this thesis are used in the restrictions to distinguish between the standby base and the standby vessels in maintaining a satisfactory level of emergency preparedness.

The two parts of the model, individually at a high level in terms of state of the art, have been combined to produce a model within an area where the state of the art is much less developed. It is therefore difficult to compare the results against other research. During the literature study I was unable to find any study or development within the area of optimizing the design of a standby vessel. The main reason might be the intangible aspect of emergency preparedness and the functionality of a standby vessel. There is a high level of technology connected to a standby vessel, and attributes within emergency preparedness are not easily compared. The fact that support from installations in other regions, ship traffic in the area and infrastructure on land will influence the level of emergency preparedness required from standby vessels, makes the value of the information obtained from an optimization model less concrete. However, when production is moved to remote regions these influences are minor or non-excising. This means that the standby vessels and the standby base included in the model are the only components affecting the level of emergency preparedness in the region. The value of using optimization as a tool for deciding the design and functionality of a standby base grows as the region of operation moves further away from infrastructure and already established emergency preparedness. As petroleum activity in remote regions gets more relevant, I believe that state of the art connected to optimizing standby vessel design will be developed further.

Chapter 10

# Conclusion

This thesis aims to develop a tool aiding naval architects in finding the design and functionality of a standby base using mathematical optimization. Another objective was also the use of a base in a standby preparedness picture for remote regions, and whether its contribution would reduce the cost of the contingency plan and/or increase the level of human and environmental safety.

The model developed will produce three sets of results: the basic design of the standby base, its attributes and the fleet of standby vessels. This limits the user to a set of predetermined basic designs and will not produce the optimal characteristics of a standby base. However, this gives the advantage of exploring the use of second-hand vessels as a standby base.

The model does not directly reflect the case of implementing the standby base in remote regions. With proper data and knowledge of how the model handles information, any scenario and region can be incorporated into the model. But the validity of the results becomes more questionable as more factors, like the support from other installations, vessels and land, gets more relevant. The model is therefore best suited for the isolated scenarios found in remote regions.

After investigating and comparing the results from the non-weighted optimization model in the case study, it is possible to draw a conclusion regarding what basic design is considered optimal as a standby base. For all three key aspects of the output from the model: total cost, alteration of functionality level and number of standby vessels in the fleet, the model produces a better result for Front Brabant than for Front Champion. Based on this, the basic design to investigate even further as a possible standby base design should be Front Brabant. However, in the model extension where the trade-off between cost and oil recovery capacity is investigated, Front Champion, with its higher capacity, produces a better trade-off situation as the weight of cost decreases. The proper weight distribution between cost and oil recovery capacity is not discussed in this thesis, and would be a natural part of the post-optimization and further work.

## 10.1 Further Work

During the process of gathering relevant literature I was unable to find research regarding optimizing the design of a standby vessel. This puts my thesis and the model developed in a position where it is difficult to compare the results. The model is a combination of state of the art within maritime fleet optimization, ship design optimization and the analytical hierarchy process. Each area has a high level connected to research and development, and the goal when transforming the problem in this thesis into a working optimization model has therefore been to utilize the resources in the state of the art. Because of the experimental approach utilized in developing an optimization model reflecting a problem within an area of little research, the possibility of further work is broad and extensive. However, in this chapter I will only highlight the possible further work improving the model developed in this thesis.

**Making the model stochastic.** Because of the uncertainty connected to the assessment of future petroleum activity in a region, a natural follow-up is to include the probability for initiation of petroleum production on a field.

**Improving the multi-objective model.** The weighted objective function only considers costs and the capacity of one attribute. An improvement might be to include multiple attributes and also distinguish between the capacity of the standby base and the standby vessels.

The improvements mentioned would improve the mathematical model in this thesis. However, when it comes to the problem of finding the optimal design of a standby base there are many possible approaches. In an early phase of the model development I investigated the possibility of solving the problem using a Fleet Size and Mix Vehicle Routing model. The model was discarded because it did not reflect the problem description and emphasized the operation of a standby base rather than its design.

The limited state of the art connected to optimizing the design of standby vessels has made the model in this thesis a version of what I consider to be a possible way of developing a tool in aiding naval architects. I hope the research and the model developed in this thesis can be of help in future research within the area of optimizing the design of standby vessels and standby bases. An area with increasing relevance as petroleum exploration moves further away from land and into remote regions.

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# Appendices

## A. Regulations and EP Assessment

(Sjøfartsdirektoratet, 1992)
**Regulation of 16 October 1991 No. 853 concerning Standby Vessels**

*Chapter IV. Special requirements for standby vessels with rescue duties*
**§ 15. Manoeuvring capabilities.**
(1) A fully equipped standby vessel shall be capable of reaching a speed in quiet weather of at least 12 knots with fully loaded bunkers and water tanks.

**§ 16. Rescue zone and freeboard**
(1) The freeboard is assessed separately for each individual vessel. The assessment is made on the basis of the vessel's type and characteristics and on the rescue equipment to be found on board. The freeboard should be as small as possible. For new standby vessels, however, it should not be less than one meter.

**§ 19. Accommodation requirements, furnishings and medical equipment for rescued persons, etc.**
(1) The standby vessel shall provide a reception area, treatment room for casualties, day room and a sanitary room with the necessary number of hand-basins, showers and toilets for rescued persons, a room for the deceased and bunks for 10% of the number of persons that can be accommodated on board. Fixed seating shall be provided in the day room. All the rooms and adjoining corridors shall have non-slip flooring.

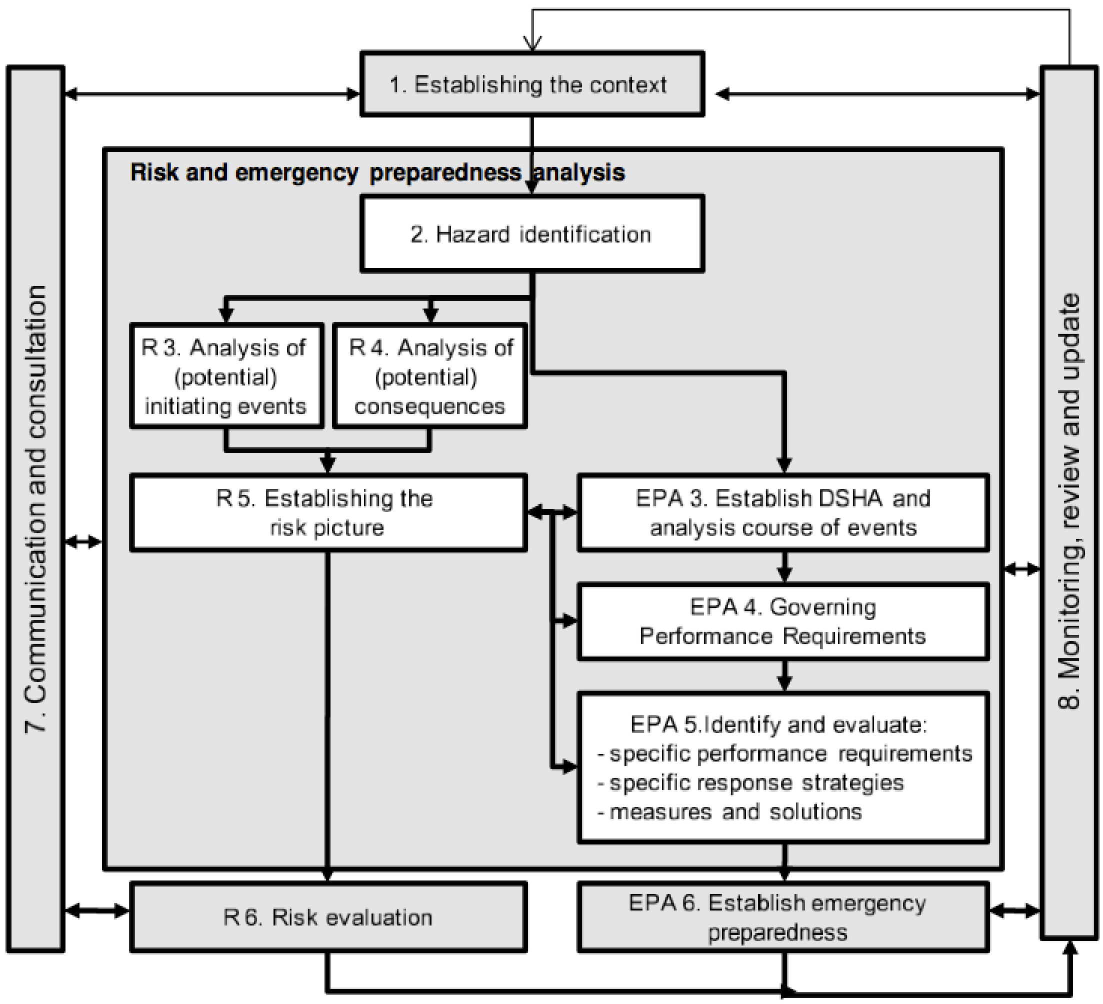
(2) The company shall calculate 0.75 $m^2$ per person when calculating area for the number of rescued persons that can be accommodated on board. Accommodation for the crew, except sanitary rooms, treatment rooms, galley, wheelhouse and, if applicable, the radio room, may be included. Floor area taken up by bunks, tables, cupboards or other regular fittings shall not be included.

(4) The location, furnishings, equipment and size of the treatment room shall be such as to ensure that medical first aid for casualties can be properly carried out. The treatment room shall be in the immediate vicinity of the reception. The floor area shall measure no less than 15 $m^2$. The room shall be used for the treatment of casualties only.

(7) The room designated for the deceased shall be large enough to cater for a number of persons equivalent to 10% of the number of persons who can be accommodated on board and be furnished so that the deceased may be accommodated in an aesthetically proper and fitting manner. The floor area shall be sufficient, when fixed beds or bunks of some kind are in place, to allow a stretcher to be brought into the room. Access to the room shall be of a size and arrangement suitable for the use of stretchers. Separate mechanical ventilation for the room is required.

(NORSOK Standard, 2010)

**Process of performing a risk and emergency preparedness assessment**




Appendix Figure I: The process of risk and emergency preparedness assessment

# B. AHP Calculations

(Coyle, 2004)

**The Saaty Rating Scale**

| Intensity of importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two factors contribute equally to the objective |
| 3 | Somewhat more important | Experience and judgment slightly favour one over the other |
| 5 | Much more important | Experience and judgment strongly favour one over the other |
| 7 | Very much more important | Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice |
| 9 | Absolutely more important | The evidence favouring one over the other is of the possible validity |
| 2,4,6,8 | Intermediate values | When compromise is needed |

Appendix Figure II: The Saaty Rating Scale

**Overall Preference Matrix for each attribute in set $A^2$**

There are four criteria to be compared; $C_1$ … $C_4$, and $a_{ij}$ denote the relative weight of $C_i$ with respect to $C_j$.

$C_1$ = Location, $C_2$ = Deployment time, $C_3$ = Speed, $C_4$ = Manoeuvrability

| $a \in A^2$ | $C_1$ | $C_2$ | $C_3$ | $C_3$ |
|---|---|---|---|---|
| $C_1$ | 1 | $a_{12}$ | $a_{13}$ | $a_{14}$ |
| $C_2$ | $1/a_{12}$ | 1 | $a_{23}$ | $a_{24}$ |
| $C_3$ | $1/a_{13}$ | $1/a_{23}$ | 1 | $a_{34}$ |
| $C_4$ | $1/a_{14}$ | $1/a_{24}$ | $1/a_{34}$ | 1 |

Appendix Figure III: Overall preference matrix

**Calculating the eigenvectors**

There are several methods for calculating the eigenvector. The method used in this thesis gives a very good approximation of the correct answer.

First the $n^{th}$ roots of the products are calculated. The $n^{th}$ root of the product for the entries in the first row in Appendix Figure III is $(1*a_{12}* a_{13}* a_{14})$^(1/4). The value of the Eigenvector for the first row is this value divided by sum of $n^{th}$ root of the products for each row.

# C. Sets and Parameters for the Case Study

Sets

| | |
|---|---|
| V = | {Stril Herkules, Stril Mariner} |
| E = | {ORO, RESC, HELI} |
| A = | {Oil Boom, Skimmer, C.Dispersants, Oil Recovery, Helipad, Helifuel, Hosp. Unit, Safe Haven, MOB, Radar, Fire Fighting, Supply} |
| $L_{Oil\ Boom}$ = | {1, 2, 3, 4, 5, 6} |
| $L_{Skimmer}$ = | {1, 2, 3, 4, 5, 6} |
| $L_{C.\ Dispersants}$ = | {1, 2, 3, 4, 5} |
| $L_{Oil\ Recovery}$ = | {1, 2, 3, 4, 5, 6} |
| $L_{Helipad}$ = | {1, 2} |
| $L_{Helifuel}$ = | {1, 2, 3} |
| $L_{Hosp.\ Unit}$ = | {1, 2, 3, 4} |
| $L_{Safe\ Haven}$ = | {1, 2, 3, 4} |
| $L_{MOB}$ = | {1, 2, 3, 4, 5} |
| $L_{Radar}$ = | {1, 2, 3} |
| $L_{Fire\ Fighting}$ = | {1, 2} |
| $L_{Supply}$ = | {1, 2, 3, 4, 5, 6, 7, 8} |
| $A^1$ = | {Oil Boom, Skimmer, C.Dispersants, Oil Recovery, Helipad, Helifuel, Hosp. Unit, Safe Haven, MOB, Radar, Fire Fighting} |
| $A^2$ = | {Oil Boom, Skimmer, C.Dispersants, Oil Recovery, Safe Haven, MOB} |
| $A^{ORO}$ = | {Oil Boom, Skimmer, C.Dispersants, Oil Recovery} |
| $A^{RESC}$ = | {Hosp. Unit, Safe Haven, MOB} |
| $A^{HELI}$ = | {Helipad, Helifuel} |
| $T$ = | {1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20} |
| $Q_{ORO}$ = | {1, 2, 3, 4} |
| $Q_{RESC}$ = | {1, 2, 3} |
| $Q_{HELI}$ = | {1, 2} |
| $A^3$ = | {Oil Recovery} |

| **C_BASE** Index: *t* | | |
|---|---|---|
| Periods | Front Brabant | Front Champion |
| 1 | NOK 931,049,820.06 | NOK 1,088,918,818.00 |
| 2 | NOK 891,363,126.13 | NOK 1,048,590,539.31 |
| 3 | NOK 851,296,131.38 | NOK 1,007,801,974.51 |
| 4 | NOK 810,812,436.99 | NOK 966,477,870.35 |
| 5 | NOK 769,872,160.37 | NOK 924,530,670.27 |
| 6 | NOK 728,431,601.76 | NOK 881,858,502.84 |
| 7 | NOK 686,442,878.84 | NOK 838,342,841.50 |
| 8 | NOK 643,853,526.46 | NOK 793,845,781.45 |
| 9 | NOK 600,606,058.02 | NOK 748,206,871.54 |
| 10 | NOK 556,637,484.79 | NOK 701,239,428.09 |
| 11 | NOK 511,878,789.40 | NOK 652,726,246.06 |
| 12 | NOK 466,254,348.75 | NOK 602,414,609.06 |
| 13 | NOK 419,681,301.83 | NOK 550,010,483.52 |
| 14 | NOK 372,068,856.92 | NOK 495,171,763.63 |
| 15 | NOK 323,317,532.59 | NOK 437,500,411.89 |
| 16 | NOK 273,318,325.99 | NOK 376,533,314.75 |
| 17 | NOK 221,951,801.52 | NOK 311,731,643.15 |
| 18 | NOK 169,087,092.31 | NOK 242,468,473.59 |
| 19 | NOK 114,580,806.18 | NOK 168,014,385.43 |
| 20 | NOK 58,275,826.77 | NOK 87,520,703.31 |

Appendix Table I: Parameter C_BASE

| **C_F** Index: *a,l* [NOK] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Levels Attributes** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Oil Boom | 6000000 | 11400000 | 16800000 | 22200000 | 27600000 | 33000000 | -1 | -1 |
| Skimmer | 7000000 | 13300000 | 19600000 | 25900000 | 32200000 | 38500000 | -1 | -1 |
| C.Dispersants | 12000000 | 15600000 | 19200000 | 22800000 | 26400000 | -1 | -1 | -1 |
| Oil Recovery | 6000000 | 7200000 | 8400000 | 9600000 | 10800000 | 12000000 | -1 | -1 |
| Helipad | 20000000 | 30000000 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | 12000000 | 16000000 | 18000000 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | 27000000 | 35000000 | 41000000 | 47000000 | -1 | -1 | -1 | -1 |
| Safe Haven | 12000000 | 16000000 | 19000000 | 21000000 | -1 | -1 | -1 | -1 |
| MOB | 4000000 | 6400000 | 8800000 | 11200000 | 13600000 | -1 | -1 | -1 |
| Radar | 7000000 | 20000000 | 23000000 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | 17000000 | 32300000 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | 6000000 | 7200000 | 8640000 | 10368000 | 12441600 | 14929920 | 17915904 | 21499085 |

Appendix Table II: Parameter C_F

| **C_L** Index: *a,l* [NOK] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Levels Attributes** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Oil Boom | 7200000 | 13680000 | 20160000 | 26640000 | 33120000 | 39600000 | -1 | -1 |
| Skimmer | 8400000 | 15960000 | 23520000 | 31080000 | 38640000 | 46200000 | -1 | -1 |
| C.Dispersants | 14400000 | 18720000 | 23040000 | 27360000 | 31680000 | -1 | -1 | -1 |
| Oil Recovery | 7200000 | 8640000 | 10080000 | 11520000 | 12960000 | 14400000 | -1 | -1 |
| Helipad | 24000000 | 36000000 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | 14400000 | 19200000 | 21600000 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | 32400000 | 42000000 | 49200000 | 56400000 | -1 | -1 | -1 | -1 |
| Safe Haven | 14400000 | 19200000 | 22800000 | 25200000 | -1 | -1 | -1 | -1 |
| MOB | 4800000 | 7680000 | 10560000 | 13440000 | 16320000 | -1 | -1 | -1 |
| Radar | 8400000 | 24000000 | 27600000 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | 20400000 | 38760000 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | 7200000 | 8640000 | 10368000 | 12441600 | 14929920 | 17915904 | 21499085 | 25798902 |

Appendix Table III: Parameter C_L

| **C_A** Index: *a,l,l* [NOK] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Levels Levels** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| **Oil Boom** | | | | | | | | |
| 1 | 0 | 9720000 | 19440000 | 29160000 | 38880000 | 48600000 | -1 | -1 |
| 2 | 1944000 | 0 | 9720000 | 19440000 | 29160000 | 38880000 | -1 | -1 |
| 3 | 3888000 | 1944000 | 0 | 9720000 | 19440000 | 29160000 | -1 | -1 |
| 4 | 5832000 | 3888000 | 1944000 | 0 | 9720000 | 19440000 | -1 | -1 |
| 5 | 7776000 | 5832000 | 3888000 | 1944000 | 0 | 9720000 | -1 | -1 |
| 6 | 9720000 | 7776000 | 5832000 | 3888000 | 1944000 | 0 | -1 | -1 |
| **Skimmer** | | | | | | | | |
| 1 | 0 | 11340000 | 22680000 | 34020000 | 45360000 | 56700000 | -1 | -1 |
| 2 | 2268000 | 0 | 11340000 | 22680000 | 34020000 | 45360000 | -1 | -1 |
| 3 | 4536000 | 2268000 | 0 | 11340000 | 22680000 | 34020000 | -1 | -1 |
| 4 | 6804000 | 4536000 | 2268000 | 0 | 11340000 | 22680000 | -1 | -1 |
| 5 | 9072000 | 6804000 | 4536000 | 2268000 | 0 | 11340000 | -1 | -1 |
| 6 | 11340000 | 9072000 | 6804000 | 4536000 | 2268000 | 0 | -1 | -1 |
| **C. Dispersants** | | | | | | | | |
| 1 | 0 | 6480000 | 12960000 | 19440000 | 25920000 | -1 | -1 | -1 |
| 2 | 1296000 | 0 | 6480000 | 12960000 | 19440000 | -1 | -1 | -1 |
| 3 | 2592000 | 1296000 | 0 | 6480000 | 12960000 | -1 | -1 | -1 |
| 4 | 3888000 | 2592000 | 1296000 | 0 | 6480000 | -1 | -1 | -1 |
| 5 | 5184000 | 3888000 | 2592000 | 1296000 | 0 | -1 | -1 | -1 |
| **Oil Recovery** | | | | | | | | |
| 1 | 0 | 2160000 | 4320000 | 6480000 | 8640000 | 10800000 | -1 | -1 |
| 2 | 432000 | 0 | 2160000 | 4320000 | 6480000 | 8640000 | -1 | -1 |
| 3 | 864000 | 432000 | 0 | 2160000 | 4320000 | 6480000 | -1 | -1 |
| 4 | 1296000 | 864000 | 432000 | 0 | 2160000 | 4320000 | -1 | -1 |
| 5 | 1728000 | 1296000 | 864000 | 432000 | 0 | 2160000 | -1 | -1 |
| 6 | 2160000 | 1728000 | 1296000 | 864000 | 432000 | 0 | -1 | -1 |
| **Helipad** | | | | | | | | |
| 1 | 0 | 18000000 | -1 | -1 | -1 | -1 | -1 | -1 |
| 2 | 3600000 | 0 | -1 | -1 | -1 | -1 | -1 | -1 |
| 1 | 0 | 5760000 | 8640000 | -1 | -1 | -1 | -1 | -1 |
| 2 | 1440000 | 0 | 5760000 | -1 | -1 | -1 | -1 | -1 |
| 3 | 2160000 | 1440000 | 0 | -1 | -1 | -1 | -1 | -1 |
| **Helifuel** | | | | | | | | |
| 1 | 0 | 11520000 | 20160000 | 28800000 | -1 | -1 | -1 | -1 |
| 2 | 2880000 | 0 | 11520000 | 20160000 | -1 | -1 | -1 | -1 |
| **Hosp. Unit** | | | | | | | | |
| 3 | 5040000 | 2880000 | 0 | 11520000 | -1 | -1 | -1 | -1 |
| 4 | 720000 | 5040000 | 2880000 | 0 | -1 | -1 | -1 | -1 |
| **Safe Haven** | | | | | | | | |
| 1 | 0 | 5760000 | 10080000 | 12960000 | -1 | -1 | -1 | -1 |
| 2 | 1440000 | 0 | 5760000 | 10080000 | -1 | -1 | -1 | -1 |
| 3 | 2520000 | 1440000 | 0 | 5760000 | -1 | -1 | -1 | -1 |
| 4 | 3240000 | 2520000 | 1440000 | 0 | -1 | -1 | -1 | -1 |
| **MOB** | | | | | | | | |
| 1 | 0 | 3456000 | 6912000 | 10368000 | 3456000 | -1 | -1 | -1 |
| 2 | 864000 | 0 | 3456000 | 6912000 | 10368000 | -1 | -1 | -1 |
| 3 | 1728000 | 864000 | 0 | 3456000 | 6912000 | -1 | -1 | -1 |
| 4 | 216000 | 1728000 | 864000 | 0 | 3456000 | -1 | -1 | -1 |
| 5 | 864000 | 2592000 | 1728000 | 864000 | 0 | -1 | -1 | -1 |
| **Radar** | | | | | | | | |
| 1 | 0 | 18720000 | 23040000 | -1 | -1 | -1 | -1 | -1 |
| 2 | 4680000 | 0 | 18720000 | -1 | -1 | -1 | -1 | -1 |
| 3 | 5760000 | 4680000 | 0 | -1 | -1 | -1 | -1 | -1 |
| **Fire Fighting** | | | | | | | | |
| 1 | 0 | 22032000 | -1 | -1 | -1 | -1 | -1 | -1 |
| 2 | 5508000 | 0 | -1 | -1 | -1 | -1 | -1 | -1 |
| **Supply** | | | | | | | | |
| 1 | 0 | 1728000 | 3801600 | 6289920 | 9275904 | 12859085 | 17158902 | 22318682 |
| 2 | 432000 | 0 | 1728000 | 3801600 | 6289920 | 9275904 | 12859085 | 17158902 |
| 3 | 950400 | 432000 | 0 | 1728000 | 3801600 | 6289920 | 9275904 | 12859085 |
| 4 | 1572480 | 950400 | 432000 | 0 | 1728000 | 3801600 | 6289920 | 9275904 |
| 5 | 2318976 | 1572480 | 950400 | 432000 | 0 | 1728000 | 3801600 | 6289920 |
| 6 | 3214771 | 2318976 | 1572480 | 950400 | 432000 | 0 | 1728000 | 3801600 |
| 7 | 4289725 | 3214771 | 2318976 | 1572480 | 950400 | 432000 | 0 | 1728000 |
| 8 | 5579671 | 4289725 | 3214771 | 2318976 | 1572480 | 950400 | 432000 | 0 |

Appendix Table IV: Parameter C_A

| **C_O** Index: *a,l* [NOK] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Levels Attributes** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Oil Boom | 7000000 | 8400000 | 10080000 | 12096000 | 14515200 | 17418240 | -1 | -1 |
| Skimmer | 9000000 | 10800000 | 12960000 | 15552000 | 18662400 | 22394880 | -1 | -1 |
| C.Dispersants | 8000000 | 9600000 | 11520000 | 13824000 | 16588800 | 19906560 | -1 | -1 |
| Oil Recovery | 6500000 | 8450000 | 10985000 | 14280500 | 18564650 | 24134045 | -1 | -1 |
| Helipad | 4000000 | 6000000 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | 3000000 | 3600000 | 4320000 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | 14000000 | 16800000 | 20160000 | 24192000 | -1 | -1 | -1 | -1 |
| Safe Haven | 9000000 | 9900000 | 10890000 | 11979000 | -1 | -1 | -1 | -1 |
| MOB | 2800000 | 3360000 | 4032000 | 4838400 | 5806080 | -1 | -1 | -1 |
| Radar | 3000000 | 3600000 | 4320000 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | 7000000 | 10500000 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | -2000000 | -4000000 | -6000000 | -8000000 | -10000000 | -12000000 | -14000000 | 0 |

Appendix Table V: Parameter C_O

| **G_O** Index: *e,q* [NOK] | | | | |
|---|---|---|---|---|
| **Shared Emergency Prep** | 1 | 2 | 3 | 4 |
| ORO | 0 | 1400000 | 2520000 | 4536000 |
| RESC | 0 | 1800000 | 2700000 | -1 |
| HELI | 0 | 1500000 | -1 | -1 |

Appendix Table VI: Parameter G_O

| **R_UNITS** Index: *a,l,t* | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Periods Levels** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| **Oil Boom** | | | | | | | | | | | | | | | | | | | | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| **Skimmer** | | | | | | | | | | | | | | | | | | | | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| **C.Dispersants** | | | | | | | | | | | | | | | | | | | | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| **Oil Recovery** | | | | | | | | | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Helipad** | | | | | | | | | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Helifuel** | | | | | | | | | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Hosp. Unit** | | | | | | | | | | | | | | | | | | | | |
| 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 |
| 2 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Safe haven** | | | | | | | | | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **MOB** | | | | | | | | | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 |
| 2 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | -1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Radar** | | | | | | | | | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 |
| 2 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Fire Fighting** | | | | | | | | | | | | | | | | | | | | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Supply** | | | | | | | | | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Appendix Table VII: Parameter R_UNIT

| **R_TOTAL** Index: *a,t* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Attributes/Periods** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Oil Boom [units] | 1 | 1 | 1 | 3 | 3 | 3 | 5 | 5 | 5 | 7 |
| Skimmer [units] | 1 | 1 | 1 | 2 | 2 | 2 | 4 | 4 | 4 | 6 |
| C.Dispersants [$m^3$] | 50 | 50 | 50 | 50 | 100 | 100 | 100 | 300 | 350 | 400 |
| Oil Recovery [$m^3$] | 0 | 0 | 0 | 4130 | 4130 | 4130 | 4800 | 4800 | 4800 | 4800 |
| Helipad | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Safe Haven [people] | 0 | 0 | 0 | 0 | 0 | 0 | 400 | 400 | 500 | 600 |
| MOB [units] | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 4 | 6 | 6 |
| Radar | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |

| **Attributes/Periods** | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| Oil Boom [units] | 9 | 9 | 9 | 7 | 7 | 7 | 4 | 4 | 2 | 2 |
| Skimmer [units] | 7 | 7 | 7 | 7 | 7 | 7 | 5 | 5 | 3 | 3 |
| C.Dispersants [$m^3$] | 400 | 400 | 400 | 400 | 400 | 350 | 300 | 300 | 300 | 300 |
| Oil Recovery [$m^3$] | 4800 | 4800 | 4800 | 4800 | 4800 | 4800 | 4800 | 4800 | 4800 | 4800 |
| Helipad | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Safe Haven [people] | 600 | 800 | 1000 | 1000 | 1000 | 1000 | 800 | 600 | 600 | 600 |
| MOB [units] | 8 | 8 | 10 | 12 | 12 | 12 | 8 | 8 | 4 | 4 |
| Radar | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |

Appendix Table VIII: Parameter R_TOTAL

| **K** Index: *a,l* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Attributes/Levels** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Oil Boom [units] | 1 | 2 | 3 | 4 | 5 | 6 | -1 | -1 |
| Skimmer [units] | 1 | 2 | 3 | 4 | 5 | 6 | -1 | -1 |
| C.Dispersants [$m^3$] | 50 | 100 | 150 | 200 | 250 | -1 | -1 | -1 |
| Oil Recovery [$m^3$] | 1000 | 1500 | 2000 | 25000 | 166383 | 336032 | -1 | -1 |
| Helipad | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel [$m^3$] | 5 | 10 | 20 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit [people] | 10 | 15 | 20 | 30 | -1 | -1 | -1 | -1 |
| Safe Haven [people] | 100 | 200 | 300 | 400 | -1 | -1 | -1 | -1 |
| MOB [units] | 1 | 2 | 3 | 4 | 5 | -1 | -1 | -1 |
| Radar | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |

Appendix Table IX: Parameter K

| **Attribute** | $\mathbf{P_a}$ |
|---|---|
| Oil Boom | 0.59 |
| Skimmer | 0.59 |
| C.Dispersants | 0.58 |
| Oil Recovery | 0.60 |
| Safe Haven | 0.72 |
| MOB | 0.69 |

Appendix Table X: Parameter P

| F_ERRV Index: *v,a,l* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Levels Attributes** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| **Stril Herkules** | | | | | | | | |
| Oil Boom | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Skimmer | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| C.Dispersants | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Oil Recovery | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Helipad | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Helifuel | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Hosp. Unit | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Safe Haven | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| MOB | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Radar | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Fire Fighting | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Supply | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Stril Mariner** | | | | | | | | |
| Oil Boom | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Skimmer | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C.Dispersants | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oil Recovery | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Helipad | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Helifuel | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Hosp. Unit | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Safe Haven | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| MOB | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Radar | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fire Fighting | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Supply | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Appendix Table XI: Parameter F_ERRV

| F_BASE Index: *a,l* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Attributes/Levels** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| **Front Brabant** | | | | | | | | |
| Oil Boom | 1 | 1 | 1 | 1 | 1 | 0 | -1 | -1 |
| Skimmer | 1 | 1 | 1 | 1 | 1 | 0 | -1 | -1 |
| C.Dispersants | 1 | 1 | 1 | 1 | 0 | -1 | -1 | -1 |
| Oil Recovery | 1 | 1 | 1 | 1 | 1 | 0 | -1 | -1 |
| Helipad | 1 | 1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | 1 | 1 | 1 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | 1 | 1 | 1 | 0 | -1 | -1 | -1 | -1 |
| Safe Haven | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 |
| MOB | 1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 |
| Radar | 1 | 1 | 0 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | 0 | 0 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Front Champion** | | | | | | | | |
| Oil Boom | 1 | 1 | 1 | 1 | 1 | 1 | -1 | -1 |
| Skimmer | 1 | 1 | 1 | 1 | 1 | 1 | -1 | -1 |
| C.Dispersants | 1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 |
| Oil Recovery | 1 | 1 | 1 | 1 | 1 | 1 | -1 | -1 |
| Helipad | 1 | 1 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | 1 | 1 | 1 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 |
| Safe Haven | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 |
| MOB | 1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 |
| Radar | 1 | 1 | 0 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | 0 | 0 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Appendix Table XII: Parameter F_BASE

| S_DECK [$m^2$] | S_VOL [$m^3$] | S_ACC [$m^2$] |
|---|---|---|
| **Front Brabant** | | |
| 5000 | 166383 | 500 |
| **Front Champion** | | |
| 8000 | 336032 | 700 |

Appendix Table XIII: Parameter S

| **U_DECK** Index: *a,l* [m²] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Attributes/Levels** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Oil Boom | 100 | 180 | 260 | 340 | 420 | 500 | -1 | -1 |
| Skimmer | 80 | 144 | 208 | 272 | 336 | 400 | -1 | -1 |
| C.Dispersants | 50 | 50 | 50 | 50 | 50 | -1 | -1 | -1 |
| Oil Recovery | 100 | 100 | 100 | 100 | 100 | 100 | -1 | -1 |
| Helipad | 400 | 600 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | 100 | 150 | 200 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | 0 | 0 | 0 | 0 | -1 | -1 | -1 | -1 |
| Safe Haven | 0 | 0 | 0 | 0 | -1 | -1 | -1 | -1 |
| MOB | 150 | 300 | 450 | 600 | 750 | -1 | -1 | -1 |
| Radar | 0 | 0 | 0 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | 100 | 200 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 |

Appendix Table XIV: Parameter U_DECK

| **U_VOL** Index: *a,l* [m³] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Attributes/Levels** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Oil Boom | 0 | 0 | 0 | 0 | 0 | 0 | -1 | -1 |
| Skimmer | 0 | 0 | 0 | 0 | 0 | 0 | -1 | -1 |
| C.Dispersants | 50 | 100 | 150 | 200 | 250 | -1 | -1 | -1 |
| Oil Recovery | 1000 | 1500 | 2000 | 2500 | 166383 | 336032 | -1 | -1 |
| Helipad | 0 | 0 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | 100 | 200 | 300 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | 0 | 0 | 0 | 0 | -1 | -1 | -1 | -1 |
| Safe Haven | 0 | 0 | 0 | 0 | -1 | -1 | -1 | -1 |
| MOB | 0 | 0 | 0 | 0 | 0 | -1 | -1 | -1 |
| Radar | 0 | 0 | 0 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | 0 | 0 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | 100 | 100 | 200 | 200 | 300 | 300 | 400 | 400 |

Appendix Table XV: Parameter U_VOL

| **U_ACC** Index: *a,l* [m²] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Attributes/Levels** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Oil Boom | 20 | 20 | 20 | 40 | 40 | 40 | -1 | -1 |
| Skimmer | 20 | 20 | 20 | 40 | 40 | 40 | -1 | -1 |
| C.Dispersants | 0 | 0 | 0 | 0 | 0 | -1 | -1 | -1 |
| Oil Recovery | 20 | 20 | 20 | 40 | 40 | 40 | -1 | -1 |
| Helipad | 50 | 50 | -1 | -1 | -1 | -1 | -1 | -1 |
| Helifuel | 0 | 0 | 0 | -1 | -1 | -1 | -1 | -1 |
| Hosp. Unit | 50 | 80 | 110 | 130 | -1 | -1 | -1 | -1 |
| Safe Haven | 100 | 200 | 300 | 400 | -1 | -1 | -1 | -1 |
| MOB | 0 | 0 | 0 | 0 | 0 | -1 | -1 | -1 |
| Radar | 0 | 0 | 0 | -1 | -1 | -1 | -1 | -1 |
| Fire Fighting | 0 | 0 | -1 | -1 | -1 | -1 | -1 | -1 |
| Supply | 100 | 100 | 200 | 200 | 300 | 300 | 400 | 400 |

Appendix Table XVI: Parameter U_ACC

| **I** Index: *q* |
|---|
| 1 |
| 2 |
| 3 |
| 4 |

Appendix Table XVII: Parameter I

# D. Scenario Development

| Year | Exploration Drilling | Discovery | Location |
|---|---|---|---|
| 2017 | Yes | (Gas) 100 bill Sm3 | 70°N, 08°E |
| 2018 | Yes | No | |
| 2019 | Yes | No | |
| 2020 | Yes | (Oil) 40 mill Sm3 | 69°N, 08°E |
| 2021 | Yes | No | |
| 2022 | Yes | No | |
| 2023 | Yes | (Oil) 40 mill Sm3 | 71°N, 09°E |
| 2024 | Yes | No | |
| 2025 | Yes | No | |
| 2026 | Yes | No | |
| 2027 | Yes | No | |

Appendix Table XVIII: Scenario Jan Mayen. Exploration drilling

| **NOFO systems calculations 71°N, 09°E**<br>**Parameter** | **Jun-Aug Summer 15°C, 5 m/s wind** | **Dec-Feb Winter 5°C, 10 m/s wind** |
|---|---|---|
| Dispersion rate (Sm3/d) | 1500 | 1500 |
| Evaporation after 2 hours at sea (%) | 17.00% | 15.00% |
| Mix after 2 hours at sea (%) | 13% | 8% |
| Oil available for emulsification (Sm3/d) | 1050 | 1155 |
| Water absorption after 2 hours on sea (%) | 50% | 8% |
| Emulsion amount for oil residue recuperation (Sm3/d) | 2100 | 1255 |
| **Requirement for NOFO-systems in barrier 1** | 0.88<br>**1** | 0.52<br>**1** |
| System effectiveness, barrier 1 (%) | 40% | 20% |
| Emulsion amount to barrier 2 (Sm3/d) | 1260 | 1004 |
| Oil residue to barrier 2 (Sm3/d) | 630 | 924 |
| Evaporation (%) | 19% | 12% |
| Mix (%) | 19% | 0% |
| Oil available for emulsification (Sm3/d) | 391 | 813 |
| Water absorption after 12 hours on sea (%) | 50% | 1% |
| Emulsion amount for oil residue recuperation (Sm3/d) | 781 | 821 |
| **Requirement for NOFO-systems in barrier 2** | 0.33<br>**1** | 0.34<br>**1** |

Appendix Table XIX: NOFO System calculations for location 71°N, 09°E

| **NOFO systems calculations 69°N, 08°E**<br><br>**Parameter** | **Jun-Aug**<br>**Summer**<br>**15°C, 5 m/s wind** | **Dec-Feb**<br>**Winter**<br>**5°C, 10 m/s wind** |
|---|---|---|
| Dispersion rate (Sm3/d) | 1500 | 1500 |
| Evaporation after 2 hours at sea (%) | 17.00% | 15.00% |
| Mix after 2 hours at sea (%) | 13% | 8% |
| Oil available for emulsification (Sm3/d) | 1050 | 1155 |
| Water absorption after 2 hours on sea (%) | 50% | 8% |
| Emulsion amount for oil residue recuperation (Sm3/d) | 2100 | 1255 |
| **Requirement for NOFO-systems in barrier 1** | 0.88<br>**1** | 0.52<br>**1** |
| System effectiveness, barrier 1 (%) | 40% | 20% |
| Emulsion amount to barrier 2 (Sm3/d) | 1260 | 1004 |
| Oil residue to barrier 2 (Sm3/d) | 630 | 924 |
| Evaporation (%) | 22% | 20% |
| Mix (%) | 48.00% | 40.00% |
| Oil available for emulsification (Sm3/d) | 189 | 370 |
| Water absorption after 12 hours on sea (%) | 50% | 31% |
| Emulsion amount for oil residue recuperation (Sm3/d) | 378 | 536 |
| **Requirement for NOFO-systems in barrier 2** | 0.16<br>**1** | 0.22<br>**1** |

Appendix Table XX: NOFO system calculations for location 69°N, 08°E

# E. Results

## Front Brabant

z(Oil Boom, Level 2, Period 10) = 1
z(Skimmer, Level 2, Period 11) = 1
z(Skimmer, Level 2, Period 12) = 1
z(Skimmer, Level 2, Period 13) = 1
z(Skimmer, Level 2, Period 14) = 1
z(Skimmer, Level 2, Period 15) = 1
z(Skimmer, Level 2, Period 16) = 1
z(Skimmer, Level 2, Period 17) = 1
z(Skimmer, Level 2, Period 18) = 1
z(Skimmer, Level 4, Period 10) = 1
z(C.Dispersants, Level 3, Period 9) = 1
z(C.Dispersants, Level 4, Period 10) = 1
z(Oil Recovery, Level 2, Period 7) = 1
z(Oil Recovery, Level 2, Period 8) = 1
z(Oil Recovery, Level 2, Period 9) = 1
z(Oil Recovery, Level 2, Period 10) = 1
z(Oil Recovery, Level 2, Period 17) = 1
z(Oil Recovery, Level 2, Period 18) = 1
z(Oil Recovery, Level 2, Period 19) = 1
z(Oil Recovery, Level 2, Period 20) = 1
z(Oil Recovery, Level 4, Period 4) = 1
z(Oil Recovery, Level 4, Period 5) = 1
z(Oil Recovery, Level 4, Period 6) = 1
z(Safe Haven, Level 2, Period 13) = 1
z(Safe Haven, Level 2, Period 14) = 1
z(Safe Haven, Level 2, Period 15) = 1
z(Safe Haven, Level 2, Period 16) = 1
z(Safe Haven, Level 3, Period 17) = 1
z(MOB, Level 1, Period 5) = 1
z(MOB, Level 1, Period 6) = 1
z(MOB, Level 1, Period 12) = 1
z(MOB, Level 3, Period 17) = 1
z(MOB, Level 3, Period 18) = 1
z(MOB, Level 5, Period 13) = 1
z(MOB, Level 5, Period 14) = 1
z(MOB, Level 5, Period 15) = 1
z(MOB, Level 5, Period 16) = 1

z(Radar, Level 1, Period 5) = 1
z(Radar, Level 1, Period 6) = 1
z(Supply, Level 2, Period 17) = 1
z(Supply, Level 4, Period 13) = 1
z(Supply, Level 4, Period 14) = 1
z(Supply, Level 4, Period 15) = 1
z(Supply, Level 4, Period 16) = 1
z(Supply, Level 7, Period 18) = 1
z(Supply, Level 8, Period 4) = 1
z(Supply, Level 8, Period 5) = 1
z(Supply, Level 8, Period 6) = 1
z(Supply, Level 8, Period 7) = 1
z(Supply, Level 8, Period 8) = 1
z(Supply, Level 8, Period 9) = 1
z(Supply, Level 8, Period 10) = 1
z(Supply, Level 8, Period 11) = 1
z(Supply, Level 8, Period 12) = 1
z(Supply, Level 8, Period 19) = 1
z(Supply, Level 8, Period 20) = 1

b(Oil Recovery, Level 4) = 1
b(Supply, Level 8) = 1

m(Oil Boom, Level 2, Period 10) = 1
m(Skimmer, Level 4, Period 10) = 1

## Front Champion

z(Oil Boom, Level 6, Period 10) = 1
z(Oil Boom, Level 6, Period 11) = 1
z(Oil Boom, Level 6, Period 12) = 1
z(Skimmer, Level 2, Period 13) = 1
z(Skimmer, Level 2, Period 14) = 1
z(Skimmer, Level 2, Period 15) = 1
z(Skimmer, Level 2, Period 16) = 1
z(Skimmer, Level 2, Period 17) = 1
z(Skimmer, Level 2, Period 18) = 1
z(Skimmer, Level 5, Period 10) = 1
z(Skimmer, Level 6, Period 11) = 1
z(Skimmer, Level 6, Period 12) = 1
z(C.Dispersants, Level 4, Period 9) = 1
z(C.Dispersants, Level 4, Period 10) = 1
z(C.Dispersants, Level 4, Period 11) = 1
z(C.Dispersants, Level 4, Period 12) = 1
z(Oil Recovery, Level 2, Period 7) = 1
z(Oil Recovery, Level 2, Period 8) = 1
z(Oil Recovery, Level 2, Period 9) = 1
z(Oil Recovery, Level 2, Period 10) = 1
z(Oil Recovery, Level 2, Period 11) = 1
z(Oil Recovery, Level 2, Period 12) = 1
z(Oil Recovery, Level 2, Period 17) = 1
z(Oil Recovery, Level 2, Period 18) = 1
z(Oil Recovery, Level 2, Period 19) = 1
z(Oil Recovery, Level 2, Period 20) = 1
z(Oil Recovery, Level 4, Period 4) = 1
z(Oil Recovery, Level 4, Period 5) = 1
z(Oil Recovery, Level 4, Period 6) = 1
z(Safe Haven, Level 2, Period 13) = 1
z(Safe Haven, Level 2, Period 14) = 1
z(Safe Haven, Level 2, Period 15) = 1
z(Safe Haven, Level 2, Period 16) = 1
z(Safe Haven, Level 3, Period 12) = 1
z(Safe Haven, Level 3, Period 17) = 1
z(MOB, Level 1, Period 5) = 1
z(MOB, Level 1, Period 6) = 1
z(MOB, Level 1, Period 10) = 1
z(MOB, Level 3, Period 17) = 1
z(MOB, Level 3, Period 18) = 1
z(MOB, Level 5, Period 11) = 1
z(MOB, Level 5, Period 12) = 1
z(MOB, Level 5, Period 13) = 1
z(MOB, Level 5, Period 14) = 1
z(MOB, Level 5, Period 15) = 1
z(MOB, Level 5, Period 16) = 1
z(Radar, Level 1, Period 5) = 1
z(Radar, Level 1, Period 6) = 1
z(Supply, Level 6, Period 4) = 1
z(Supply, Level 6, Period 5) = 1
z(Supply, Level 6, Period 12) = 1
z(Supply, Level 6, Period 17) = 1
z(Supply, Level 7, Period 6) = 1
z(Supply, Level 8, Period 7) = 1
z(Supply, Level 8, Period 8) = 1
z(Supply, Level 8, Period 9) = 1
z(Supply, Level 8, Period 10) = 1
z(Supply, Level 8, Period 11) = 1
z(Supply, Level 8, Period 13) = 1
z(Supply, Level 8, Period 14) = 1
z(Supply, Level 8, Period 15) = 1
z(Supply, Level 8, Period 16) = 1
z(Supply, Level 8, Period 18) = 1

m(C.Dispersants, Level 3, Period 9) = 1
m(Oil Recovery, Level 2, Period 17) = 1
m(Safe Haven, Level 2, Period 13) = 1
m(MOB, Level 1, Period 5) = 1
m(MOB, Level 1, Period 12) = 1
m(Radar, Level 1, Period 5) = 1

w(Skimmer, Level 2, Level´ 2, Period 12) = 1
w(Skimmer, Level 2, Level´ 2, Period 13) = 1
w(Skimmer, Level 2, Level´ 2, Period 14) = 1
w(Skimmer, Level 2, Level´ 2, Period 15) = 1
w(Skimmer, Level 2, Level´ 2, Period 16) = 1
w(Skimmer, Level 2, Level´ 2, Period 17) = 1
w(Skimmer, Level 2, Level´ 2, Period 18) = 1
w(Skimmer, Level 4, Level´ 2, Period 11) = 1
w(C.Dispersants, Level 3, Level´ 4, Period 10) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 8) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 9) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 10) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 18) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 19) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 20) = 1
w(Oil Recovery, Level 4, Level´ 2, Period 7) = 1
w(Oil Recovery, Level 4, Level´ 4, Period 5) = 1
w(Oil Recovery, Level 4, Level´ 4, Period 6) = 1
w(Safe Haven, Level 2, Level´ 2, Period 14) = 1
w(Safe Haven, Level 2, Level´ 2, Period 15) = 1
w(Safe Haven, Level 2, Level´ 2, Period 16) = 1
w(Safe Haven, Level 2, Level´ 3, Period 17) = 1
w(MOB, Level 1, Level´ 1, Period 6) = 1
w(MOB, Level 1, Level´ 5, Period 13) = 1
w(MOB, Level 3, Level´ 3, Period 18) = 1
w(MOB, Level 5, Level´ 3, Period 17) = 1
w(MOB, Level 5, Level´ 5, Period 14) = 1
w(MOB, Level 5, Level´ 5, Period 15) = 1
w(MOB, Level 5, Level´ 5, Period 16) = 1
w(Radar, Level 1, Level´ 1, Period 6) = 1
w(Supply, Level 2, Level´ 7, Period 18) = 1
w(Supply, Level 4, Level´ 2, Period 17) = 1
w(Supply, Level 4, Level´ 4, Period 14) = 1
w(Supply, Level 4, Level´ 4, Period 15) = 1
w(Supply, Level 4, Level´ 4, Period 16) = 1
w(Supply, Level 7, Level´ 8, Period 19) = 1
w(Supply, Level 8, Level´ 4, Period 13) = 1
w(Supply, Level 8, Level´ 8, Period 5) = 1
w(Supply, Level 8, Level´ 8, Period 6) = 1
w(Supply, Level 8, Level´ 8, Period 7) = 1
w(Supply, Level 8, Level´ 8, Period 8) = 1
w(Supply, Level 8, Level´ 8, Period 9) = 1
w(Supply, Level 8, Level´ 8, Period 10) = 1
w(Supply, Level 8, Level´ 8, Period 11) = 1
w(Supply, Level 8, Level´ 8, Period 12) = 1
w(Supply, Level 8, Level´ 8, Period 20) = 1

y(Stril Herkules, Period 4) = 1
y(Stril Herkules, Period 5) = 1
y(Stril Herkules, Period 6) = 1
y(Stril Herkules, Period 7) = 2
y(Stril Herkules, Period 8) = 2
y(Stril Herkules, Period 9) = 2
y(Stril Herkules, Period 10) = 2
y(Stril Herkules, Period 11) = 3
y(Stril Herkules, Period 12) = 3
y(Stril Herkules, Period 13) = 3
y(Stril Herkules, Period 14) = 3
y(Stril Herkules, Period 15) = 3
y(Stril Herkules, Period 16) = 3
y(Stril Herkules, Period 17) = 2
y(Stril Herkules, Period 18) = 2
y(Stril Herkules, Period 19) = 2
y(Stril Herkules, Period 20) = 2
y(Stril Mariner, Period 1) = 1
y(Stril Mariner, Period 2) = 1
y(Stril Mariner, Period 3) = 1

h(ORO, Period 9, Shared 2) = 1
h(ORO, Period 10, Shared 4) = 1

z(Supply, Level 8, Period 19) = 1
z(Supply, Level 8, Period 20) = 1

b(Oil Recovery, Level 4) = 1
b(Supply, Level 6) = 1

m(Oil Boom, Level 6, Period 10) = 1
m(Skimmer, Level 5, Period 10) = 1
m(C.Dispersants, Level 4, Period 9) = 1
m(Oil Recovery, Level 2, Period 17) = 1
m(Safe Haven, Level 3, Period 12) = 1
m(MOB, Level 1, Period 5) = 1
m(MOB, Level 1, Period 10) = 1
m(Radar, Level 1, Period 5) = 1

w(Oil Boom, Level 6, Level´ 6, Period 11) = 1
w(Oil Boom, Level 6, Level´ 6, Period 12) = 1
w(Skimmer, Level 2, Level´ 2, Period 14) = 1
w(Skimmer, Level 2, Level´ 2, Period 15) = 1
w(Skimmer, Level 2, Level´ 2, Period 16) = 1
w(Skimmer, Level 2, Level´ 2, Period 17) = 1
w(Skimmer, Level 2, Level´ 2, Period 18) = 1
w(Skimmer, Level 5, Level´ 6, Period 11) = 1
w(Skimmer, Level 6, Level´ 2, Period 13) = 1
w(Skimmer, Level 6, Level´ 6, Period 12) = 1
w(C.Dispersants, Level 4, Level´ 4, Period 10) = 1
w(C.Dispersants, Level 4, Level´ 4, Period 11) = 1
w(C.Dispersants, Level 4, Level´ 4, Period 12) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 8) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 9) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 10) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 11) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 12) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 18) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 19) = 1
w(Oil Recovery, Level 2, Level´ 2, Period 20) = 1
w(Oil Recovery, Level 4, Level´ 2, Period 7) = 1
w(Oil Recovery, Level 4, Level´ 4, Period 5) = 1
w(Oil Recovery, Level 4, Level´ 4, Period 6) = 1
w(Safe Haven, Level 2, Level´ 2, Period 14) = 1
w(Safe Haven, Level 2, Level´ 2, Period 15) = 1
w(Safe Haven, Level 2, Level´ 2, Period 16) = 1
w(Safe Haven, Level 2, Level´ 3, Period 17) = 1
w(Safe Haven, Level 3, Level´ 2, Period 13) = 1
w(MOB, Level 1, Level´ 1, Period 6) = 1
w(MOB, Level 1, Level´ 5, Period 11) = 1
w(MOB, Level 3, Level´ 3, Period 18) = 1
w(MOB, Level 5, Level´ 3, Period 17) = 1
w(MOB, Level 5, Level´ 5, Period 12) = 1
w(MOB, Level 5, Level´ 5, Period 13) = 1
w(MOB, Level 5, Level´ 5, Period 14) = 1
w(MOB, Level 5, Level´ 5, Period 15) = 1
w(MOB, Level 5, Level´ 5, Period 16) = 1
w(Radar, Level 1, Level´ 1, Period 6) = 1
w(Supply, Level 6, Level´ 6, Period 5) = 1
w(Supply, Level 6, Level´ 7, Period 6) = 1
w(Supply, Level 6, Level´ 8, Period 13) = 1
w(Supply, Level 6, Level´ 8, Period 18) = 1
w(Supply, Level 7, Level´ 8, Period 7) = 1
w(Supply, Level 8, Level´ 6, Period 12) = 1
w(Supply, Level 8, Level´ 6, Period 17) = 1
w(Supply, Level 8, Level´ 8, Period 8) = 1
w(Supply, Level 8, Level´ 8, Period 9) = 1
w(Supply, Level 8, Level´ 8, Period 10) = 1
w(Supply, Level 8, Level´ 8, Period 11) = 1
w(Supply, Level 8, Level´ 8, Period 14) = 1
w(Supply, Level 8, Level´ 8, Period 15) = 1
w(Supply, Level 8, Level´ 8, Period 16) = 1
w(Supply, Level 8, Level´ 8, Period 19) = 1
w(Supply, Level 8, Level´ 8, Period 20) = 1

y(Stril Herkules, Period 4) = 1
y(Stril Herkules, Period 5) = 1
y(Stril Herkules, Period 6) = 1
y(Stril Herkules, Period 7) = 2
y(Stril Herkules, Period 8) = 2
y(Stril Herkules, Period 9) = 2

h(ORO, Period 17, Shared 2) = 1
h(ORO, Period 18, Shared 2) = 1
h(RESC, Period 13, Shared 2) = 1
h(RESC, Period 14, Shared 2) = 1
h(RESC, Period 15, Shared 2) = 1
h(RESC, Period 16, Shared 2) = 1
h(RESC, Period 17, Shared 2) = 1

y(Stril Herkules, Period 10) = 2
y(Stril Herkules, Period 11) = 2
y(Stril Herkules, Period 12) = 2
y(Stril Herkules, Period 13) = 3
y(Stril Herkules, Period 14) = 3
y(Stril Herkules, Period 15) = 3
y(Stril Herkules, Period 16) = 3
y(Stril Herkules, Period 17) = 2
y(Stril Herkules, Period 18) = 2
y(Stril Herkules, Period 19) = 2
y(Stril Herkules, Period 20) = 2
y(Stril Mariner, Period 1) = 1
y(Stril Mariner, Period 2) = 1
y(Stril Mariner, Period 3) = 1
h(ORO, Period 9, Shared 2) = 1
h(ORO, Period 10, Shared 4) = 1
h(ORO, Period 11, Shared 4) = 1
h(ORO, Period 12, Shared 4) = 1
h(ORO, Period 17, Shared 2) = 1
h(ORO, Period 18, Shared 2) = 1
h(RESC, Period 12, Shared 2) = 1
h(RESC, Period 13, Shared 2) = 1
h(RESC, Period 14, Shared 2) = 1
h(RESC, Period 15, Shared 2) = 1
h(RESC, Period 16, Shared 2) = 1
h(RESC, Period 17, Shared 2) = 1

Appendix Table XXI: (Xpress) Nonzero binary and integer variables for case study

y(Stril Herkules, Period 4) = 2
y(Stril Herkules, Period 5) = 2
y(Stril Herkules, Period 6) = 2
y(Stril Herkules, Period 7) = 2
y(Stril Herkules, Period 8) = 2
y(Stril Herkules, Period 9) = 2
y(Stril Herkules, Period 10) = 3
y(Stril Herkules, Period 11) = 3
y(Stril Herkules, Period 12) = 3
y(Stril Herkules, Period 13) = 3
y(Stril Herkules, Period 14) = 4
y(Stril Herkules, Period 15) = 4
y(Stril Herkules, Period 16) = 4
y(Stril Herkules, Period 17) = 2
y(Stril Herkules, Period 18) = 2
y(Stril Herkules, Period 19) = 2
y(Stril Herkules, Period 20) = 2

y(Stril Mariner, Period 1) = 1
y(Stril Mariner, Period 2) = 1
y(Stril Mariner, Period 3) = 1
y(Stril Mariner, Period 4) = 1
y(Stril Mariner, Period 5) = 1
y(Stril Mariner, Period 6) = 1
y(Stril Mariner, Period 7) = 1
y(Stril Mariner, Period 8) = 1
y(Stril Mariner, Period 9) = 1
y(Stril Mariner, Period 11) = 1
y(Stril Mariner, Period 12) = 1
y(Stril Mariner, Period 13) = 1
y(Stril Mariner, Period 17) = 1
y(Stril Mariner, Period 18) = 1
y(Stril Mariner, Period 19) = 1
y(Stril Mariner, Period 20) = 1

Appendix Table XXII: (Xpress) Nonzero variables when no standby base

# F. Extended Model Results

| Front Champion | | | | |
|---|---|---|---|---|
| Weights | TOTAL COSTS [NOK] | | | Capacity Recovered oil [$m^3$] |
| $\alpha$ | Total Cost | Standby Base | Standby Vessels | |
| 1 | 5893434745 | 1399434745 | 4494000000 | 587149 |
| 0.5 | 5893867705 | 1399867705 | 4494000000 | 587149 |
| 0.1 | 5894945145 | 1400945145 | 4494000000 | 587149 |
| 0.02 | 5895806265 | 1401806265 | 4494000000 | 587149 |
| 0.015 | 5953917574 | 1459917574 | 4494000000 | 1412064 |
| 0.01 | 6071958424 | 1577958424 | 4494000000 | 2901511 |
| 0.005 | 6312245321 | 1818245321 | 4494000000 | 4937299 |
| 0.001 | 6762082035 | 1810082035 | 4952000000 | 6800640 |
| 0.0005 | 6762082038 | 1810082038 | 4952000000 | 6800640 |
| 0.0001 | 6763882038 | 1811882038 | 4952000000 | 6800640 |
| 0.00005 | 6762082038 | 1810082038 | 4952000000 | 6800640 |
| 0.00004 | 6860972038 | 1820972038 | 5040000000 | 6804640 |
| 0.00003 | 6850082032 | 1810082032 | 5040000000 | 6804640 |
| 0.00002 | 7823599718 | 1583599718 | 6240000000 | 6824640 |
| | | | | |
| **Front Brabant** | | | | |
| Weights | TOTAL COSTS [NOK] | | | Capacity Recovered oil [$m^3$] |
| $\alpha$ | Total Cost | Standby Base | Standby Vessels | |
| 1 | 5828811803 | 1094811803 | 4734000000 | 164000 |
| 0.5 | 5852558821 | 1118558821 | 4734000000 | 164000 |
| 0.1 | 5852558821 | 1118558821 | 4734000000 | 164000 |
| 0.02 | 5852558821 | 1118558821 | 4734000000 | 164000 |
| 0.015 | 5852558821 | 1118558821 | 4734000000 | 164000 |
| 0.01 | 5912404944 | 1178404944 | 4734000000 | 447266 |
| 0.005 | 6164072019 | 1430072019 | 4734000000 | 2481362 |
| 0.001 | 6488844459 | 1536844459 | 4952000000 | 3407660 |
| 0.0005 | 6492761595 | 1540761595 | 4952000000 | 3407660 |
| 0.0001 | 6494146323 | 1542146323 | 4952000000 | 3407660 |
| 0.00005 | 6487002290 | 1535002290 | 4952000000 | 3407660 |
| 0.00004 | 6591932008 | 1551932008 | 5040000000 | 3411660 |
| 0.00003 | 6582165904 | 1542165904 | 5040000000 | 3411660 |
| 0.00002 | 7240957717 | 1360957717 | 5880000000 | 3425660 |

Appendix Table XXIII: Results from the case study with the extended model

# G. FICO™ Xpress Model

```
(!
This FICO Xpress model is developed for finding preliminary design parameters for a stand-
by base. The model considers a scenario for petroleum development in a remote region and
finds the optimal basic design and attributes of a stand-by base complimented by a dynamic
fleet of stand-by vessels.

This model consists of both the original model developed and the model extension
consisting of a weighted multi-objective function. The rows in the model unique to the
original model and the model extension is given either "(!1!) or (!2!) respectively on the
rights side of the row. The model is connected to a MS Excel sheet from where input data
is gathered and output results are written.

Developer: Even Sunde Andresen, Marin Teknikk, NTNU
!)

model OptimalDesignStandbyBase
uses "mmodbc", "mmxprs"; !gain access to MS Excel and the Xpress-Optimizer solver

options explterm
!This option means that all lines must end with a ;
options noimplicit
!This option means that everything must be declared before it is used

!Declairing the sets and indexes
declarations
    Vessels:        set of string;
    EmergencyPrep:  set of string;
    Attributes:     set of string;
    Levels:         set of integer;
    A1:             set of string;
    A2:             set of string;
    A3:             set of string;  (!2!)
    AORO:           set of string;
    ARESC:          set of string;
    AHELI:          set of string;
    Periods:        set of integer;
    Shared:         set of integer;
    Totvessels:     set of integer;

    nVessels:                                  integer;
    nLevels:            array(Attributes) of integer;
    nMaxlevels:                                integer;
    nPeriods:                                  integer;
    nShared:         array(EmergencyPrep) of integer;
    nMaxshared:                                integer;
end-declarations

!Read from spreadsheet. Save file as Microsoft Excel 07-2003 Worksheet
initializations from "mmodbc.excel:DataInput130520ChampionWeighted.xls"
    Vessels         as "Vessels";
    EmergencyPrep   as "EmergencyPrep";
    Attributes      as "Attributes";
    A1              as "Ax";
    A2              as "Ay";
    A3              as "Az";    (!2!)
    AORO            as "AORO";
    ARESX           as "ARESC";
    AHELI           as "AHELI";

    nVessels        as "nVessels";
    nLevels         as "nLevels";
    nMaxlevels      as "nMaxlevels";
    nPeriods        as "nPeriods";
    nShared         as "nShared";
    nMaxshared      as "nMaxshared";
end-initializations
```

```
!Define the sets Levels, Periods, Shared and Totvessels based on
!nLevels, nPeriods and nShared
Levels          := 1 .. nMaxlevels;
Periods         := 1 .. nPeriods;
Shared          := 1 .. nMaxshared;
finalize(Levels);
finalize(Periods);
finalize(Shared);

!Declaration of the parameters
declarations
    C_BASE:     array(Periods)                      of real;
    C_F:        array(Attributes, Levels)           of real;
    C_L:        array(Attributes,Levels)            of real;
    C_A:        array(Attributes, Levels, Levels)   of real;
    C_O:        array(Attributes, Levels)           of real;
    G_O:        array(EmergencyPrep, Shared)        of real;
    C_ERRV:     array(Vessels, Periods)             of real;
    R_UNITS:    array(Attributes, Levels, Periods)  of integer;
    R_TOTAL:    array(Attributes, Periods)          of real;
    K:          array(Attributes, Levels)           of real;
    P:          array(Attributes)                   of real;
    F_ERRV:     array(Vessels, Attributes, Levels)  of integer;
    F_BASE:     array(Attributes, Levels)           of integer;
    S_DECK:                                            real;
    S_VOL:                                             real;
    S_ACC:                                             real;
    U_DECK:     array(Attributes, Levels)           of real;
    U_VOL:      array(Attributes, Levels)           of real;
    U_ACC:      array(Attributes, Levels)           of real;
    I:          array(Shared)                       of integer;
    Alfa:                                              real;    (!2!)
    Beta:                                              real;    (!2!)
end-declarations

!Initialization of the parameters from Spreadsheet.
initializations from "mmodbc.excel:skiph;noindex;DataInput130520ChampionWeighted.xls"
    C_BASE      as "C_BASE";
    C_F         as "C_F";
    C_L         as "C_L";
    C_A         as "C_A";
    C_O         as "C_O";
    G_O         as "G_O";
    C_ERRV      as "C_ERRV";
    R_UNITS     as "R_UNITS";
    R_TOTAL     as "R_TOTAL";
    K           as "K";
    P           as "P";
    F_ERRV      as "F_ERRV";
    F_BASE      as "F_BASE";
    S_DECK      as "S_DECK";
    S_VOL       as "S_VOL";
    S_ACC       as "S_ACC";
    U_DECK      as "U_DECK";
    U_VOL       as "U_VOL";
    U_ACC       as "U_ACC";
    I           as "I";
    Alfa        as "Alfa";  (!2!)
    Beta        as "Beta";  (!2!)
end-initializations

!Declaration of the variables
declarations
    x:  dynamic array(Periods)                              of mpvar;
    b:  dynamic array(Attributes, Levels)                   of mpvar;
    m:  dynamic array(Attributes, Levels, Periods)          of mpvar;
    w:  dynamic array(Attributes, Levels, Levels, Periods)  of mpvar;
    z:  dynamic array(Attributes, Levels, Periods)          of mpvar;
    y:  dynamic array(Vessels, Periods)                     of mpvar;
    h:  dynamic array(EmergencyPrep, Periods, Shared)       of mpvar;
end-declarations
```

```
!Creating binary variables
forall (tt in Periods) do
    create(x(tt));
    x(tt) is_binary;
end-do

forall (aa in Attributes, ll in Levels|ll<=nLevels(aa)) do
    create(b(aa,ll));
    b(aa,ll) is_binary;
end-do

forall (aa in Attributes, ll in Levels|ll<=nLevels(aa), tt in Periods) do
    create(z(aa,ll,tt));
    z(aa,ll,tt) is_binary;
end-do

forall (aa in Attributes, ll in Levels|ll<=nLevels(aa), tt in Periods|tt<>1) do
    create(m(aa,ll,tt));
    m(aa,ll,tt) is_binary;
end-do

forall (aa in Attributes, ll in Levels|ll<=nLevels(aa),
jj in Levels|jj<=nLevels(aa), tt in Periods|tt<>1) do
    create(w(aa,ll,jj,tt));
    w(aa,ll,jj,tt) is_binary;
end-do

forall (vv in Vessels, tt in Periods) do
    create(y(vv,tt));
    y(vv,tt) is_integer;
end-do

forall (ee in EmergencyPrep, tt in Periods, qq in Shared) do
    create(h(ee,tt,qq));
    h(ee,tt,qq) is_binary;
end-do

!Declerate objective function and linear constraints
declarations
    Pareto:                 linctr;
    TotCost:                linctr;
    InvestementCost:        linctr;
    EquipementCost:         linctr;
    InstallationCost:       linctr;
    AlterationCost:         linctr;
    OperationCost:          linctr;
    SharedoperationGain:    linctr;
    CharteringCost:         linctr;
    NewObj:                 linctr;      (!2!)

    OnebaseCon:                                                         linctr;
    Req1Con:            dynamic array(A1, Levels, Periods)           of linctr;
    Req2Con:            dynamic array(A2, Periods)                   of linctr;
    DeckCon:            dynamic array(Periods)                       of linctr;
    VolCon:             dynamic array(Periods)                       of linctr;
    AccCon:             dynamic array(Periods)                       of linctr;
    OnelevelCon:        dynamic array(Attributes, Periods)           of linctr;
    FunctionalityCon:   dynamic array(Attributes, Levels, Periods)   of linctr;

    CreateSub_b:        dynamic array(Attributes, Levels, Periods)   of linctr;
    CreateSub_m:        dynamic array(Attributes, Levels, Periods)   of linctr;
    CreateSub_w:        dynamic array(Attributes, Levels, Levels, Periods) of linctr;
    CreateSub_h_ORO:    dynamic array(EmergencyPrep, Periods, Shared)   of linctr;
    CreateSub_h_RESC:   dynamic array(EmergencyPrep, Periods, Shared)   of linctr;
    CreateSub_h_HELI:   dynamic array(EmergencyPrep, Periods, Shared)   of linctr;
    CreateCon_h_max:    dynamic array(EmergencyPrep, Periods)           of linctr;
end-declarations
```

```
!Calculating objective function
InvestementCost
:= sum(tt in Periods)C_BASE(tt)*x(tt);

EquipementCost
:= sum(aa in Attributes, ll in Levels|ll<=nLevels(aa))C_F(aa,ll)*b(aa,ll);

InstallationCost
:= sum(aa in Attributes, ll in Levels|ll<=nLevels(aa), tt in
Periods)C_L(aa,ll)*m(aa,ll,tt);

AlterationCost
:= sum(aa in Attributes, ll in Levels|ll<=nLevels(aa),
jj in Levels|jj<=nLevels(aa), tt in Periods)C_A(aa,ll,jj)*w(aa,ll,jj,tt);

OperationCost
:= sum(aa in Attributes, ll in Levels|ll<=nLevels(aa),
tt in Periods)C_O(aa,ll)*z(aa,ll,tt);

SharedoperationGain
:= sum(ee in EmergencyPrep, tt in Periods, qq in Shared|qq<=nShared(ee))
G_O(ee,qq)*h(ee,tt,qq);

CharteringCost
:= sum(vv in Vessels, tt in Periods)C_ERRV(vv,tt)*y(vv,tt);

NewObj := sum(vv in Vessels, aa in A3, ll in Levels|ll<=nLevels(aa), tt in Periods) (!2!)
K(aa,ll)*F_ERRV(vv,aa,ll)*y(vv,tt)+sum(aa in A3, ll in Levels|ll<=nLevels(aa),       (!2!)
tt in Periods)K(aa,ll)*z(aa,ll,tt);                                                  (!2!)


Pareto          := Alfa*(InvestementCost+EquipementCost+InstallationCost+AlterationCost
                +OperationCost-SharedoperationGain+CharteringCost)-Beta*NewObj; (!2!)

TotCost         := InvestementCost+EquipementCost+InstallationCost+AlterationCost
                +OperationCost-SharedoperationGain+CharteringCost;

!Constraints
OnebaseCon := sum(tt in Periods)x(tt) <= 1;

forall (aa in A1, ll in Levels|ll<=nLevels(aa), tt in Periods) do
Req1Con(aa,ll,tt) := sum(vv in Vessels, jj in Levels|jj>=ll)
F_ERRV(vv,aa,jj)*y(vv,tt)+sum(jj in Levels|jj>=ll)z(aa,jj,tt) >= R_UNITS(aa,ll,tt);
end-do

forall (aa in A2, tt in Periods) do
Req2Con(aa,tt) := sum(vv in Vessels, ll in Levels|ll<=nLevels(aa))
K(aa,ll)*F_ERRV(vv,aa,ll)*y(vv,tt)
+sum(ll in Levels|ll<=nLevels(aa))P(aa)*K(aa,ll)*z(aa,ll,tt) >= R_TOTAL(aa,tt);
end-do

forall (tt in Periods) do
DeckCon(tt) := sum(aa in Attributes, ll in
Levels|ll<=nLevels(aa))U_DECK(aa,ll)*z(aa,ll,tt)
<= S_DECK*sum(jj in 1..tt)x(jj);

VolCon(tt)  := sum(aa in Attributes, ll in Levels|ll<=nLevels(aa))U_VOL(aa,ll)*z(aa,ll,tt)
 <= S_VOL*sum(jj in 1..tt)x(jj);

AccCon(tt)  := sum(aa in Attributes, ll in Levels|ll<=nLevels(aa))U_ACC(aa,ll)*z(aa,ll,tt)
<= S_ACC*sum(jj in 1..tt)x(jj);
end-do

forall (aa in Attributes, tt in Periods) do
OnelevelCon(aa,tt) := sum(ll in Levels|ll<=nLevels(aa))z(aa,ll,tt)
<= sum(jj in 1..tt)x(jj);
end-do

forall (aa in Attributes, ll in Levels|ll<=nLevels(aa), tt in Periods) do
FunctionalityCon(aa,ll,tt) := z(aa,ll,tt) <= F_BASE(aa,ll)*sum(jj in 1..tt)x(jj);
end-do

forall(aa in Attributes, ll in Levels|ll<=nLevels(aa), tt in Periods) do
CreateSub_b(aa,ll,tt) := b(aa,ll)+1 >= x(tt)+z(aa,ll,tt);
end-do
```

```
forall(aa in Attributes, ll in Levels|ll<=nLevels(aa), tt in Periods|tt<>1) do
CreateSub_m(aa,ll,tt) := m(aa,ll,tt)+sum(jj in Levels)z(aa,jj,tt-1)+x(tt)>= z(aa,ll,tt);
end-do

forall(aa in Attributes, ll in Levels|ll<=nLevels(aa),
jj in Levels|jj<=nLevels(aa), tt in Periods|tt<>nPeriods) do
CreateSub_w(aa,ll,jj,tt) := w(aa,ll,jj,tt+1)+1>=z(aa,ll,tt)+z(aa,jj,tt+1);
end-do

forall(ee in EmergencyPrep|ee = 'ORO', tt in Periods, qq in Shared|qq<=nShared(ee)) do
CreateSub_h_ORO(ee,tt,qq)
    := I(qq)*h(ee,tt,qq)<=sum(jj in AORO, ll in Levels|ll<=nLevels(jj))z(jj,ll,tt);
end-do

forall(ee in EmergencyPrep|ee = 'RESC', tt in Periods, qq in Shared|qq<=nShared(ee)) do
CreateSub_h_RESC(ee,tt,qq)
    := I(qq)*h(ee,tt,qq)<=sum(jj in ARESC, ll in Levels|ll<=nLevels(jj))z(jj,ll,tt);
end-do

forall(ee in EmergencyPrep|ee = 'HELI', tt in Periods, qq in Shared|qq<=nShared(ee)) do
CreateSub_h_HELI(ee,tt,qq)
    := I(qq)*h(ee,tt,qq)<=sum(jj in AHELI, ll in Levels|ll<=nLevels(jj))z(jj,ll,tt);
end-do

forall(ee in EmergencyPrep, tt in Periods) do
CreateCon_h_max(ee,tt)
    := sum(qq in Shared|qq<=nShared(ee))h(ee,tt,qq)<=sum(jj in 1..tt)x(jj);
end-do

!minimize(TotCost); (!1!)
minimize(Pareto);   (!2!)

!The remaining part of the model makes Xpress and Excel write the wanted results
declarations
    Implementation:          real;
    NewObjOUT:               real;   (!2!)
    TotCostOUT:              real;
    InvestementCostOUT:      real;
    EquipementCostOUT:       real;
    InstallationCostOUT:     real;
    AlterationCostOUT:       real;
    OperationCostOUT:        real;
    SharedoperationGainOUT:  real;
    CharteringCostOUT:       real;
end-declarations

NewObjOUT:=                  getsol(NewObj); (!2!)
TotCostOUT:=                 getsol(TotCost);
InvestementCostOUT:=         getsol(InvestementCost);
EquipementCostOUT:=          getsol(EquipementCost);
InstallationCostOUT:=        getsol(InstallationCost);
AlterationCostOUT:=          getsol(AlterationCost);
OperationCostOUT:=           getsol(OperationCost);
SharedoperationGainOUT:=     getsol(SharedoperationGain);
CharteringCostOUT:=          getsol(CharteringCost);
```

```
 (!Writes the value of total cost in both original model and the extension.
In the model extension, the value of the new objective function, e.g. the toal
capacity of oil recovery, will be displayed!)

writeln('Value of Total cost ',getsol(TotCost));
writeln('Value of capacity for weighted attributet ',getsol(NewObj));   (!2!)
write('The stand-by base is implemented in period ');
forall (tt in Periods|getsol(x(tt)) > 0.01) do
    Implementation := tt;
    write(tt);
end-do

!Writes the nonzero variables
writeln;
writeln;
forall (aa in Attributes, ll in Levels, tt in Periods|getsol(z(aa,ll,tt)) > 0.01) do
    write('z(',aa);
    write(', Level ',ll);
    write(', Period ', tt);
    writeln(') = ',getsol(z(aa,ll,tt)));
end-do

writeln;
forall (aa in Attributes, ll in Levels|getsol(b(aa,ll)) > 0.01) do
    write('b(',aa);
    write(', Level ',ll);
    writeln(') = ',getsol(b(aa,ll)));
end-do

writeln;
forall (aa in Attributes, ll in Levels, tt in Periods|getsol(m(aa,ll,tt)) > 0.01) do
    write('m(',aa);
    write(', Level ',ll);
    write(', Period ', tt);
    writeln(') = ',getsol(m(aa,ll,tt)));
end-do

writeln;
forall (aa in Attributes, ll in Levels,
    jj in Levels, tt in Periods|getsol(w(aa,ll,jj,tt)) > 0.01) do
    write('w(',aa);
    write(', Level ',ll);
    write(', Level´ ',jj);
    write(', Period ', tt);
    writeln(') = ',getsol(w(aa,ll,jj,tt)));
end-do

writeln;
forall (vv in Vessels, tt in Periods|getsol(y(vv,tt)) > 0.01) do
    write('y(',vv);
    write(', Period ', tt);
    writeln(') = ',getsol(y(vv,tt)));
end-do

writeln;
forall (ee in EmergencyPrep, tt in Periods, qq in Shared|getsol(h(ee,tt,qq)) > 0.01) do
    write('h(',ee);
    write(', Period ', tt);
    write(', Shared ', qq);
    writeln(') = ',getsol(h(ee,tt,qq)));
end-do

declarations
Deck_left           : array(Periods) of linctr;
Vol_left            : array(Periods) of linctr;
Acc_left            : array(Periods) of linctr;
CapAttBase          : array(Periods) of linctr; (!2!)
CapAttVessel        : array(Periods) of linctr; (!2!)
end-declarations
```

```
!Writes the suplus available deckarea, tank volume and accomodation for each period
writeln;
forall (tt in Periods) do
Deck_left(tt)
:= S_DECK-sum(aa in Attributes, ll in Levels|ll<=nLevels(aa))U_DECK(aa,ll)*z(aa,ll,tt);

Vol_left(tt)
:= S_VOL-sum(aa in Attributes, ll in Levels|ll<=nLevels(aa))U_VOL(aa,ll)*z(aa,ll,tt);

Acc_left(tt)
:= S_ACC-sum(aa in Attributes, ll in Levels|ll<=nLevels(aa))U_ACC(aa,ll)*z(aa,ll,tt);

CapAttBase(tt)
:= sum(aa in A3, ll in Levels|ll<=nLevels(aa))K(aa,ll)*z(aa,ll,tt); (!2!)

CapAttVessel(tt)
:= sum(vv in Vessels,aa in A3, ll in Levels|ll<=nLevels(aa))
K(aa,ll)*F_ERRV(vv,aa,ll)*y(vv,tt); (!2!)

writeln('In period ',tt);
writeln(' surplus deckarea is ',getsol(Deck_left(tt)),' m2');
writeln(' surplus tank volume is ',getsol(Vol_left(tt)),' m3');
writeln(' surplus accomodation is ',getsol(Acc_left(tt)),' m2');
writeln(' capacity of weighted attribute is ',          (!2!)
    getsol(CapAttBase(tt)),' at stand-by base');        (!2!)
writeln(' capacity of weighted attribute is ',          (!2!)
    getsol(CapAttVessel(tt)),' at stand-by vessels');   (!2!)
writeln;
end-do

!The values in the "Results" sheet in the Excel Spreadsheet
initializations to "mmodbc.excel:DataInput130520ChampionWeighted.xls"
    Implementation            as "Implementation";
    NewObjOUT                 as "NewObjOUT"; (!2!)
    TotCostOUT                as "TotCostOUT";
    InvestementCostOUT        as "InvestementCostOUT";
    EquipementCostOUT         as "EquipementCostOUT";
    InstallationCostOUT       as "InstallationCostOUT";
    AlterationCostOUT         as "AlterationCostOUT";
    OperationCostOUT          as "OperationCostOUT";
    SharedoperationGainOUT    as "SharedoperationGainOUT";
    CharteringCostOUT         as "CharteringCostOUT";
end-initializations

end-model
```

# H. Microsoft Excel File

| Attributes | Levels |
|---|---|
| Oil Boom | 6 |
| Skimmer | 6 |
| C.Dispersants | 5 |
| Oil Recovery | 6 |
| Helipad | 2 |
| Helifuel | 3 |
| Hosp. Unit | 4 |
| Safe Haven | 4 |
| MOB | 5 |
| Radar | 3 |
| Fire Fighting | 2 |
| Supply | 8 |

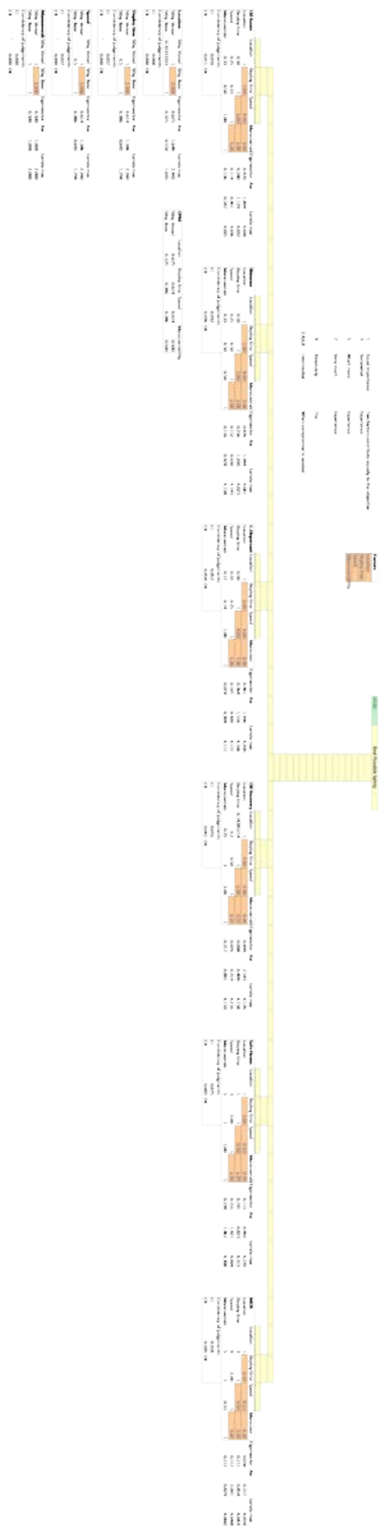
| A1 | A2 |
|---|---|
| Oil Boom | Oil Boom |
| Skimmer | Skimmer |
| C.Dispersants | C.Dispersants |
| Oil Recovery | Oil Recovery |
| Helipad | Safe Haven |
| Helifuel | MOB |
| Hosp. Unit | |
| Safe Haven | |
| MOB | |
| Radar | |
| Fire Fighting | |

| Emergency Prep. groups | |
|---|---|
| ORO | 4 |
| RESC | 3 |
| HELI | 2 |

| AORO | ARESC | AHELI |
|---|---|---|
| Oil Boom | Hosp. Unit | Helipad |
| Skimmer | Safe Haven | Helifuel |
| C.Dispersants | MOB | |
| Oil Recovery | | |

| | |
|---|---|
| Periods | 20 |
| Number of attributes | 12 |
| Maximum number of levels | 8 |
| Number of vessels | 2 |
| Maximum number of attributes in an emergency preparedness group | 4 |
| Number of stand-by vessels | 6 |
| Weighted attribute extended model | |
| Oil Recovery | |

| Vessels |
|---|
| Stril Herkules |
| Stril Mariner |



Appendix Figure IV: Cuttings from MS Excel sheets: *Sets* (left) and *AHP Input* (right)

| Oil Boom | Location | Deploy time | Speed | Maneuverability | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|---|---|
| Location | 1 | 2.00 | 4.00 | 3.00 | 0.470 | 1.894 | 4.026 |
| Deploy time | 0.50 | 1 | 3.00 | 2.00 | 0.280 | 1.129 | 4.037 |
| Speed | 0.25 | 0.33 | 1 | 1.00 | 0.114 | 0.461 | 4.036 |
| Maneuverability | 0.33 | 0.50 | 1.00 | 1 | 0.136 | 0.547 | 4.025 |
| Consistency of judgements | | | | | | | |
| CI | 0.010 | | | | | | |
| CR | 0.011 OK | | | | | | |

| Skimmer | Location | Deploy time | Speed | Maneuverability | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|---|---|
| Location | 1 | 2.00 | 4.00 | 3.00 | 0.476 | 1.944 | 4.081 |
| Deploy time | 0.50 | 1 | 2.00 | 2.00 | 0.256 | 1.030 | 4.023 |
| Speed | 0.25 | 0.50 | 1 | 2.00 | 0.152 | 0.630 | 4.143 |
| Maneuverability | 0.33 | 0.50 | 0.50 | 1 | 0.116 | 0.478 | 4.138 |
| Consistency of judgements | | | | | | | |
| CI | 0.032 | | | | | | |
| CR | 0.036 OK | | | | | | |

| C.Dispersants | Location | Deploy time | Speed | Maneuverability | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|---|---|
| Location | 1 | 2.00 | 3.00 | 6.00 | 0.461 | 1.936 | 4.200 |
| Deploy time | 0.50 | 1 | 4.00 | 7.00 | 0.364 | 1.516 | 4.166 |
| Speed | 0.33 | 0.25 | 1 | 1.00 | 0.101 | 0.420 | 4.151 |
| Maneuverability | 0.17 | 0.14 | 1.00 | 1 | 0.074 | 0.304 | 4.111 |
| Consistency of judgements | | | | | | | |
| CI | 0.052 | | | | | | |
| CR | 0.058 OK | | | | | | |

| Oil Recovery | Location | Deploy time | Speed | Maneuverability | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|---|---|
| Location | 1 | 7.00 | 5.00 | 4.00 | 0.609 | 2.543 | 4.176 |
| Deploy time | 0.142857143 | 1 | 2.00 | 0.33 | 0.098 | 0.409 | 4.158 |
| Speed | 0.2 | 0.50 | 1 | 0.33 | 0.076 | 0.319 | 4.216 |
| Maneuverability | 0.25 | 3 | 3.00 | 1 | 0.217 | 0.891 | 4.110 |
| Consistency of judgements | | | | | | | |
| CI | 0.055 | | | | | | |
| CR | 0.061 OK | | | | | | |

| Safe Haven | Location | Deploy time | Speed | Maneuverability | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|---|---|
| Location | 1 | 1.00 | 0.33 | 0.20 | 0.115 | 0.492 | 4.270 |
| Deploy time | 1 | 1 | 0.50 | 1.00 | 0.191 | 0.823 | 4.313 |
| Speed | 3 | 2.00 | 1 | 1.00 | 0.355 | 1.421 | 4.004 |
| Maneuverability | 5 | 1 | 1.00 | 1 | 0.339 | 1.461 | 4.308 |
| Consistency of judgments | | | | | | | |
| CI | 0.075 | | | | | | |
| CR | 0.083 OK | | | | | | |

| MOB | Location | Deploy time | Speed | Maneuverability | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|---|---|
| Location | 1 | 0.33 | 0.11 | 0.20 | 0.056 | 0.227 | 4.059 |
| Deploy time | 3 | 1 | 0.50 | 1.00 | 0.211 | 0.854 | 4.047 |
| Speed | 9 | 2.00 | 1 | 3.00 | 0.517 | 2.091 | 4.048 |
| Maneuverability | 5 | 1 | 0.33 | 1 | 0.217 | 0.879 | 4.060 |
| Consistency of judgements | | | | | | | |
| CI | 0.018 | | | | | | |
| CR | 0.020 OK | | | | | | |

Appendix Figure V: Case study: AHP ratings of attributes

| Location | Stby. Vessel | Stby. Base | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|
| Stby. Vessel | 1 | 3.000 | 0.675 | 1.649 | 2.442 |
| Stby. Base | 0.333333333 | 1 | 0.325 | 0.550 | 1.693 |
| Consistency of judgements | | | | | |
| CI | 0.068 | | | | |
| CR | 0.000 | OK | | | |

| Deploy time | Stby. Vessel | Stby. Base | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|
| Stby. Vessel | 1 | 2.000 | 0.614 | 1.386 | 2.260 |
| Stby. Base | 0.5 | 1 | 0.386 | 0.693 | 1.794 |
| Consistency of judgements | | | | | |
| CI | 0.027 | | | | |
| CR | 0.000 | OK | | | |

| Speed | Stby. Vessel | Stby. Base | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|
| Stby. Vessel | 1 | 2.000 | 0.614 | 1.386 | 2.260 |
| Stby. Base | 0.5 | 1 | 0.386 | 0.693 | 1.794 |
| Consistency of judgements | | | | | |
| CI | 0.027 | | | | |
| CR | 0.000 | OK | | | |

| Maneuverability | Stby. Vessel | Stby. Base | Eigenvector | Aw | Lambda max |
|---|---|---|---|---|---|
| Stby. Vessel | 1 | 1.000 | 0.500 | 1.000 | 2.000 |
| Stby. Base | 1 | 1 | 0.500 | 1.000 | 2.000 |
| Consistency of judgements | | | | | |
| CI | 0.000 | | | | |
| CR | 0.000 | OK | | | |

| OPM | Location | Deploy time | Speed | Maneuverability |
|---|---|---|---|---|
| Stby. Vessel | 0.675 | 0.614 | 0.614 | 0.500 |
| Stby. Base | 0.325 | 0.386 | 0.386 | 0.500 |

Appendix Figure VI: Case study: AHP ratings of Standby base and Standby vessels