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Allocation of Emergency Response Assets in the Barents Sea

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PREFACE

Marina Myhrvold Riple has written this report during the spring semester of 2015. This report presents my thesis for the degree of Master of Science in Marine Technology at the Norwegian University of Science and Technology, NTNU.

The overall objective in this thesis is to develop an optimization model in order to locate the optimal location for emergency response assets when minimizing response time.

The hub solution considered in this report, is based on Akselsen (2014) that developed a optimization model for minimizing total cost for supplying oil and gas installations in the Barents Sea.

The aim in this thesis is to investigate if a hub vessel can be utilized as an extension to the onshore base in order to have a more robust system for emergency response, and improve the emergency preparedness in the Barents Sea.

I would like to thank my academic supervisor, Professor Stein Ove Erikstad, for valuable input and great guidance throughout my final year at NTNU.

Trondheim, 10th June 2015

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 Marina Myhrvold Riple

SUMMARY

This report presents an academic study of the allocation of emergency response assets in the Barents Sea. Operations research is utilized to examine a hub solution in order to allocate the assets.

The main strategy for oil spill preparedness is to oppose the spill as close as possible to its source, this requires a quick response time. A hub solution is introduced in order to allocate required assets for emergency response as near as possible to the operating installations. The hub will operate as an extension to the onshore base in order to reduce the response time and possibly strengthen the overall preparedness system.

The overall objective in this thesis, is to develop an optimization model in order to locate the optimal location for emergency response assets when minimizing response time. The aim is to utilize this model as an analysis tool when the hub solution for emergency preparedness in the Barents Sea is evaluated.

A general formulation of the problem is developed and presented in order to give an overall understanding of the scope and limitations to the problem. This formulation of the problem is then simplified and reformulated to a Set Partitioning Problem, and solved in two steps.

In the first step, the preprocessing phase, parameters are stated and calculated and used as input to the second step, the mathematical problem. In the preprocessing phase, the locations for the installations are decided and a hub grid is generated. The grid represents all possible locations where a hub can be located. Distances between hub locations are calculated, as well as the response time. These values are used as input for step two of the solution approach. As a final preparatory input, maximum allowable response time for the different operational phases, or critical levels are stated and bound to the operating installations. Solving the mathematical problem, one single hub is allocated at one of the generated site possibilities that meets all requirements and minimizes the response time.

As an extended analysis to this study, the emergency response model is introduced to an existing model for supplying installations. This extended study is used to investigate if a hub combination of the two purposes for hub solutions provide an added benefit.

The results presented, indicate that the response time will be considerably reduced when a hub solution is utilized, compared to serving the installations from an onshore base. With the stated requirements however, one single hub will not be able to cover the installations in all scenarios. From the extended analysis, it is indicated that storing the emergency assets on a hub supplying installations, will not affect the results for supply.

SAMMENDRAG

Denne rapporten presenterer en akademisk studie av plassering av kriseberedskaps utstyr. Operasjonsanalyse er tatt i bruk for å undersøke en løsning hvor en hub, installert med nødvendig utstyr, blir plassert i Barentshavet.

I dag er strategien for beredskap mot oljeutslipp å stoppe oljen så nær som mulig kilden for utslipp, det krever rask respons tid når ulykken er ute. En hub løsning er introdusert for å plassere nødvendig utstyr så nært som mulig til de opererende installasjonene. Huben vil fungere som en forlengelse av land basen, og på den måten redusere responstiden og muligens styrke det generelle beredskapssystemet.

Hovedfokuset i denne oppgaven er å utvikle en optimeringsmodell som finner den optimale lokasjonen for utstyr når responstiden skal minimeres. Målet er å bruke modellen til å evaluere hub- løsningen for kriseberedskap i Barentshavet.

En generell formulering av problemet er utviklet og presentert for å gi en forståelse av omfang og begrensinger til problemet. Den generelle formuleringen av problemet blir deretter forenklet og reformulert til et Set Partitioning Problem, og løst i to omganger.

I første omgang, i preprosesserings fasen, blir parametere kalkulert og bestemt. Parameterne blir så brukt som input i siste steg hvor den matematiske modellen blir reformulert og løst. I prosesserings fasen blir lokasjoner for installasjonene bestemt, og et nett av mulige plasseringer for huben blir generert. I preprosesserings fasen er avstander mellom alle mulige hub lokasjoner og installasjoner regnet ut i tillegg til responstiden. Både avstand og responstid blir brukt som input til steg to, der modellen blir løst. Til slutt er den maksimalt tillatte responstiden for forskjellige operasjons faser og kritiske nivå bestemt, og bundet opp mot de opererende installasjonene. Når det matematiske problemet skal løses, blir en hub plassert ved en av de forhånds genererte lokasjonene. Plasseringen den får må oppfylle alle krav, i tillegg til at den minimerer responstiden til installasjonene.

I tillegg til å plassere huben med tanke på å minimere responstid, vil de bestemte kravene for plassering av utstyr bli inkludert i en eksisterende modell som bruker hub løsningen til å forsyne opererende installasjoner. Dette er gjort for å undersøke muligheten for å bruke en hub løsning til et bredere spekter av bruksområder.

Resultatene som er presentert i denne oppgaven indikerer at responstiden vil reduseres betydelig dersom en hub løsning tas i bruk, sammenlignet med plassering av utstyr ved en land base. Med de bestemte kravene som er brukt i denne oppgaven, vil plassering av kun en hub ikke kunne dekke alle behov for alle senarioer. Resultatet fra den utvidede analysen indikerer at lagring av beredskaps utstyr på en hub som forsyner installasjoner, ikke påvirker resultatet for forsyning.

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LIST OF ABBREVIATIONS

GMCLP – Generalized Maximum Covering Location Problem

LP – Linear Programming

MCLP – Maximum Covering Location Problem

NCS – Norwegian Continental Shelf

NOFO – Norwegian Clean Seas Association for Operating Companies

OR – Oil Recovery

PSV – Platform Supply Vessel

SCP – Set Covering Problem

SPP – Set Partitioning Problem

CHAPTER 1

INTRODUCTION

The global energy demand is constantly increasing. The population is growing, and so is the share of people in the middle class. This results in higher energy consumption per person. It is anticipated that the energy demand will increase with 35 percent from 2010 to 2040. Even though more environmental friendly energy is requested from the society, 30 percent of this demand will be covered by oil and gas the next 25 years. It is not possible to supply the global energy demand purely based on renewable energy today or in the relative near future (ExxonMobile, 2015).

The arctic continental shelf is anticipated to become the petroleum area with the highest potential of oil and gas in the future. It is estimated that around 30 percent of the worlds undiscovered natural gas and 13 percent of the yet to find oil lay in the arctic. This is around 400 billion barrels of oil equivalents, 10 times the total oil and gas produced to date in the North Sea (Shell, 2015). 20 of January 2015, the government announced the 23 licensing round. Out of 57 blocks or part of blocks, three of them where on the North Sea while 54 where in the Barents Sea (Norwegian Petroleum Directorate, 2015).

The arctic is considered to be specifically vulnerable to oil spills. Low temperatures usually mean longer persistence of hydrocarbons in the environment and slow recovery in highly seasonal ecosystems (Knol & Arbo, 2014). Petroleum activity in the arctic is highly debated due to environmental vulnerability in this area. Oil spills, whether from blowouts, pipeline leaks or shipping accidents pose a tremendous risk to arctic ecosystems (WWF, 2015). Other challenges related to activity in the arctic are harsh weather conditions, darkness, ice, icing, large distances and limited infrastructure. Installations can operate up to 243 nautical miles from shore, making the installations difficult to reach. An example is helicopters transporting people to and from the installations, today they only travels 200 nm from shore (TU, 2015).

The risk of a big oil blowout accident as a consequence of exploration drilling and oil production on the Norwegian Continental Shelf (NCS) is highly unlikely. Nevertheless, it is not guaranteed that it won't happen. Consequently, the oil companies need to have a big focus on oil spill preparedness (Norwegian Oil and Gas Association, 2003). A recent example for an oil spill accident is the Deepwater Horizon accident at the Macondo well in 2010. Around 5 million barrels of oil spilled into the Gulf of Mexico, causing extensive damage to marine and wildlife habitats, and to the fishing and tourism industries in the area. The clean up process at some point involved 50 000 people, and had a tremendous cost (CSB, 2014).

There have also been accidents on the NCS. The largest spill accident was on the Ekofisk Bravo platform in 1977, the blowout lasted for eight days before it was stopped. As a response to this, requirements for better preparedness and more efficient equipment rose. This accident is the direct cause for the establishment of the Norwegian Clean Seas Association for Operating Companies (NOFO) in 1978 (NOFO a, 2013).

1.1 BACKGROUND

Akselsen (2014) propose a hub network solution in order to reduce sailing distances when supplying oil and gas installations as much as possible, and consequently keep transportation costs at a minimum. The hub network solution is an extension of the conventional supply, where a forward storage unit is included. A proposed system with a hub network is illustrated in Figure 1.
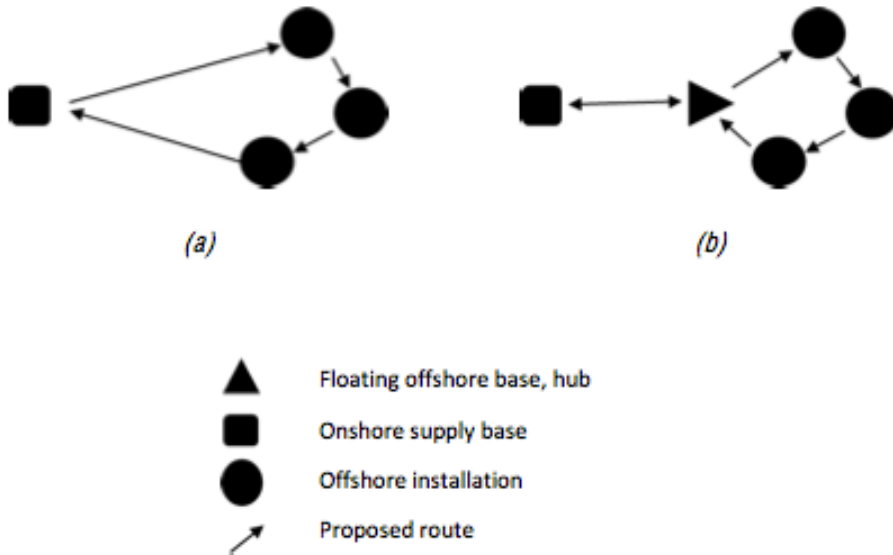
Figure 1 Offshore supply concepts (Akselsen, 2014)

Instead of sailing from the onshore base in order to supply the installations, the PSV sails between the hub and the installations. (a) Illustrates the conventional supply scenario between the onshore base and the installations. (b) Illustrates offshore supply with a hub network solution with one hub. The hub vessel shuttles between an onshore base and a given offshore position. From this position, the PSVs load cargo to supply the offshore installations.

With inspiration from this solution, a hub network solution for emergency preparedness is introduced. Required assets for the emergency response can be placed on the hub and as near as possible to the operation area. The hub will operate as an extension to the onshore base, and hopefully make a significant reduction in the response time and possibly strengthen the overall preparedness system.

1.2 OBJECTIVE

The overall objective in this thesis is to develop an optimization model in order to locate the optimal location for emergency response assets when minimizing response time. The aim is use the model to investigate if a hub vessel can be utilized as an extension to the onshore base in order to have a more robust system for emergency response and improve the emergency preparedness in the Barents Sea.

1.3   SCOPE AND LIMITATIONS

The specific tasks for this thesis include:
1) A state of the art literature review
2) A brief description of the existing emergency preparedness system
3) Generation of a general mathematical model
4) Collection of essential data necessary to run the mathematical model
5) Solve a simplified version of the problem
6) Solve a problem where the hub is used for both allocation of emergency response assets and supply
7) Presentation of the results and aspects to the model

1.4   UNDERLYING ASSUMPTIONS

1) The first system arriving at site is investigated
2) Only one accident can occur at the same time
3) There is always a tugboat ready to operate when an OR vessel is ready
4) The OR vessel operates at a constant speed

1.5   STRUCTURE OF THE THESIS

In the first part of the report, an overall overview is given. In Chapter 1 the background for the proposed solution is presented together with the overall objective, scope and underlying assumptions. In Chapter 2, solution methods is presented. Several possible methods are discussed before one method is decided. Chapter 3 presents previous work on allocation problems and Chapter 4 presents an overview of the NOFO preparedness system on the NCS.

In the main part of the report, the problem is presented and solved. The problem is described in Chapter 5, before a general model of the problem is presented in Chapter 6. Chapter 6 also presents the solution approach of the problem in this report where both the preprocessing phase and the simplified version of the problem is presented. Chapter 7 presents the data used to solve the problem and Chapter 8 presents the solution approach for solving an extension of the problem. Chapter 9 presents the results while they are discussed in Chapter 10 .

In the final part of the report, the final conclusion is presented together with proposed future work in Chapter 11.

CHAPTER 2

METHOD

This chapter provides an overview of the methods that are used in this report. A general description of the problem is presented before a simplified version is generated and solved with a two-stage solution approach. In the first step, potential facility sites, distances and schedule for operations in the Barents Sea is implemented and generated. In the second step a Set-Partitioning Problem (SPP) is solved by using the data generated in step one. The solution approach is illustrated in Figure 2.
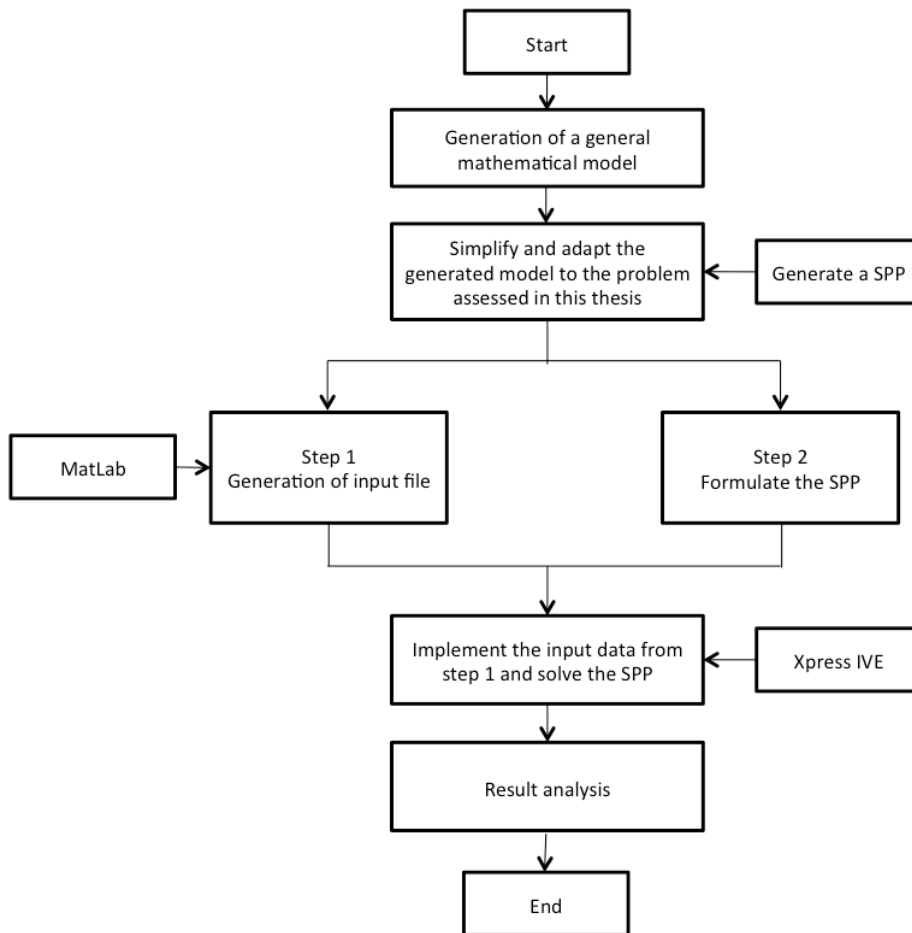
Figure 2 Flowchart of the solution method

The method is performed a set of times where all the phases in the planned schedule for the operating installation in the Barents Sea is considered. This is to study all the optimal locations for the extended base for all possible periods in the schedule. In addition, the results for a hub solution is compared to the results for a conventional solution, where assets are placed at an onshore base.

2.1   IMPLEMENTATION IN COMMERCIAL SOFTWARE

Two different types of commercial software are used to generate the results in this report, MatLab and Xpress IVE. MatLab is used in step 1, where the input data is generated. In step 2, the generated data in step 1 is implemented in Xpress IVE, where the generated optimization model is solved.

MatLab is a high-level language and interactive environment for numerical computation visualizing and programming (MathWorks a, 2015), while the Xpress optimization suit is developed to solve mathematical models and optimization (FICO, 2012). The Xpress software is suitable for mixed integer linear problems and the solution process for Xpress IVE contains of three main phases. In a pre-solving phase, various numerical methods are applied to reduce the problem. Then the linear programming (LP) relaxation of the problem is found by using the LP relaxation method. Finally, branch and bound is performed to search for improved lower bounds and finally find the best feasible integer solution.

2.2   OPTIMIZATION MODEL

There are several models that can be used in order to allocate assets for emergency response. Relevant models are described and discussed in this chapter.

2.2.1   Set- Covering and Set- Partitioning Problem

The Set-Covering Problem (SCP) is one alternative for allocating assets. As it is described in Chapter 3, Literature Review, this problem tries to minimize location cost satisfying a specified level of coverage. The objective function minimizes the cost of locating facilities (Owen & Daskin, 1998).

Table 1 Sets, indices, parameters and variables in the SCP and SPP

Inputs	Description
Sets	
I	Set of demand nodes, indexed by i
J	Set of potential facility sites, indexed by j
N_i	Set of facility sites j within acceptable distance of node i
Parameters	
C_j	Cost for siting a facility at site j
Decision Variables	
x_j	1 if we locate at potential facility site j
	0 if not

Minimize

$$\sum_j C_j x_j \tag{2.1}$$

S.t

$$\sum_{j \in N_i} x_j \geq 1 \qquad\qquad i \in I \quad (2.2)$$

$$x_j \in [0,1] \qquad\qquad j \in J \quad (2.3)$$

(2.1) Represents the objective function and minimize the total cost. The set N_i contains all facility sites j, within an acceptable service distance to demand i. (2.2) Makes sure that all demands i are covered by at least one facility site j, within an acceptable service distance. An optimal solution would provide the location, x_j, of the least number of facilities required to service all demands.

The problem statement in this report allocate one hub only. This means that instead of (2.2) making sure that all demands i is covered by at least one facility site, (2.2) should assure that demands are covered by exactly one facility site. This can be done by changing the constraint (2.2) from a ≥ constraint to a = constraint, (2.4). The problem becomes a set-partitioning problem (SPP).

Minimize

$$\sum_j C_j x_j \tag{2.1}$$

S.t

$$\sum_{j \in N_i} x_j = 1 \qquad\qquad i \in I \quad (2.4)$$

$$x_j \in [0,1] \qquad\qquad j \in J \quad (2.3)$$

For both the SCP and the SPP, the relevant location have to be generated in advance, making it necessary with a two-step solution approach. There are advantages as well as drawbacks with such an approach. The most obvious drawback is that the problem must be solved in two steps. The advantage is that possible locations are generated beforehand, and only the locations that meet the requirements are used as input to the model. These problems have a nice structure that is much easier to solve then direct formulated models. It is also often easy to include new constraints (Fagerholt, 2014).

2.2.2 Vertex P – Center Problem

Another possible model described in the Literature Review, is the vertex P – center problem. The objective in this model minimizes the maximum distance between any

demand node and its nearest facility when facility locations are restricted to the nodes of the network (Owen & Daskin, 1998).

Table 2 Sets, indices, parameters and variables in the vertex P problem

Inputs	Description
Sets	
I	Set of demand nodes, indexed by i
J	Set of potential facility sites, indexed by j
Parameters	
P	Number of facilities to be located
D	Maximum distance between a demand node and the nearest facility
d_{ij}	Distance between demand node i and potential facility site j
Decision Variables	
Xj	1 if we locate at potential facility site j
	0 if not
Yij	1 if demands at node i are served by a facility at node j
	0 if not

Minimize

$$D \qquad (2.5)$$

S.t

$$\sum_j X_j = P \qquad (2.6)$$

$$\sum_j Y_{ij} = 1 \qquad i \in I \qquad (2.7)$$

$$Y_{ij} - X_j \leq 0 \qquad i \in I, j \in J \qquad (2.8)$$

$$D \geq \sum_j d_{ij}Y_{ij} \qquad j \in J \qquad (2.9)$$

$$X_j \in [0,1] \qquad j \in J \qquad (2.10)$$

$$Y_{ij} \in [0,1] \qquad i \in I, j \in J \qquad (2.11)$$

The objective function (2.5), minimizes the maximum distance between any demand node and its nearest facility. (2.6) Requires that exactly P facilities are located. (2.7) Ensures that every demand is assigned to some facility site, while (2.8) allows assignment only to sites at which facilities have been located. (2.9) Defines the maximum distance between any demand node, i, and the nearest facility, j. (2.10) and (2.11) are integrality constraints for the decision variables.

As the objective function in the vertex P – center problem only minimizes the maximum distance, the model has lower flexibility than an SPP. As for the SPP, the potential facility sites also have to be generated in the vertex P problem.

Because of the missing flexibility in the objective function for the vertex p problem, the SPP will be the foundation for the further development of the mathematical model in this report. The goal is to make a generalized model, with a high degree of flexibility regarding the possible installations and locations, a covering problem offers more flexibility as it is easy to extend the model with new constraints.

2.3 GENERATION OF LOCATION POINTS

There are several ways to determine the locations that should be considered for the extended base. Two methods is described in this chapter.

2.3.1 Circles

A maximum distance or duration between the installations and the location of the hub is defined. This means that the restrictions for the allocation of the hub can be presented with circles. This is illustrated in Figure 3 below.
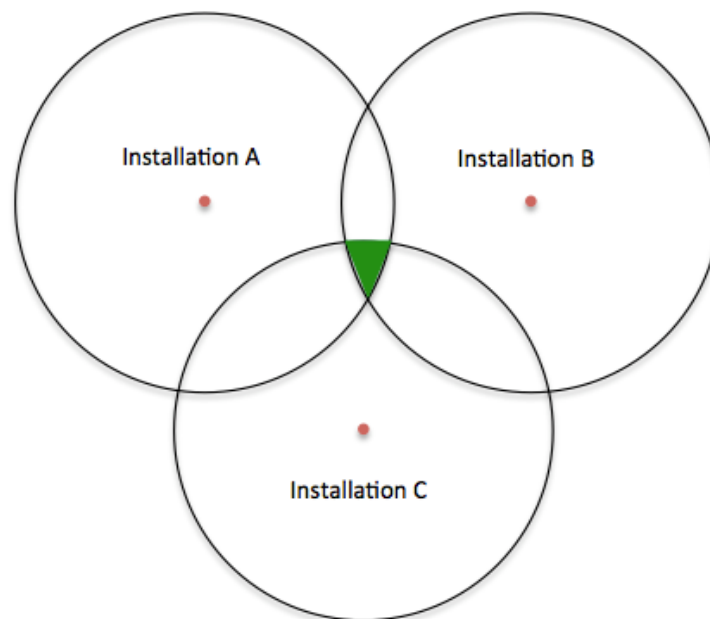
Figure 3 Circle overlap and maximum distance from installations

The figure illustrates three installations, where the overlapping area is marked. The overlapping area represents the area where the requirements are met for all installations. Literature exists on how to cope with these regions. Librino et al (2012) present an algorithm for efficient computation of intersection areas of an arbitrary number of circles, and its application to wireless communications. In order to reduce the

computational load, the algorithm utilizes the areas computed in earlier checks when looking for existence of intersections in each of the iterations. The algorithm assumes scattered circles with few overlaps. It is emphasized that there are challenges in checking the existence of overlapping areas when there are three or more overlaps. The complexity of the problem grows as the number of circles increases, and when more circles are intersecting. This implies that the proposed algorithm is not suitable for a problem where the density of overlapping circles vary with variations of installations and size of the problem.

2.3.2 Hub Grid Generation

Another way to find the location of the hub, and the chosen solution in this report, is to generate a grid of possible locations over a relevant area. This solution is chosen due to the challenges of overlapping areas when there are three or more overlaps with the circle overlap algorithm.

With the hub grid solution, the accuracy of the answer given by the objective function will vary depending on the density of the generated locations. If the density is too low, the answer given may be located far from the optimal location. In addition, there may not be a possible location in overlapping regions. This might lead to unfeasible solutions. The possible locations generated in the grid are given by longitudinal and latitudinal coordinates. In this report the grid is generated in a square where a new point is set for each half latitudinal and longitudinal degree, as it is illustrated in Figure 4 below.
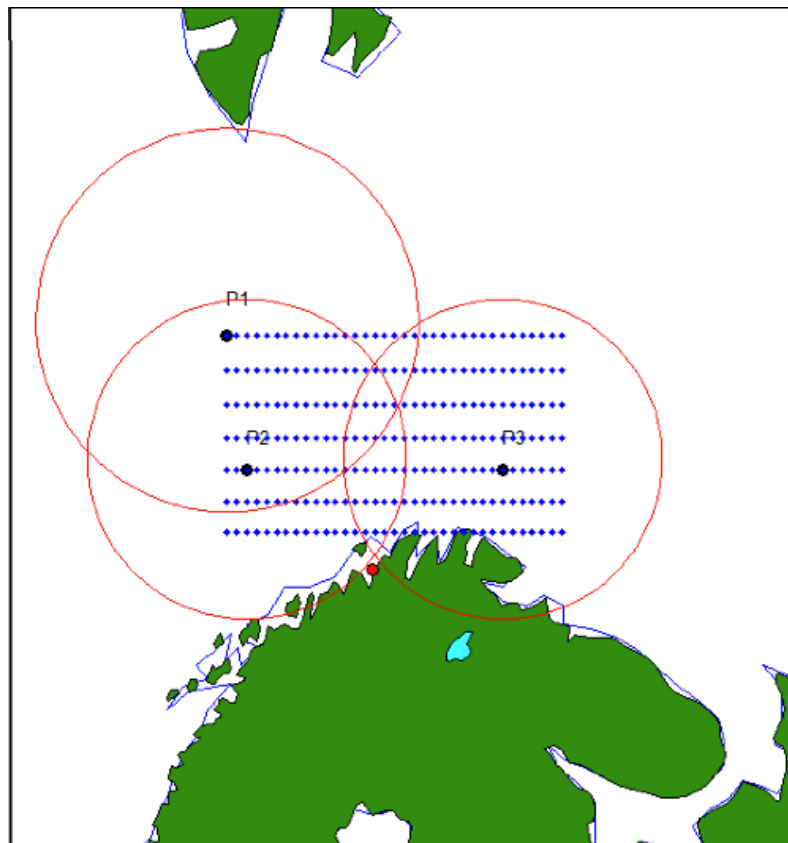
Figure 4 Possible hub locations with illustration of overlapping areas

2.4   CALCULATING DISTANCES

In plane geometry, lines have two important characteristics. A line represents the shortest path between two points, and the slope of such a line is constant. When describing lines on the surface of a spheroid, only one of these characteristics can be guaranteed at a time (Math Works b, 2015). This means that the distance between the hubs and the installations can be calculated based on two tracking types.

A great circle is the shortest path between two points along the surface of a sphere. The intersection of the surface with a plane passing through the center of the planet, defines a great circle. Thus, great circles always bisect the sphere. A ruhmb line is a curve that crosses each meridian at the same angle. A great circle is a shortest path, but it is difficult to navigate because your bearing continuously changes as you proceed. Therefore, following a rhumb line covers more distance than following a the shortest path, but it is easier to navigate (Math Works b, 2015)

All parallels, including the equator, are rhumb lines, since they cross all meridians at 90°. This means that all meridians are rhumb lines, in addition to being great circles. Figure 5 illustrates a great circle and a rhumb line connecting two distant locations (Math Works b, 2015).
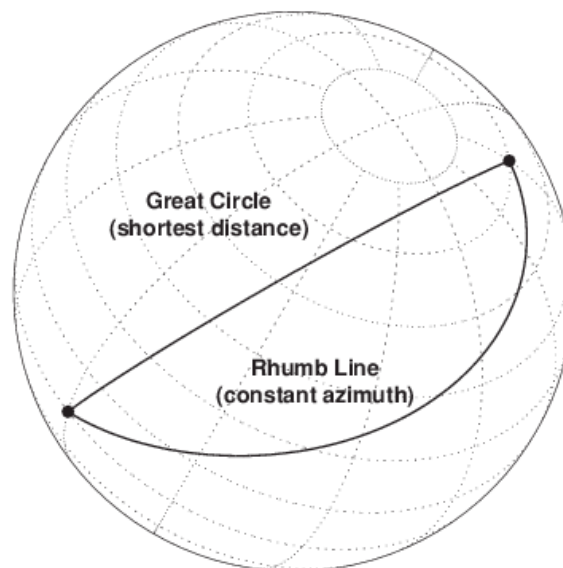
Figure 5 Great Circle and Rhumb Line (Math Works, 2015)

In this report, the great circle has been used in combination with the distance-function in MatLab. This is done when calculating distances between the possible hub locations and the installations, and between the onshore base and the hubs. The great circle is used, as it is assumed that the traveling distances is small and therefore will not differ considerably from the actual traveling distance.

CHAPTER 3

LITERATURE REVIEW

Facility location is a critical aspect of strategic planning for a broad spectrum of public and private firms. Strategic planners are often challenged by difficult spatial resource allocation decisions, whether it is a retail chain siting a new outlet, a manufacturer choosing where to position a warehouse, or a city planner selecting locations for fire stations (Owen & Daskin, 1998).

This chapter presents a literature survey on allocating problems and an introduction to the current literature relevant for building the model in this thesis. The first section addresses general literature on allocating problems, as the aim of this thesis is to allocate the optimal location for an extended base for emergency preparedness. The last section presents an overview of optimization models developed for oil spill preparedness.

3.1   GENERAL LITERATURE ON ALLOCATING PROBLEMS

Owen & Daskin (1998) describe the p- median model that was first introduced in 1964. This model determines the optimal locations for p facilities, when demand-weighted distance between demand nodes and the facility nodes they are assigned to is minimized. This problem can be used to locate a wide range of public and private facilities.

According to Owen & Daskin (1998), selecting locations that minimize the average distance traveled may not be appropriate. An example is a city locating emergency service facilities such as fire stations or ambulances. The critical nature of demands for service will dictate a maximum acceptable travel distance or time. These facilities will thus require a different measure of location efficiency. To locate these facilities, the key issue is to cover requirements within specified demands.

Farahini et al. (2012) review covering problems in facility location. According to this study, models that use the concept of covering can be divided in two categories. Set Covering Problem (SCP) where coverage is required and Maximum Covering Location Problem (MCLP) where coverage is optimized.

The SCP tries to minimize location cost, satisfying a specified level of coverage. The objective function minimizes the cost of locating facilities. The study also presents other versions of the standard SCP. In addition to the SCP, Farahini et al. (2012) presents several versions to the MCLP problem. Among them is the generalized MCLP (GMCLP). In this problem, partial coverage of customers is modeled where the level of coverage is a non – increasing step function of the distance to the nearest facility. Application of this model is in locating retail facilities. The objective function maximizes the coverage of demand areas regardless of whether the areas are fully or partially covered.

A problem class that avoids the set covering problems potential infeasibility is the class of P – center problems. In these problems, it is required coverage of all demands, but the problem aim to locate a given number of facilities in such way that minimizes coverage distance. Rather than taking an input coverage distance S, this model determines the minimal coverage distance associated with locating P facilities. The P-center problem is also known as the minmax problem, as the goal is to minimize the maximum distance between any demand and its nearest facility. If facility locations are restricted to the nodes of the network, the problem is a vertex center problem. Center problems, which allow facilities to be located anywhere on the network, are absolute center problems. The objective function minimizes the maximum distance between any demand node and its nearest facility (Owen & Daskin, 1998).

It can also be interesting to look at dynamic models, as the extended base is movable, and the optimal location can vary with time. Brotcorne et al. (2003) traces the evolution of ambulance location and relocation model proposed over the past 30 years. The models are classified in two main categories. Deterministic models are used at the planning stage and ignore stochastic considerations regarding the availability of ambulances. Probabilistic models reflect the fact that ambulances operate as servers in a queuing system and cannot always answer a call. In addition, dynamic models have been developed to repeatedly relocate ambulances throughout the day.

Andersson & Värbrand (2007) presents a model that is used for decision support to ambulance dispatch and relocation problems. The objective is to find new locations for some of the ambulances, in order to increase the preparedness in the area of responsibility. Preparedness is a way of evaluation the ability to serve potential patients with ambulances now and in the future. The relocation algorithm is dynamic and is resolved when there is a lack of ambulances in some area. As the extended base can be in motion like the ambulances, this model could be suitable.

3.2   PRESENT MODELS FOR POSITIONING OF OIL SPILL ASSETS

Verma et al. (2012) presents a two-step stochastic programming approach that tackles both the location and stockpile of equipment at the emergency response facilities in the south coast of Newfoundland, Canada. The focus in this study is on marine transportation of oil. The study deals with location under uncertainty and is concerned with both the strategic and tactical aspects of the oil-spill response problem for the south coast of Newfoundland. The objective function in the mathematical model minimizes the cost of the facility location and cost of the equipment package.

Gkonis et al (2007) addresses the tactical level of the oil spill response decision-making process that determines the actions required to respond to a specific spill. The objective is to respond to a specific oil spill in an optimal way, by balancing system costs and potential damage costs. The problem is modeled as a mixed integer-programming problem. It is assumed that a given number of facilities exist, mainly located at ports, which contain known quantities and types of oil spill response equipment. The model

decides from which facilities to dispatch the number of units of the different equipment types when an oil spill accident occurs.

Iakovou et al. (1996) propose an integrated framework that addresses some important strategic issues such as determining the optimal location and capacity of cleanup equipment, taking into account their post event implications. To this end, a linear integer-programming model was first developed and a mixed integer relaxation of the original problem was solved. The objective function is compromised of the fixed cost of opening a facility site, the operation costs of storing the equipment at facility sites and the transportation costs of transporting the equipment from a facility site to the demand point to respond to a spill. The constraints addresses feasibility, capacity and critical time issues.

Psaraftis et al. (1986) has developed a model for the problem of locating appropriate levels and types of cleanup capability to respond to oil spills and allocating such capability among points of high oil spill potential. The model is formulated as a mixed integer-programming problem. The study takes into account frequency of spill occurrence, variability of spill volumes, different cleanup technologies, equipment efficiency and operability, fixed costs to open a facility, equipment acquisition, transportation and operating costs, and costs of damage as function of spill volume and level response. The objective of the strategic problem is to minimize the expected sum of response system costs and the costs due to damages from spills that may occur in the area.

Belardo et al. (1984) has applied a partial set covering model to the problem of locating oil spill response equipment. The model includes both assessments of the relative probability of occurrence and the impact after occurrence of various spill types. A multiple objective approach enables the decision-maker to evaluate strategies without confounding the probability of occurrence with the impact of occurrence. The paper discusses how the model can be used to support the decisions of emergency response planners. The planners must subjectively solve the problem of attaining the best overall protection with existing resources, while minimizing the risk of being unprepared for politically and environmentally sensitive events. The models basic limitation was that equipment needs were determined of the basis of a single spill volume. Thus, neglecting the large variability of the volume of an individual spill, which is perhaps the most important probabilistic feature of the problem.

CHAPTER 4

EMERGENCY PREPAREDNESS

This chapter gives a short introduction to the emergency preparedness system at the Norwegian Continental Shelf (NCS).

The emergency system to combat oil pollution on the NCS can be divided into three principal components: private, municipal and governmental preparedness. The private preparedness is represented by the Norwegian Clean Seas Association For Operating Companies (NOFO) and was established in 1978 as a respond to the blow out accident at Ekofisk Bravo platform in 1977. The municipal preparedness should handle smaller, sudden spills caused by normal activities, such as pollution from local industry and tank installations that are not the responsibility of the private sector. The governmental preparedness should handle oil spills that are neither covered by the private nor the municipal sector. This means in practice spills from shipping traffic and unidentified sources. The government has the superior responsibility for coordinating the private, municipal and governmental preparedness as one national system, and imposes cooperation whenever necessary (NOFO b, 2013).

This thesis focus on the private preparedness, where accidental oils pills from installations in the Barents Sea is handled. The private preparedness is represented by NOFO, and therefore the emergency system that NOFO has established is the main focus in this report.

NOFO is working according to defined requirements for oil spill preparedness, specific for each installation. Type and number of equipment needed, and within what time window they should be present is clearly stated. On behalf of 30 operating companies, NOFO has access to people and equipment to secure this preparedness. NOFO is supposed to handle sudden accidents caused by the operating companies own operations (NOFO d, 2013).

It is the operating companies that has the main responsibility of combating oil spill from the installations whether it is on the sea bottom or at sea level. The responsibility also includes the strategic management. NOFO has the responsibility for the tactical and operational management for the preparedness recourses (NOFO b, 2013). NOFO operates according to the multi- barrier principle imposed by the government. These barriers are an attempt to prevent oil spill to reach the shore and is illustrated in Figure 6 below (NOFO a, 2013).

- Barrier 0: Preventative measures on the installation
- Barrier 1: Combating close to source
- Barrier 2: Combating in open sea
- Barrier 3: Combating in the coastal zone
- Barrier 4: Beach cleanup
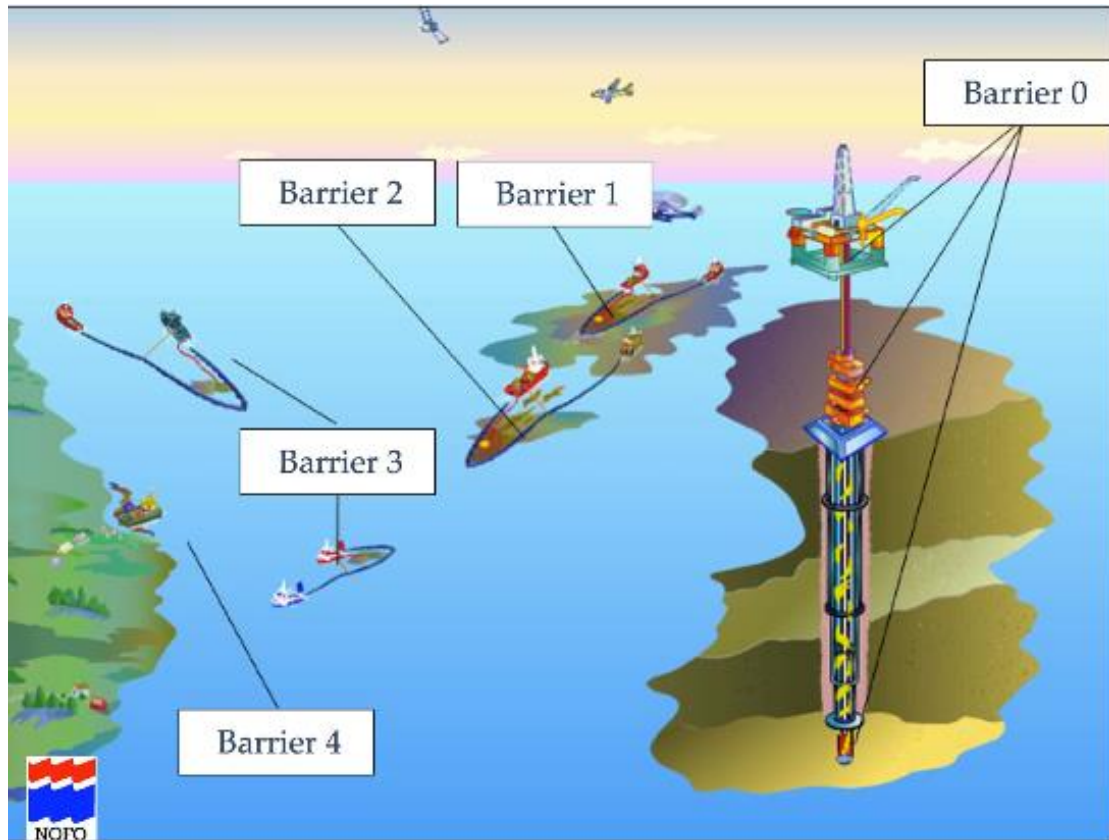
Figure 6 Illustration of barriers (NOFO c, 2014)

There is a focus on preventative measures in the preparedness system, as the main strategy in case of oil spill is to oppose the spill as close as possible to its source. If oil spill has occurred, the main focus is to prevent diffusion by collecting the spilled oil as close to its source as possible. Mechanical containment and recovery of oil is performed in barrier 1. Due to safety requirements considering fire- and explosion danger, the oil will drift for one to two hours before action is taken. In addition, the oil will attain and adequate viscosity making it easier to collect. Further, dispersant is used for the oil to easier be decomposed by microorganisms in the water column. Normally, barrier 2 is established shortly after Barrier 1 is in place. The same equipment for collecting oil in Barrier 1 is used in Barrier 2. In Barrier 3, a wider specter of resources is used, and the arrangement of these depends on location of environmental vulnerable resources and diffusion of the oil. In this barrier the cooperation model of Norwegian oil spill preparedness is very important. In barrier 4, land- based equipment and personnel from the private, municipal and governmental sector will contribute to the land zone clean up (NOFO a, 2013). The focus in this thesis will be on barrier 1.

NOFO presently operates five bases located in Stavanger, Mongstad, Kristiansund, Sandnessjøen and Hammerfest. These bases are equipped to perform heavier repairs and maintenance on he equipment, and are staffed by shifts day and night. Today all bases have two NOFO systems, except the base in Hammerfest, which holds three illustrated in Figure 7. The total NOFO systems offshore and at bases are 21 (Høyland & Walslag, 2012).

Figure 7 Locations of the NOFO bases (Høyland & Walslag, 2012)

4.1 EQUIPMENT

NOFO operate with a system consisting of one Oil Recovery Vessel (OR vessel), a tugboat, one 400 meters long boom, and skimmers for both light and heavy oils in Barrier 1. The tugboat is necessary to drag the boom (Høyland & Walslag, 2012). This system is illustrated in Figure 8, and in this thesis this combination is referred to as a NOFO system.

Figure 8 The NOFO system (NOFO c, 2014)

With the OR vessel at one end and the tug vessel at the other, the boom is inflated to float on the water, and towed downwind of the oil slick in a U – shape. This way, the oil is trapped and concentrated in the oil boom. Skimmers can be applied to skim the oil from the surface in the apex, and further be pumped into tankers on board the OR vessel (Høyland & Walslag, 2012).

Some OR vessel have a boom on board at all times, these vessels are classified as standing emergency. Other booms are placed on NOFO bases along the coastline, and are picked up by classified ships whenever necessary (Høyland & Walslag, 2012). Vessels classified as standing emergency are not considered in this report.

Other necessary equipment, such as dispersants is placed in depots along the coast. With a hub as an extension of the onshore base, the dispersants can also be placed closer to the installations.

4.2   RESPONSE TIME

The time it takes from an oil spill warning is received, until a recovery operation is implemented is referred to as the systems response time. The total response time is a sum of the following three components (NOFO d, 2014).

- Release time
- Transit time
- Deployment time

The release time is the time required before the OR vessel can start sailing. When the NOFO system is located at an onshore base, this time covers mobilizing necessary staff, equipment, and overall preparation of the OR vessel. The first system at a base should

be ready within 10 hours, and is referred to the system working in Barrier 1. The second system, corresponding to Barrier 2 has an upper time limit of 30 hours before transit. Due to the guard arrangement, only one of the systems can be ready within 10 hours. The first guard team has to be in place within three hours, but still there is time required to get a vessel to shore and prepared. The second guard team must be present within 30 hours. The second OR vessel is supposed to be ready for transit, when the guard team arrives. These time limits are set by NOFO as a guarantee to the operating oil companies (NOFO d, 2013).

For the OR vessel that operates as standing emergency, release time depends on other factors. Today NOFO operates with 7 geographical areas: Tampen, Troll/Oseberg 01, Troll/Oseberg 02, Haltenbakken, Sleipner, Volve, Gjøa and Balder. An OR vessel that operates as standing emergency, belongs to a given geographical area (NOFO d, 2013). The OR vessel that operates as standing emergency is immediately ready for transit when the OR vessel is sent to operate in the geographical area it belongs to. In that case, the release time can be eliminated. However, if the OR vessel is commanded to operate outside its given geographical area, extra time is required before transit can begin. This is because another vessel must be in place to undertake the responsibility for possible events in that area. These events may be man over board or fire at an installation. The new vessel does not need to possess oil protection equipment. The OR vessel cannot transit before this vessel is in its dedicated area (Høyland & Walslag, 2012).

The release time of tugboats is not as important as the release time of the OR vessels. This is due to the many and well spread tugboats on the NCS. NOFO have contracted 25 boats to mobilize as tugboats whenever necessary. Additionally, an agreement with the Norwegian Society for Sea Rescue (NSSR) states that some of their rescue boats is available as towing vessels if needed. All these vessels must be certified for towing an oil boom (Høyland & Walslag, 2012).

Transit time depends on sailing speed, as it is the time needed for sailing from one location to another. The needed time for deploying the boom and the time it takes to inflate it, is covered by the deployment time. The deployment time is approximately one hour, independent of vessels and geographical areas. The response time is calculated by adding the release time for a system, the transit time and the required duration for deploying the boom (NOFO d, 2013).

CHAPTER 5

PROBLEM DESCRIPTION

This chapter explains the problem this report should answer. It describes verbally the scope of the optimization model and the assumptions made in order to solve the problem.

The proposal in this thesis is to apply an extended base in order to improve the existing emergency preparedness system. The background for the proposal in this thesis is described in Chapter 1. In Figure 9 below, the new proposal is illustrated.
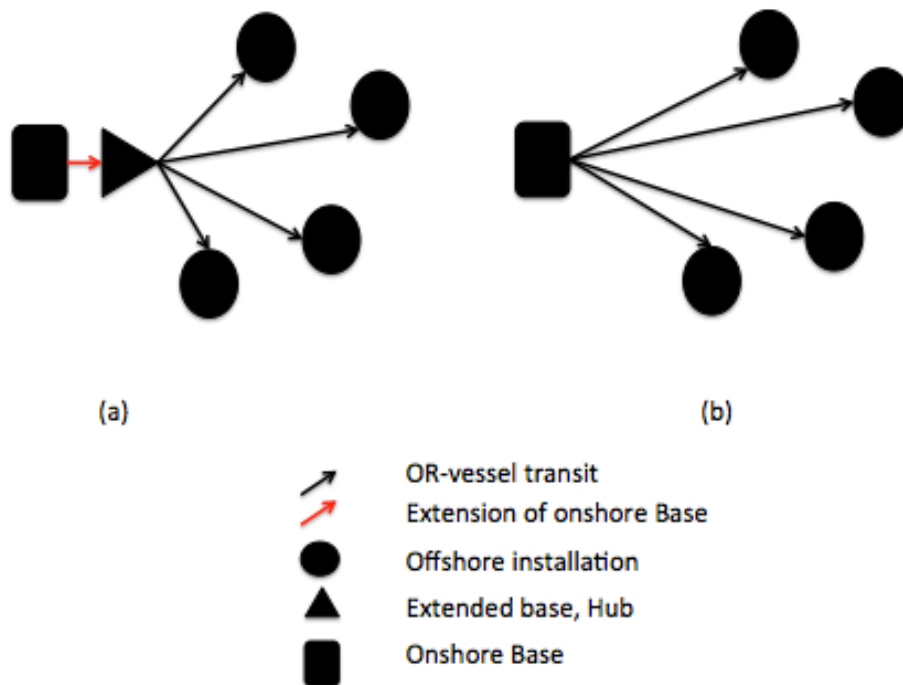
Figure 9 Allocation of emergency response assets

(a) Describes the solution where a hub is used as an extension for the onshore base. The hub is movable, and should be located near the operating installations. Consequently, the assets needed for emergency operations will be placed closer to the installations and possible emergencies. (b) Describes the conventional solution. The transit from the base is longer, thus the response time will increase.

The overall aim is to develop a model that finds the optimal location for the hub when the criticality of an operation installations is dependent on the phase of the operation.

The developed model should be used to investigate the possible advantages of utilizing an extended base for allocating emergency response assets compared to placing the assets at an onshore base.

5.1 ONSHORE BASE

The onshore base in this report is a base established for supporting offshore oil and gas activity. The base supplies operating installations. In addition, necessary service on equipment, installations and vessels can be performed at the base. Emergency response assets can be stored and maintained here. The onshore base is assumed to be open at all times.

5.2 EXTENDED BASE, HUB

In this report, the hub is considered as an extension for the onshore base. The hub can be a container carrier of another type of vessel big enough for carrying required oil recovery equipment, and to perform necessary mobilizations and maintenance can be performed onboard the vessel. The hub is movable, and the location for the hub is not given. In addition to store emergency equipment, the hub can be used for supply, or operate as an emergency hospital. Further, the hub can be used as a stop over for helicopters, due to their restricted range.

Based on a set of predefined locations given in latitudinal and longitudinal coordinates. The objective is to decide the optimal location of the hub in order to minimize the response time in case of oil spill accidents. Further more, the response time when utilizing a hub for emergency preparedness should be compared to the response time with a conventional solution. The hub is open and operating at all times and it is assumed that a guard team is present at the hub ready to respond at all times.

5.3 OR VESSEL

The OR vessel is an oil recovery vessel designed to recover spilled oil. The OR vessel is located around the coast, ready to respond to an emergency. If an emergency should occur, the oil recovery equipment is mobilized onboard the hub instead of the onshore base. Further, the necessary equipment is loaded onto the OR vessel. After the OR vessel is mobilized, the vessel transit from the hub to the installation where the oil spill occurred. It is assumed that the OR vessel operates with a constant speed and that there will always be a tugboat ready to operate when the OR vessel is ready.

5.4 OFFSHORE INSTALLATIONS

Offshore installations are either exploration installations or permanent installations that produces oil. The installations are presented by locations, where one installation is placed per location. The location is given in latitudinal and longitudinal coordinates.

Installations operate in different phases, and it is considered to as reasonable to divide operations into four phases:

- Arriving the drilling site
- Drilling in rock
- Drilling in oil producing layers
- Production

For the purposes of this report, it is assumed that some phases are more critical than others. In order to minimize risk, it is desired that the hub moves towards the installation during the most critical phase. This phase represent the location where an accident most likely will occur. In addition, where the accident represent the most serious impact. It is assumed that an emergency will occur only at one installation at a time. Consequently, the emergency preparedness will only be scaled to cover one emergency and the response will always transit from the hub location to the relevant installation.

5.5 BASE CASE

To illustrate the use of the model, an assumed scenario is created. Based on this scenario, the model should provide the optimal location for the extended base. In the following a description of the base case is presented, the assumed scenario for utilizing the model in this report.

The focus area of this report is emergency preparedness in the Barents Sea. Today, the emergency preparedness system in the Barents Sea is covered from the PolarBase at Hammerfest. It is assumed that four installations is placed and operating at the same time in the Barents Sea. The locations for these installations are generated randomly in the first run of the MatLab script.

The installation operate in different phases and the optimal location is anticipated to vary for each phase during a stated time period.

One single hub should be allocated and the optimal location for the extended base should be found both when the model minimize the average traveling distance as well as the response time. Further, these results should be compared with the case when the emergency response assets are placed at the onshore base at Hammerfest.

In this assumed scenario, the operations in the Barents Sea take place over ten time periods. In each period, the installations are operating in one of the four stated phases and each phase can last over several time periods. Which phase each installation is operating in, is defined in the installations schedule. This means that the optimal location for the extended base must be found ten times for both minimal average distance and minimal longest response time. The assumed schedule for the four installations is stated in Chapter 7.4.

5.5.1 Extension of the Base Case

Utilizing a hub solution on order to allocate emergency response assets might be an expensive solution. In combination with other areas of applications, these costs could be shared, resulting in alternate beneficial solutions for several parties.

To illustrate how the model developed in the base case can be combined with other areas of application, the stated restrictions for allocation of assets is added in the developed model in Akselsen (2014).

The scenario from the base case is still assessed, but in addition, all installations have demands for supply and services. It is assumed that installations have equal demands and requirement for services from the PSVs, and parameters from the existing model can be utilized.

The main objective of this case is to find the optimal placement of the hub where requirement for emergency response is met, at the same time as the transportation cost is kept at a minimum by reducing the number of required PSVs in the fleet. The objective function minimizes the total cost for a hub solution. After a solution is found for the hub solution, it should be compared to the results without a hub in order to discuss potential benefits and drawbacks. In the extension of the base case, the results for a hub solution for supply only is also assessed.

CHAPTER 6

DEVELOPMENT OF THE MATHEMATICAL MODEL

This chapter presents the mathematical formulation of the problem. The objective function, constraints and the required parameters are described. A general formulation is presented before a simplified version of the model is used to solve the specific problem in this report. The simplified version is described as a Set Partitioning Problem (SPP) with a two-step solution approach.

The location for the emergency assets can be found in several ways. By changing the objective function, either distances, durations or cost can be considered.

When the mathematical formulation is further developed in this report, the hub location is found by minimizing the average distance and the response time. The average distance is utilized in order to locate the hub as close as possible to all installations, and represent the average distance from a hub to all installations when stated requirements are fulfilled. The different critical levels and maximum allowable distance for each critical level is taken into account. The distance is indifferent of speed, therefore the distance can be important to consider. However, NOFO operates with response time when the preparedness system is developed. Therefore, it is the response time that is further assessed in this report. The installation that operates at the highest criticality level is also defined as the most likely accident site. The hub should therefore be located as near as possible to this installation, but still fulfill other stated requirements. This is done by minimizing the response time to the installation operating at the highest critical level. Finally, requirements for placement of emergency response assets are combined with an already existing model, where a hub solution is used for supplying oil and gas installations. This model minimizes the total operational costs. When the requirements for allocating emergency assets is implemented in the existing model, costs associated with storing and maintaining the assets is neglected. This is further explained in Chapter 8.

6.1   GENERAL FORMULATION OF THE OPTIMIZATION PROBLEM

In order to formulate the described problem in Chapter 5 and generate a general formulation of the problem, necessary sets, indices, parameters and decision variables must be stated.

The first sets to be defined are the set of installations, I, and the set of potential hub locations, J, as installations are to be served from a hub. Further, a set of critical levels, K, and a set of periods, P, is defined. Installations operate with different critical levels for different periods in time, and therefore these sets are necessary. The response time depends on the service speed of the vessels transiting between the hub and the different installations, as a consequence a set of vessels, V, in the fleet is created. The last set is a set where installations are bound to a critical level for a period in time, I_{kp}.

The required parameters are the distances between all possible hub locations and installations, D_{ij}. The distance divided by the service speed of the vessel, S_v, is the foundation for calculating the response time, together with the release time, F_v and the deployment time, T_v. The maximum allowed response time for critical level k, R_k, must also be defined.

The decision variables are binary variables stating if a hub location or a vessel is chosen or not. In addition, decision variables for installations served by a hub and a hub served by a vessel, is defined. The described sets, parameters and decision variables described above, are presented in Table 3 below.

Table 3 Sets, indices, parameters and variables in the general model

Input	Description
Sets	
I	Set of installations, indexed by i
J	Set of potential hub locations, indexed by j
K	Set of critical levels, indexed by k
P	Set of periods, indexed by p
V	Set of Vessels in fleet, indexed by v
I_{kp}	Set of installations with critical level k in period p, indexed by i, where $I_{kp} \subset I$
Parameters	
D_{ij}	Distance between installation i and potential hub location j
R_k	Maximum allowable response time for critical level k
N^i	Number of installations
N^h	Number of hubs to be located
S_v	Service speed for vessel v
F_v	Release time for vessel v
T_v	Deployment time for vessel v
Decision Variables	
x_j	1 if the hub is located at potential hub location j 0 if not
y_v	1 if vessel v is chosen 0 if not
z_{ij}	1 if installation i are served by hub location j 0 if not
δ_{jv}	1 if hub location j is served by vessel v 0 if not

For period p = p $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $p \in P$

Minimize total response time

$$\sum_i \sum_j \sum_v \left(\frac{D_{ij}}{S_v} + T_v + F_v\right)\delta_{jv} \qquad\qquad (6.1)$$

S.t

$$\sum_j x_j = N^h \qquad\qquad\qquad\qquad\qquad j \in J \quad (6.2)$$

$$\sum_j z_{ij} = 1 \qquad\qquad\qquad\qquad\qquad i \in I \quad (6.3)$$

$$\left(\frac{D_{ij}}{S_v} + T_v + F_v\right)\delta_{jv} \leq R_k \qquad i \in I_{kp}, j \in J, k \in K, v \in V \quad (6.4)$$

$$z_{ij} - x_j \leq 0 \qquad\qquad\qquad\qquad i \in I, j \in J \quad (6.5)$$

$$\sum_v \delta_{jv} - x_j \leq 0 \qquad\qquad\qquad v \in V, j \in J \quad (6.6)$$

$$\delta_{jv} - y_v \leq 0 \qquad\qquad\qquad v \in V, j \in J \quad (6.7)$$

$$x_j \in [0,1] \qquad\qquad\qquad\qquad\qquad j \in J \quad (6.8)$$

$$y_v \in [0,1] \qquad\qquad\qquad\qquad\qquad v \in V \quad (6.9)$$

$$z_{ij} \in [0,1] \qquad\qquad\qquad\qquad i \in I, j \in J \quad (6.10)$$

$$\delta_{jv} \in [0,1] \qquad\qquad\qquad\qquad j \in J, v \in V \quad (6.11)$$

The objective function (6.1) minimizes the total response time between installations and the extended base. The period p indicates what period the location is found for. Constraint (6.2) makes sure that exactly N^h hubs are located. Constraint (6.3) ensures that every demand is assigned to some facility. Constraint (6.4) makes sure that the response time between the installation and the base, is less than the maximum allowed response time for an installation. The critical level where the installation is operating in the current period, is considered. Constraint (6.5) allows assignment only to sites at which hubs have been located. Constraint (6.6) allows one vessel to serve one chosen hub location. Constraint (6.7) ensures that if a vessel is chosen, it is assigned to a located hub. Constraints (6.8), (6.9), (6.10) and (6.11) are integrality constraints for the decision variables.

6.2   STEP 1 – PREPROCESSING

A general formulation of the problem is stated. In order to solve the specified problem in this report, the optimization problem is reformulated to an SPP. This is a simplified formulation of the general problem. The SPP is presented in Chapter 2, together with drawbacks and benefits of using this method. In this part of the report, data implemented and generated in the preprocessing phase is presented.

The preprocessing phase is done in MatLab where many of the sets, and parameters can be handled. This leaves a simple problem to solve in Step 2. The results from Step 1 are used as input to Step 2, where the data is implemented in the optimization model, and solved in the optimization solver, Xpress IVE.

The necessary data to solve the SPP problem is a generated set of installations, I, and a set of potential facility sites, J. Further, the calculated response time between installations and potential hub locations, R_{ij}, should be known together with the maximum allowable response time for the each installation, R_i^{MAX}. The process and input of generating the input file in order use it as input in the SPP problem is described in the following part of this report.

6.2.1   Stated Values

In the first part of the MatLab script, direct input parameters are stated for the specific problem in this report. The necessary parameters are described in this chapter, while the value of the parameters is stated in Chapter 7.

In order to develop the model, the *number of operating installations, N^i,* in the Barents Sea is stated.

The installations are operating in a number of possible periods, N^p. The *current period, p,* is equal to the period the installations are operating in, at a period in time. As the installations are operating in different operational stages for different periods, the allocation of the hub will vary. In order to document the location for the hub in all phases, the script should run N^p times, one for each of the possible periods.

The *schedule* for the operation of each installation is implemented as a N^ixN^p matrix. This schedule is manually implemented in this report. The schedule states the installations operational stage as a critical level for all periods.

The maximum distance depends on the current operational stage for the installation. The *maximum allowable response time for critical level k, R_k,* between the hub and the installation is stated.

In the described problem in this report, there is only one vessel considered. This vessel has a *service speed*, S_v, a *release time*, F_v, and a *deployment time*, T_v. These parameters are stated as variables in the generated MatLab Script. The calculated response time is dependent on these values.

The *location of the installations* represent the set of installations, I. The locations are randomly generated for the first run, but to compare the results, it is required that the location of each installation has the same location. Therefore, the location of the installations has to be stated for the rest of the N^p runs. The location for the different installations is generated within a predefined area. The predefined area is further explained in Chapter 7.1.

The *hub grid size,* defines how many possible hub locations that should be generated.

6.2.2 Calculated Values

The generation of the hub grid represents the *set of potential facility sites*, J, covering the entire relevant area in the Barents Sea. This is explained in Chapter 2.3.2. 245 possible facility sites are generated with regular intervals.

The length of all *distances between all installations and possible hub locations, D_{ij},* is represented in a 4x245 matrix. The method for calculating the distance is discussed in chapter 2.4. The points for potential sites are generated for each half longitudinal and latitudinal degree.

The *Response time, R_{ij},* from the hub to the installations is calculated from the distance between the hub and installations. The distance is divided by the OR vessels service speed, in addition, F_v and T_v is added.

The *maximum allowable response time for an installation, R_i^{MAX},* depends on the phase that the installation is operating in, as explained in Chapter 5.4. Which phase the installation is operating in must be stated. It is the current period that decides what the maximum distance can be for each of the installations.

Distances and durations larger than the defined maximum between hub and installation will not be considered in this step. They will be eliminated in step 2, in the optimization solver.

6.3 STEP 2 – OPTIMIZATION MODEL

When the input file for step 2 is generated, the optimization model that solves the problem is formulated as an SPP.

From the pre-processing phase, a set of installations is generated, I, with random locations within a predefined area. Further, a set of potential facility sites is generated, J. The distance between the installations and the potential hub sites, D_{ij}, are then calculated. As it is explained in Chapter 7, there is one type of vessels that responds to a possible accident and this vessel has a stated speed, S_v, a stated release time, F_v and a stated deployment time, T_v. This makes it possible to calculate the response time between the installations and all possible hub locations, R_{ij}.

R_{ij} can replace D_{ij} as a parameter in the mathematical model. Thus, S_v, F_v, and T_v can be removed from the model, as they are considered in the pre-processing phase. Also the set of vessels, V, or the decision variable y_v are no longer necessary in the mathematical model.

In the pre-processing phase, the schedule is implemented. This schedule presents critical levels for the installations in different periods in time I_{kp}. The maximum

response time for an installation with critical level k, R_k, is stated. The maximum response time for the installations in the current period is given as R_i^{MAX}, and generated for all installations based on the schedule and the current period in the MatLab script. This means that the set of installations with critical level k in period p are handled in step one, and can be removed from the mathematical formulation together with the set of critical levels.

The problem to be solved in this report is represented by a singular hub. This means that the parameter N^h is replaced by the number 1 in constraint (6.2). The decision variable z_{ij} can be removed, as only one hub is serving the installations. Thus, Constraint (6.3), (6.5), (6.6), (6.7), (6.9) and (6.10) are no longer necessary, and removed from the problem.

Taken all this into account, a new formulation of the mathematical can be presented. The model contains a set of installations and a set of potential facility sites. Further, the parameters constrains the response time between the extended base and installations for all potential facility sites, and all the installations. It also contains the stated maximum allowed response time between the installations and the hub location for the different critical levels. These values are given as input from step 1. Table 4 below presents the simplified version of the model described in Chapter 6.1, and the model solved in Xpress IVE.

Table 4 Sets, indices, parameters and variables in the simplified model

Input	Description
Sets	
I	Set of installations, index by i
J	Set of potential hub locations, index by j
P	Set of periods, index by p
Parameters	
R_{ij}	Response time between installation i and potential hub location j
R_i^{MAX}	Maximum response time for installation i
N^i	Number of installations
Decision Variables	
x_j	1 if the hub is located at hub location j
	0 if not

For period P = p $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $p \in P$

Minimize average response time

$$\sum_i \sum_j R_{ij} x_j \qquad\qquad\qquad (6.12)$$

S.t

$$\sum_j x_j = 1 \qquad\qquad\qquad i \in I \quad (6.13)$$

$$R_{ij} x_j \leq R_i^{MAX} \qquad\qquad\qquad i \in I, j \in J \quad (6.14)$$

$$x_j \in [0,1] \qquad\qquad\qquad j \in J \quad (6.15)$$

The objective function (6.12) minimizes the total response time between the extended base and the installations for one period in time. Constraint (6.13) makes sure that one facility site is chosen only. Constraint (6.14) requires that the response time between the installation and the facility site is less or equal to the maximum response time. Constraint (6.15) is an integrality constraint for the decision variable.

As mentioned earlier, it is not only the response time between the hub and the installations that is assessed. The objective function developed can also consider distances between installations and the hub. This change requires minimal effort, and the changes are all done in the preprocessing phase, except for reformulating the objective function, which has to be handled in the optimization solver in step 2. In the preprocessing phase, the calculation of the distance between the installations and the hub, D_{ij}, is used instead of the response time, R_{ij}. Further, the maximum allowed response time for critical level k, must be stated as the maximum allowable distance for critical level k, D_k.

When the response time to the installation operating at the highest critical level is minimized, the objective function is changed to minimize the response time between installation i.

CHAPTER 7

DATA ASSEMBLING

This Chapter presents all the input data used in this study.

7.1   INSTALLATION LOCATIONS

The number of installations operating in the Barents Sea can vary. Random locations within the area given for the 23rd licensing round are used for the location of each installation. Figure 10 below illustrate the area of the 23rd licensing round regarding announced oil and gas blocks in the Barents Sea. In this report, possible locations for the installation span from 16.00 to 33.00 degrees in the longitudinal direction and from 71.00 to 74.00 degrees in the latitudinal direction.
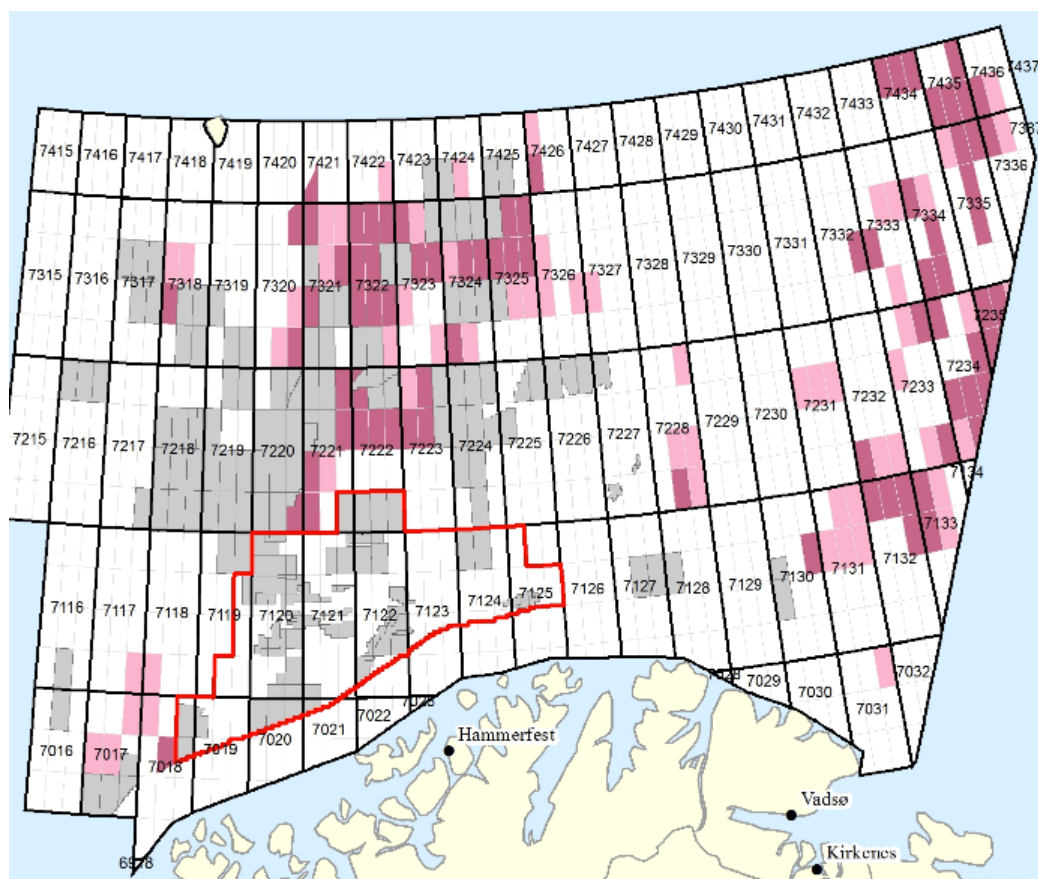
Figure 10 The 23rd licensing round (Norwegian Petroleum Directorate, 2015)

7.2   OPERATIONAL PHASES AND LEVEL OF CRITICALITY

From Chapter 5.4, installations are assumed to operate in four different phases, with four different levels of criticality. Table 5 presents the different phases and the critical level corresponding to each phase.

Table 5 Operational phases and their critical levels

Operational phase	Level of criticality	Description of critical level
Arrival at location where the well is located	0	Low risk phase
Drilling through rock	1	Low to medium risk phase
Drilling through oil producing layer	3	High risk phase
Production of oil	2	Medium to high risk phase

7.3   MAXIMUM DISTANCES AND DURATIONS

With each critical level, it is defined a maximum distance or duration between the installation and the hub location. It is desired that the hub should move towards the installation that operates at a higher criticality level. Four levels of maximum distance are defined, illustrated in Figure 11 below.
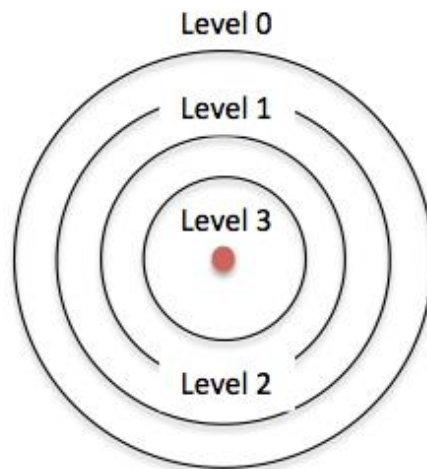
Figure 11 Constraints for different levels of criticality at installations

The maximum allowable distance between the hub and the installation is defined as follows: The distance from the onshore base to the furthest located installation, divided by two.

In this report, the installation furthest from the onshore base is located at the north east corner of the possible are of operation. The definition is based on the assumption that the restriction will result less distance between the hub and the installation than the distance between the installation and the onshore base in most cases. Hence, it will be made sure that assets will be placed as near as possible to the installations.

The distance between the base and the north east corner of the defined area for operation is 279 nm. This means that the maximum distance should not be larger than 140 nm.

The maximum response time is based on the decided maximum distances. It is assumed that the OR vessel has a constant speed, S_v, of 14 knots. NOFO states that 14 knots is a conservative assumption, but this speed has been proven to be an appropriate mean value for planning purposes (NOFO e, 2014).

Table 6 Service speed for the OR vessel

	Service Speed	Unit
OR Vessel	14	[Knot]

The maximum distance for critical level 0 is 140 nm, resulting in a transit time between the hub and the installation of 10 hours. The response time, from Chapter 4, is the total of release time, transit time and deployment time. The release time, F_v is set to 10 hours in accordance with the first NOFO system requirements, and the deployment time, T_v is set to 1 hour.

Table 7 Release time and Deployment time for the OR vessel

	Duration	Unit
Release time, F_v	10	[Hours]
Deployment time, T_v	1	[Hour]

As the release time for the vessel is set to 10 hours in this report, the location of the OR vessel at a time of emergency will not be considered in this report.

With the stated release time and deployment time, total maximum response time is set to 21 hours for critical level 0.

Table 8 Max distance and max response time for critical level 0

Critical level	Max distance [nm]	Release time [Hours]	Transit time (Distance/Speed) [Hours]	Deployment time [Hours]	Max response time [Hours]
0	140	10	140/14 = 10	1	21

For purposes of this analysis, the maximum distances are defined to decrease with 10 nm for each level of criticality, and the duration is similarly set to decrease with one hour. By doing this, the maximum values of duration and distance have a clean number, but with minor variations. These variations are assumed to be negligible. Table 9 below present the constraints for maximum allowable distance, D_k, and maximum allowable response time, R_k, for critical level k.

Table 9 Max distance and max response time for critical levels

Operational stage	Critical level	Max distance to hub [nm]	Max response time [Hours]
Arrival	0	140	21
Drilling in rocks	1	130	20
Drilling in oil producing layers	3	110	18
Production	2	120	19

7.4   SCHEDULE FOR THE INSTALLATIONS

The phase in which an installation operates, changes over time. This means that the maximum distance allowed between installation and hub will vary with time. In this report a schedule for the operating installations in the Barents Sea is assumed. The schedule is divided into ten phases, and each of the installations is at different stages in the operation. The hub should be moved between the installations, satisfying the maximum distance or response time requirement. Table 10 below illustrates the schedule used in this report. The critical levels stated in the schedule, defines the operational phase.

Table 10 Schedule for the different installations

Phase/ Installation	1	2	3	4	5	6	7	8	9	10
Inst 1	0	1	1	3	3	2	2	2	2	2
Inst 2	0	0	0	1	1	3	3	2	2	2
Inst 3	0	0	1	1	1	3	3	3	2	2
Inst 4	3	3	3	2	2	2	2	2	2	2

As the operational stages for each vary over time, and is independent from the other installations, the optimal location for the extended base should be stated for each of the different phases. The duration of the period is not defined in this report.

7.5   ONSHORE BASE

In this report, the situation in the Barents Sea is investigated and the only onshore base considered is the PolarBase at Hammerfest, which is the Barents Sea main base for oil and offshore activities. The exact location of the PolarBase is presented in Table 11 below.

Table 11 Location of the onshore base

Onshore base	Latitude [^{o}N]	Longitude [^{o}E]
PolarBase	70.38	23.40

7.6   POTENTIAL HUB LOCATIONS

The hub grid generation that is described in Chapter 2, requires inputs that define the matrix- size and an initial hub location, defined as the south west corner. The hub grid is generated as a rectangle over the area where the blocks are nominated in the 23rd licensing round, and equal to the restricted area for the location of installations. The corner points of the rectangle for the generated hub grid is illustrated in Figure 12. One point for every half degree in each direction is generated. 245 potential facility sites is generated in the hub grid.
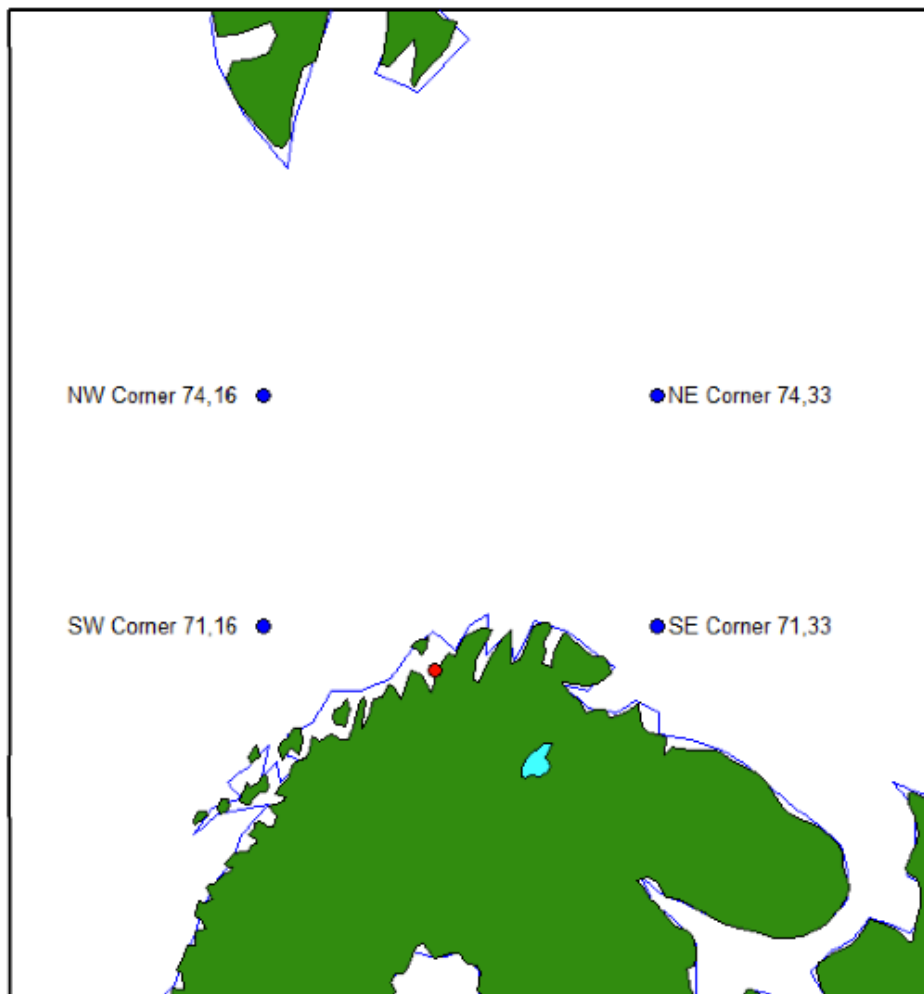
Figure 12 Corner points for potential hub locations

CHAPTER 8

EXTENSION OF THE BASE CASE

Utilizing a hub solution on order to allocate emergency response assets might be an expensive solution. In combination with other areas of applications, these costs could be shared, resulting in alternate beneficial solutions for several parties. Therefore a hub used for placing emergency response assets are combined with a hub used for supplying oil and gas installations. In this part of the report, the chosen existing model is presented together with a description of the steps of combining the two models.

8.1 PRESENTATION OF EXISTING MODEL

Akselsen (2014) presents a model where the hub solution is utilized for supplying oil and gas installations in the Barents Sea. This concept is described in the Introduction.

The chosen model is solved with a two-step solution approach. In the first step, Phase 1, routes are generated together with parameters used as input in the second step, Phase 2.

The routes are generated manually. The potential hub locations are generated as a hub grid, where 12 possible locations are developed with regular intervals. The length of all the routes is calculated from each potential hub location. The duration of each route is determined based on the distances and a given required services per period. Other parameters calculated in Phase 1 are cost for serving hub-vessels, minimum number of required hub vessels, and big M values required for three coupling constraints in the mathematical model.

Parameters that are given as direct input is the period, the unit cost for using one PSV and one hub vessel, the base cost, the required number of weekly services at each installation and the capacity for all PSVs.

In Phase 2, the optimization model for a single hub-allocating problem is solved with the parameters from Phase 1 used as input. The problem determines the hub location and the onshore supply base in order to minimize the transportation cost. The mathematical formulation is described below, where Table 12 presents sets indices, parameters and decision variables from the existing model.

Table 12 Sets, indices, parameters and variables in existing mathematical model

Input	Description
Sets	
I	Set of installations, indexed by i
H	Set of alternative hub locations, indexed by h
B	Set of alternative base locations, indexed by b
R	Set of routes between hub and installation(s), indexed by r
P	Fleet of possible PSVs p used for supply, indexed by p
K	Set of times a route r can be sailed per period, indexed by k
Parameters	
T^{hr}	Duration of route r originating and ending at hub location h
C_{ET}	Cost per unit chartered and used PSV per period
C_{bh}	Cost per unit chartered and used hub – vessel h per period
C_b	Cost of making use of supply base b per ton cargo transported from base
W	Constant, limit on sailing hours per period
S_i	Required number of demanded weekly services for installation i
A_{ir}	If installation i is visited of route r, 0 otherwise
Q_p	Deck load capacity for PSV p
D_i	Demand at installation i per period
M_p	Constant, big number
M_r	Constant, big number
Decision Variables	
δ_h	1 if hub location h is used 0 otherwise
γb	1 if base location b is used 0 otherwise
α_p	1 if PSC p is used 0 otherwise
ρ_{bh}	1 if a vessel shuttle between base b and hub h 0 Otherwise
x_{prh}	Integer variable, number of timers PSC p sails on route r starting and ending in hub h each period
q_{iprk}	Integer variable, volume of cargo delivered to installation I on route r by PSV p time number k the route is sailed
β_{prk}	1 if PSV p sails on route r time number k 0 otherwise

Mathematical model
Minimize total cost:

$$\sum_i C^{ET} \alpha_p + \sum_{b \in B} \sum_{h \in H} C_{bh} \rho_{bh} + \sum_{b \in B} \sum_{i \in I} C_b D_i \gamma_b \qquad (8.1)$$

S.t

$$\sum_{h \in H} \sum_{p \in P} \sum_{r \in R} A_{ir} x_{prh} \geq S_i \qquad\qquad i \in I \quad (8.2)$$

$$\sum_{h \in H} \delta_h = 1 \qquad\qquad (8.3)$$

$$\sum_{b \in B} \gamma_b = 1 \qquad\qquad (8.4)$$

$$\sum_{h \in H} x_{prh} - M^p \alpha_p \leq 0 \qquad\qquad p \in P, r \in R \quad (8.5)$$

$$\sum_{h \in H} \sum_{r \in R} x_{prh} - M^p \delta_h \leq 0 \qquad\qquad p \in P, h \in H \quad (8.6)$$

$$\gamma_b = \sum_{h \in H} \rho_{bh} \qquad\qquad b \in B \quad (8.7)$$

$$\delta_h = \sum_{b \in B} \rho_{bh} \qquad\qquad h \in H \quad (8.8)$$

$$\sum_{r \in R} T_{hr} x_{prh} \leq W \qquad\qquad p \in P, h \in H \quad (8.9)$$

$$\sum_{p \in P} \sum_{r \in R} \sum_{k \in K} q_{iprk} \geq D_i \qquad\qquad i \in I \quad (8.10)$$

$$q_{iprk} - M^r \beta_{prk} \leq 0 \qquad i \in I, r \in R, p \in P, k \in K \quad (8.11)$$

$$\sum_{k \in K} \beta_{prk} = \sum_{h \in H} x_{prh} \qquad\qquad r \in R, p \in P \quad (8.12)$$

$$Q_p \geq \sum_{k \in K} \sum_{i \in I} q_{iprk} \qquad\qquad r \in R, p \in P \quad (8.13)$$

$$q_{ipr,k+1} \leq q_{iprk} \qquad i \in I, p \in P, r \in R, k \in (K-1) \quad (8.14)$$

$$\beta_{ipr,k+1} \leq \beta_{iprk} \qquad p \in P, r \in R, k \in (K-1) \quad (8.15)$$

$$\delta_h \in [0,1] \qquad\qquad h \in H \quad (8.16)$$

$$\gamma_b \in [0,1] \qquad\qquad b \in B \quad (8.17)$$

$$\alpha_p \in [0,1] \qquad\qquad p \in P, r \in R \quad (8.18)$$

$$\rho_{bh} \in [0,1] \qquad\qquad h \in H, b \in B \quad (8.19)$$

$$x_{prh} \geq 0 \; integer \qquad\qquad p \in P, r \in R \quad (8.20)$$

$$q_{iprk} \geq 0 \; integer \qquad\qquad i \in I, r \in R, p \in P \quad (8.21)$$

$$\beta_{prk} \in [0,1] \qquad\qquad p \in P, r \in R, k \in K \quad (8.22)$$

The objective function (8.1), minimizes the total costs of the charter, use of supply vessels and use of bases in a logistic hub network. Constraint (8.2) assures that each platform is serviced at least as many times as the minimum requirement during one period. Constraint (8.3) assures that only one hub is used and constraint (3.4) assures that exactly one onshore service base is used. Constraint (8.5) is a coupling constraint assuring that if route r is selected, the corresponding binary variable is used and that vessels existence for the vessels that are given a route. Constraint (8.6) assure that the same hub is used both in echelon 1 and 2. Constraint (8.7) is a base existence constraint imposing that if base b does not exist, no vessel sails from the given location. In addition, it ensures that if there is a connection between base b and hub h, the given base is chosen. Constraint (8.8) is the hub existence constraint assuring that if a given hub is not used, no shuttle vessel shall sail to the hub. Constraint (8.9) assure that the duration on all routes sailed by each PSV are within the given time period. Constraint (8.10) assure that there is delivered at least the required amount of cargo to each installation. Constraint (8.11) and (8.12) are coupling constraints. Constraint (8.13) assures that the total supply delivered at the installations does not exceed the capacity in the vessel for each route. Constraint (8.10) and (8.13) assures consistency between demand at installations and capacity at vessels. Constraint (8.14) and (8.15) is anti-symmetry constraints used on variable indexed by k. Constraint (8.16) – (8.22) impose binary and integer restrictions for the variables.

8.2 STEP 1 – PREPROCESSING

The problem is solved in two steps as a partial set covering problem, and has an equal approach to the problem generated and solved in this report.

The part considering the allocation of emergency response assets are described earlier, and will not be repeated as a part of the description of the preprocessing phase. In the following, the preprocessing considering the existing model, and not presented earlier will, be described.

8.2.1 Stated Values

The *base cost*, C_b, is given per ton cargo shipped from the base. In this report, only one base is considered. Time value of money is not taken into consideration.

The *required number of weekly services* at each installation, S_i, is given as input directly. To ensure correct scaling, S_i is multiplied by the number of periods.

The capacity for the PSVs, Q_p, is the same for all PSVs, as the fleet is assumed homogenous. The value is given as input directly. The capacity for the hub vessel is the same for all vessels.

The *period*, W, is given directly as an input parameter. W influences how many times each route maximally can be sailed. One period in the existing model is equal to one full week.

Below, Table 13 describes the values used in this part of the report, taken directly from Akselsens (2014) model.

Table 13 Data used in existing model (Akselsen, 2014)

	Value	Unit
Yearly cost per hub	120 000	[10^3 NOK]
Yearly cost per PSV	80 000	[10^3 NOK]
Capacity hub	750	[Ton]
Capacity PSV	450	[Ton]
Service Speed hub	12	[Knot]
Service speed PSV	15	[Knot]
Base Cost, PolarBase	1,0	[10^3 NOK / Ton]
Demand at installations	230	[Ton]
Services per installations per period	3	-

8.2.2 Calculated Values

The number of operating installations is the basis for the route generation representing all possible combinations of sailing distances between the hub and the installations. The number of installations is stated, and the possible routes are automatically generated. The routes are presented in a A_{ir} matrix where the matrix describes which installations are visited on each route. In the existing model, the route generation and generation of the A_{ir} matrix were handled manually. In this report, they are handled automatically.

When all possible routes are generated, the *duration of sailing the route, T_{hr},* is calculated. The calculated value is the shortest path of the route.

The total cost for utilizing a hub vessel, C_{bh}^{EO}, are found in the preprocessing phase. It varies with the number of hub vessel required to serve the installations. C_{bh}^{EO} is calculated for all possible base and hub combination. The yearly cost for chartering one hub vessel is given. Based on this, the cost per period is calculated. The cost is multiplied with the minimum number of hub-vessels required, *nVessel*, to transit between the onshore base and the hub location. The size depends on number of hubs and installations. All elements are then given the value 2, due to the assumption of always being open. If a hub vessel breaks with time or capacity constraints, a third intermediate unit is added to the fleet.

The unit cost for using one PSV, C_{ET}, is based on the yearly chartering cost, and is dependent on the period, W.

Constraints in the mathematical model require *big M values* for both the *maximum number of trips* and *maximum required cargo delivery* for all installations. The maximum number of trips one PSV can sail on one route between the hub and the installation, determines M^p. Thus, it is calculated by dividing the period W by the minimum duration of all routes. The amount of cargo a PSV delivers to each installation on a route determines M^r. The calculation of M^r builds on the assumption of that delivered cargo is equal to the demand of the installation. The maximum required cargo delivery for all installations rule as the M^r value.

8.3   STEP 2 – MATHEMATICAL MODEL

In Table 14 sets, indices, parameters and variables form the model in Akselsens (2014) is presented. The parameters in the existing model is used, consequently the stated parameters for the generated model in this thesis are changed to correspond with the existing model.

The set of periods is added, as the criticality level at each installation changes in time. The optimal location of the hub has to be found for all phases of the scheduled in order to meet requirements for response time.

Two new parameters has to be added, the response time for the OR vessel between a hub location and the installation, T_{hi}^{OR}, and maximum response time for each of the installations, T_i^{Max}, previous R_{ij} and R_i^{Max} respectively. These parameters are calculated in the preprocessing phase.

In the mathematical formulation, one constraint is added, constraint (8.23). This is the constraint that makes sure that the response time between a hub and an installation is smaller or equal to the maximum allowed response time, $T_{ih}^{OR}\delta_h \leq T_i^{MAX}$. In the generated model in this report, the constraint corresponds to $R_{ij}x_j \leq R_i^{MAX}$.

The objective function minimizes the total cost for supplying the installations. The cost of storing emergency response assets is not considered. As long as the requirements for response time is fulfilled, the allocation of the hub is considered to be sufficient for the emergency response assets. 10 runs is required when the problem is solved, due to the operational phases for the installations.

When the result from conventional supply is found, the cost for chartering the hub vessel is sat to zero, the hub grid is removed and the only possible location is the PolarBase in the MatLab script. T_{hi}^{OR} and T_i^{Max} is also removed from the script. In Xpress IVE, the added constraint for response time must be removed, together with the parameters T_{hi}^{OR} and T_i^{Max}. The same procedure must be done when supply only is assessed, but then the hub grid and the hub charter cost is kept in the MatLab script.

Table 14 Sets, indices, parameters and variables for the combined model

Input	Description
Sets	
I	Set of installations, indexed by i
H	Set of alternative hub locations, indexed by h
B	Set of alternative base locations, indexed by b
R	Set of routes between hub and installation(s), indexed by r
P	Fleet of possible PSCs p used for supply, indexed by p
K	Set of times a route r can be sailed per period, indexed by k
Parameters	
T^{hr}	Duration of route r originating and ending at hub location h
T_{hi}^{OR}	Response time for a OR vessel between hub h and installation i
T_i^{Max}	Maximum response time for OR vessel between hub h and installation i
C_{ET}	Cost per unit chartered and used PSV per period
C_{bh}	Cost per unit chartered and used hub – vessel h per period
C_b	Cost of making use of supply base b per ton cargo transported from base
W	Constant, limit on sailing hours per period
S_i	Required number of demanded weekly services for installation i
A_{ir}	If installation i is visited on route r, 0 otherwise
Q_p	Deck load capacity for PSV p
D_i	Demand at installation i per period
M_p	Constant, big number
M_r	Constant, big number
Decision Variables	
δ_h	1 if hub location h is used 0 otherwise
γb	1 if base location b is used 0 otherwise
α_p	1 if PSV p is used 0 otherwise
ρ_{bh}	1 if a vessel shuttle between base b and hub h 0 Otherwise
x_{prh}	Integer variable, number of timers PSV p sails on route r starting and ending in hub h each period
q_{iprk}	Integer variable, volume of cargo delivered to installation I on route r by PSV p time number k the route is sailed
β_{prk}	1 if PSV p sails on route r time number k 0 otherwise

Mathematical model

For period P = p $\hspace{6cm} p \in P$

Minimize total cost:

$$\sum_i C^{ET} \alpha_p + \sum_{b \in B} \sum_{h \in H} C_{bh} \rho_{bh} + \sum_{b \in B} \sum_{i \in I} C_b D_i \gamma_b \hspace{2cm} (8.1)$$

S.t

$$\sum_{h \in H} \sum_{p \in P} \sum_{r \in R} A_{ir} x_{prh} \geq S_i \hspace{3cm} i \in I \hspace{0.5cm} (8.2)$$

$$\sum_{h \in H} \delta_h = 1 \hspace{6cm} (8.3)$$

$$\sum_{b \in B} \gamma_b = 1 \hspace{6cm} (8.4)$$

$$T_{ih}^{OR} \delta_h \leq T_i^{MAX} \hspace{5cm} (8.23)$$

$$\sum_{h \in H} x_{prh} - M^p \alpha_p \leq 0 \hspace{3cm} p \in P, r \in R \hspace{0.5cm} (8.5)$$

$$\sum_{h \in H} \sum_{r \in R} x_{prh} - M^p \delta_h \leq 0 \hspace{2cm} p \in P, h \in H \hspace{0.5cm} (8.6)$$

$$\gamma_b = \sum_{h \in H} \rho_{bh} \hspace{4cm} b \in B \hspace{0.5cm} (8.7)$$

$$\delta_h = \sum_{b \in B} \rho_{bh} \hspace{4cm} h \in H \hspace{0.5cm} (8.8)$$

$$\sum_{r \in R} T_{hr} x_{prh} \leq W \hspace{3cm} p \in P, h \in H \hspace{0.5cm} (8.9)$$

$$\sum_{p \in P} \sum_{r \in R} \sum_{k \in K} q_{iprk} \geq D_i \hspace{3cm} i \in I \hspace{0.5cm} (8.10)$$

$$q_{iprk} - M^r \beta_{prk} \leq 0 \hspace{2cm} i \in I, r \in R, p \in P, k \in K \hspace{0.5cm} (8.11)$$

$$\sum_{k \in K} \beta_{prk} = \sum_{h \in H} x_{prh} \hspace{3cm} r \in R, p \in P \hspace{0.5cm} (8.12)$$

$$Q_p \geq \sum_{k \in K} \sum_{i \in I} q_{iprk} \hspace{3cm} r \in R, p \in P \hspace{0.5cm} (8.13)$$

$$q_{ipr,k+1} \leq q_{iprk} \hspace{2cm} i \in I, p \in P, r \in R, k \in (K-1) \hspace{0.5cm} (8.14)$$

$$\beta_{ipr,k+1} \leq \beta_{iprk} \hspace{2cm} p \in P, r \in R, k \in (K-1) \hspace{0.5cm} (8.15)$$

$$\delta_h \in [0,1] \hspace{4cm} h \in H \hspace{0.5cm} (8.16)$$

$$\gamma_b \in [0,1] \hspace{4cm} b \in B \hspace{0.5cm} (8.17)$$

$$\alpha_p \in [0,1] \hspace{4cm} p \in P, r \in R \hspace{0.5cm} (8.18)$$

$$\rho_{bh} \in [0,1] \hspace{4cm} h \in H, b \in B \hspace{0.5cm} (8.19)$$

$$x_{prh} \geq 0 \text{ integer} \hspace{3cm} p \in P, r \in R \hspace{0.5cm} (8.20)$$

$$q_{iprk} \geq 0 \text{ integer} \hspace{3cm} i \in I, r \in R, p \in P \hspace{0.5cm} (8.21)$$

$$\beta_{prk} \in [0,1] \hspace{3cm} p \in P, r \in R, k \in K \hspace{0.5cm} (8.22)$$

CHAPTER 9

RESULTS

In this chapter, generated results are presented. In this study, two different cases from the base case have been carried out, and one extension of the base case.

- The hub is allocated when the average distance between a hub and the installations is minimized
- The hub is allocated when the response time between the hub and the installation operating at the highest critical level is minimized
- The hub is allocated when total cost for supply is minimized and emergency assets is stored at the hub

Two different combinations of locations for the installations have been assessed, scenario 1 and scenario 2. In this chapter, the results are presented and commented only. The results are discussed in Chapter 10.

The results for all cases are compared to the result for allocation of emergency assets at the onshore base at Hammerfest. For the extended case, the results are also compared to the results if the hub was used for supply only, and results for supply with a conventional solution.

9.1 INSTALLATION LOCATION

In the scenario created in this report, four installations operate in the Barents Sea and the installations have two different combinations of locations. These locations are used throughout the rest of the report. The coordinates for the installations are given in the tables below, while Figure 13 illustrate their positions. The presented locations for the installations in Table 15, is referred to as scenario 1. The presented locations for the installations in Table 16, is referred to as scenario 2.

Table 15 Locations for installations in scenario 1

Installation	Latitude [^{o}N]	Longitude [^{o}E]
Inst 1	72	19
Inst 2	72	24
Inst 3	74	24
Inst 4	74	27

Table 16 Locations for the installations in scenario 2

Installation	Latitude [^{o}N]	Longitude [^{o}E]
Inst 1	72	26
Inst 2	74	16
Inst 3	73.5	27.5
Inst 4	71.5	18
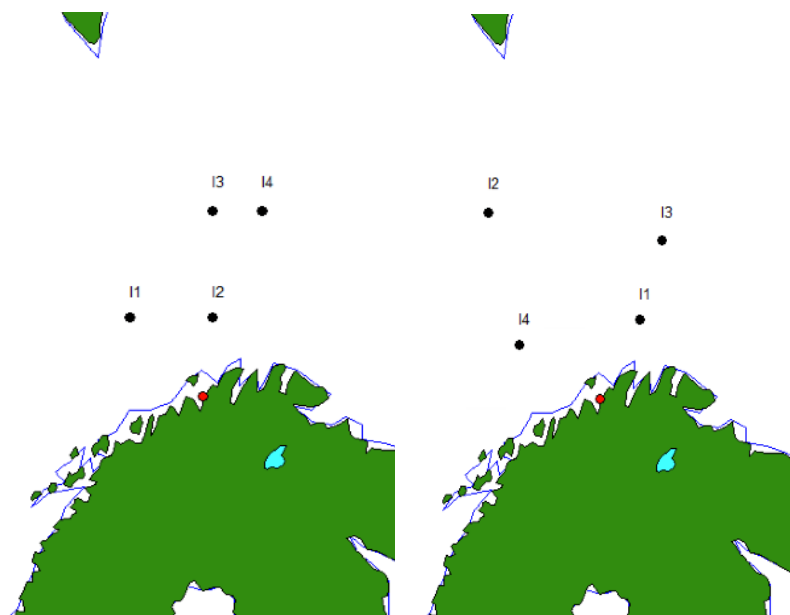
Figure 13 Positions for the installations in scenario 1 and scenario 2

9.2   LOCATION FOR HUB WHEN AVERAGE DISTANCE IS MINIMIZED

When the average distance is minimized the results is presented in two tables and one figure for both scenarios. One table presents the results for a hub solution, while the other presents results if the onshore base is used. The figure illustrates the optimal locations. The objective function when the average distance is minimized states:

$$minimize \sum_i \sum_j D_{ij}x_j/N^i$$

9.2.1   Presentation of Results from Scenario 1

Table 17 below presents the results for scenario 1 when the average distance is minimized. The coordinates for the optimal hub locations are presented in Table 17, and illustrated in Figure 14. Table 18 presents the result from the onshore base.

Table 17 Results for scenario 1 when the average distance is minimized

Period	Average distance [nm]	Hub location	Hub location [lat long]	Inst 1 [nm]	Inst 2 [nm]	Inst 3 [nm]	Inst 4 [nm]
1	76.5	125	[73.5 24.5]	133	90	31	52
2	76.5	118	[73.5 24.0]	127	90	30	59
3	76.5	118	[73.5 24.0]	127	90	30	59
4	76.75	117	[73.0 24.0]	108	60	60	79
5	76.75	117	[73.5 24.0]	108	60	60	79
6	76.75	117	[73.5 24.0]	108	60	60	79
7	76.75	117	[73.5 24.0]	108	60	60	79
8	76.75	117	[73.5 24.0]	108	60	60	79
9	76.75	117	[73.5 24.0]	108	60	60	79
10	76.75	117	[73.5 24.0]	108	60	60	79
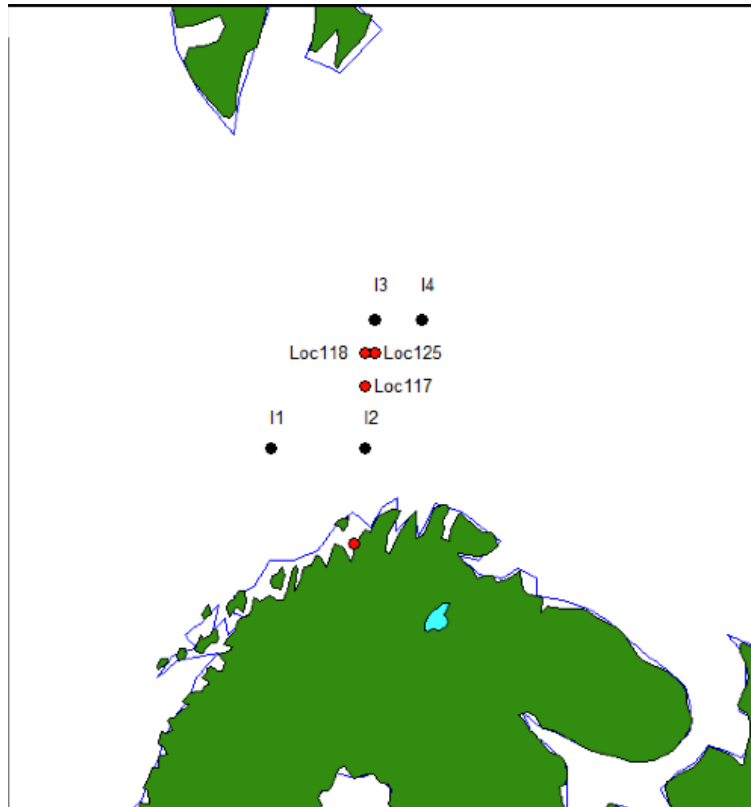
Figure 14 Optimal hub locations for minimized average distance in scenario 1

Table 18 Results when the assets is placed at Hammerfest

Installation	Distance from base [nm]	Average distance [nm]	Difference for hub location 117 [nm]
Inst 1	129		
Inst 2	98	168	91.25
Inst 3	218		
Inst 4	227		

When the average distance is minimized for scenario 1, three locations are chosen as optimal. These locations are located as close as possible to all installations for every period. With the use of a hub solution, the average distance between the hub and the installations are improved by at least 91.25 nm compared to a conventional solution. Hub location 117 could be used in all periods, as it is closer than 110 nm to all installations. This distance represents the requirement for critical level 3, the highest critical level.

9.2.2 Presentation of Results from Scenario 2

Table 19 below presents the results for the scenario 2 when the average distance is minimized. The coordinates for the optimal hub locations are presented in Table 19, and illustrated in Figure 15. Table 20 presents the results from the onshore base.

Table 19 Results for scenario 2 when the average distance is minimized

Period	Average distance [nm]	Hub location	Hub location [lat long]	Inst 1 [nm]	Inst 2 [nm]	Inst 3 [nm]	Inst 4 [nm]
1	106.25	88	[72.5 22.0]	79	137	114	95
2	106.25	88	[72.5 22.0]	79	137	114	95
3	106.25	88	[72.5 22.0]	79	137	114	95
4	107.25	89	[73.0 22.0]	94	119	100	116
5	107.25	89	[73.0 22.0]	94	119	100	116
6	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-
8	107.25	89	[73.0 22.0]	94	119	100	116
9	107.25	89	[73.0 22.0]	94	119	100	116
10	107.25	89	[73.0 22.0]	94	119	100	116
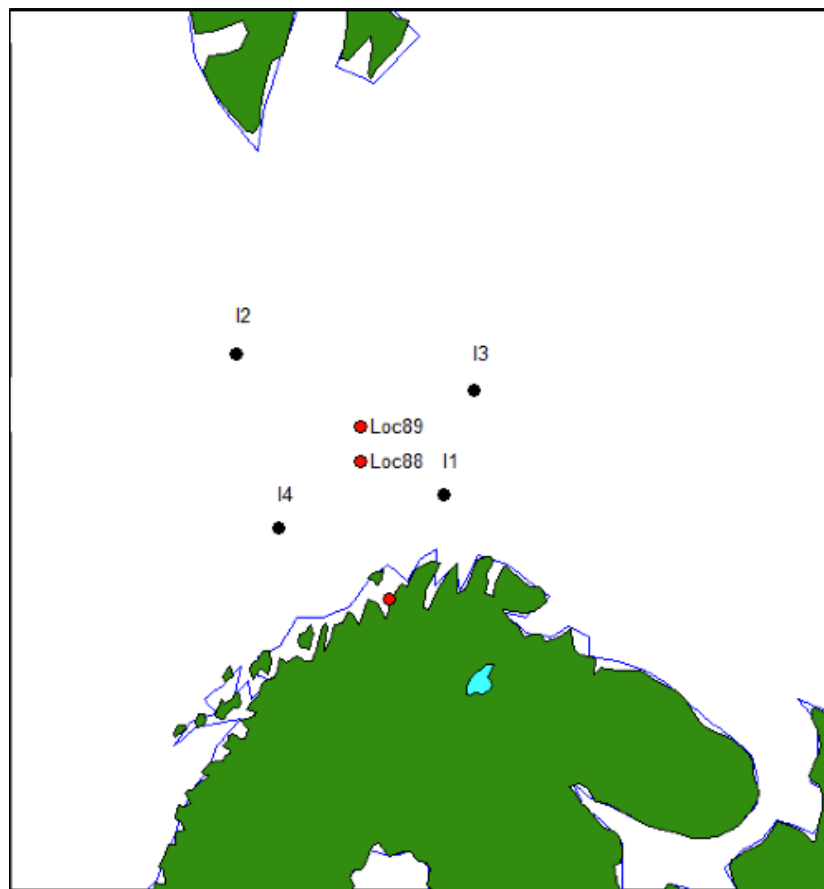
Figure 15 Optimal hub locations for minimized average distance in scenario 2

Table 20 Results when the assets is placed at Hammerfest

Installation	Distance from base [nm]	Average distance [nm]	Difference for hub location 89 [nm]
Inst 1	109		
Inst 2	256	173	65.75
Inst 3	202		
Inst 4	125		

When the average distance is minimized for scenario 2, two locations are chosen as optimal. Both locations are necessary in order to fulfill stated requirements. With the use of a hub solution, the average distance between the hub and the installations are improved by at least 65.75 nm compared to a conventional solution. For period 5 and 6, no feasible solution is found.

9.3 LOCATION FOR HUB WHEN RESPONSE TIME IS MINIMIZED

The installations where the response time should be minimized are based on the stated schedule. One of the installations operating at the highest level of criticality in the current period, is to be placed as near as possible to the hub. Consequently, the response time for this installation is minimized. The release time, transit time and deployment time is included in the response time. Table 21 states which installation is selected for the analysis of minimized response time.

Table 21 Installations where the response time is to be minimized

Period	1	2	3	4	5	6	7	8	9	10
Critical Inst	Inst4	Inst4	Inst4	Inst1	Inst1	Inst3	Inst3	Inst3	Inst3	Inst3

When the response time is minimized, two tables and one figure for both scenarios presents the results. One table presents the results for a hub solution. The other table presents the difference between required response time and the response time when the hub is allocated. Further, the response time from the base to the installation is calculated. Finally, the improved response time considering a hub or a no hub solution is presented in this table. The figure illustrates the optimal locations.

The objective function when the shortest response time for installation 4 is minimized states:

$$minimize \sum_j R_{4j} x_j$$

9.3.1 Presentation of Results from Scenario 1

Table 22 below presents the results for scenario 1 when the shortest response time is minimized. The coordinates for the optimal hub locations are presented in Table 22, and illustrated in Figure 16. Table 23 presents the improvements when a hub solution is utilized compared to the onshore base.

Table 22 Results for scenario 1 when the response time is minimized

Period	Critical Inst	Hub location	Hub location [lat long]	Inst 1 [hours]	Inst 2 [hours]	Inst 3 [hours]	Inst 4 [hours]
1	4	132	[73.5 25.0]	21	18	13	14
2	4	118	[73.5 24.5]	20	17	13	15
3	4	118	[73.5 24.5]	20	17	13	15
4	1	95	[72.5 22.5]	16	14	18	19
5	1	95	[72.5 22.5]	16	14	18	19
6	3	104	[72.5 22.5]	19	18	13	16
7	3	104	[73.5 23.0]	19	18	13	16
8	3	104	[73.5 23.0]	19	18	13	16
9	3	104	[73.5 23.0]	19	18	13	16
10	3	104	[73.5 23.0]	19	18	13	16
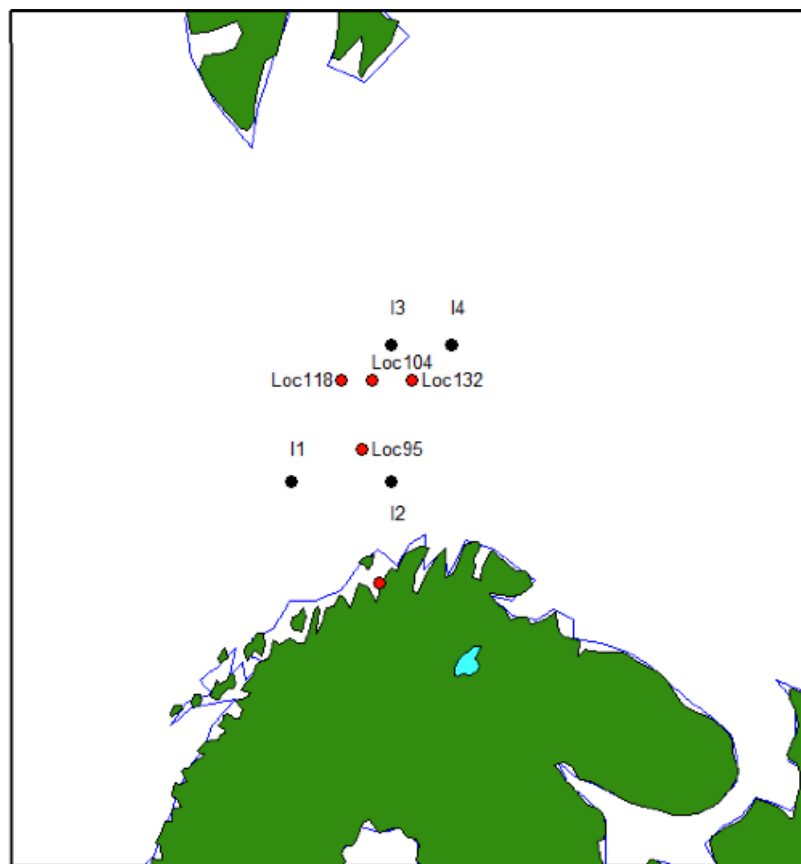
Figure 16 Optimal hub locations for minimized response time in scenario 1

Table 23 Improvements when the shortest response time is minimized

Period	1	2	3	4	5	6	7	8	9	10
Requirement	18	18	18	18	18	18	18	18	19	19
Value	14	15	15	16	16	13	13	13	13	13
Difference	4	3	3	2	2	5	5	5	6	6
PolarBase	20	20	20	20	20	27	27	27	27	27
Improvement	6	5	5	4	4	14	14	14	14	14

Four locations are chosen as optimal when the response time is minimized, all locations are necessary in order to fulfill the stated requirements. For period 4 and 5, the chosen hub location is closer to Inst 2, then to Inst 1, the critical installation. This is due to the requirements for Inst 3 and 4. The response time is improved with a minimum of 4 hous and 14 hours maximum for the hub solution, compared to a conventional solution.

9.3.2   Presentation of Results from Scenario 2

Table 24 below presents the results for scenario 2 when the shortest response time is minimized. The coordinates for the optimal hub locations are presented in Table 24, and illustrated in Figure 17. Table 25 presents the improvements when a hub solution is utilized compared to the onshore base.

Table 24 Results for scenario 2 when the shortest response time is minimized

Period	Critical Inst	Hub location	Hub location [lat long]	Inst 1 [hours]	Inst 2 [hours]	Inst 3 [hours]	Inst 4 [hours]
1	4	67	[72.5 20.5]	19	19	21	16
2	4	67	[72.5 20.5]	19	19	21	16
3	4	74	[72.5 21.0]	18	20	20	17
4	1	81	[72.5 21.5]	17	20	20	17
5	1	81	[72.5 21.5]	17	20	20	17
6	3	-	-	-	-	-	-
7	3	-	-	-	-	-	-
8	3	89	[73.0 22.0]	18	19	18	19
9	3	89	[73.0 22.0]	18	19	18	19
10	3	89	[73.0 22.0]	18	19	18	19
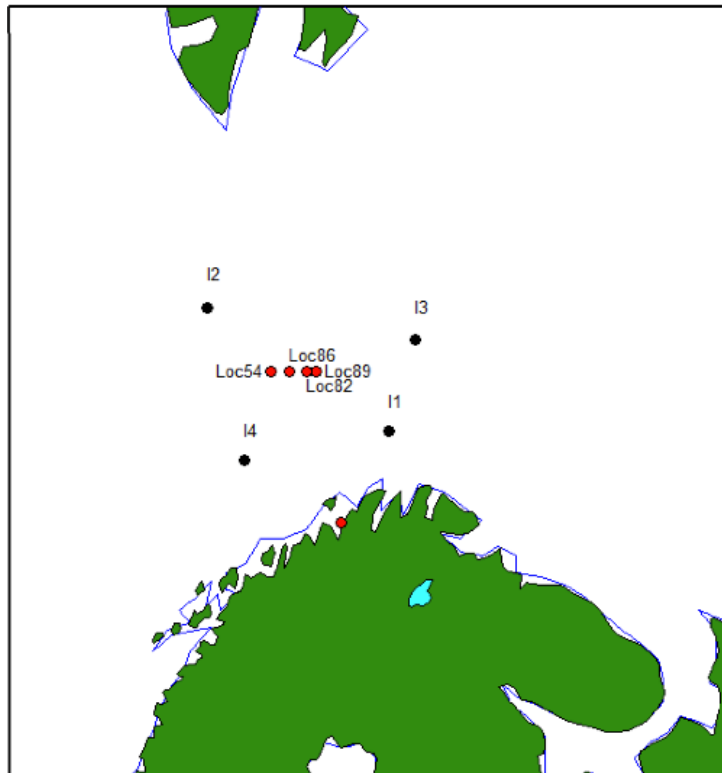
Figure 17 Optimal hub locations for minimized response time in scenario 2

Table 25 Improvements when the shortest response time is minimized

Period	1	2	3	4	5	6	7	8	9	10
Requirement	18	18	18	18	18	18	18	18	19	19
Value	14	15	15	16	16	-	-	13	13	13
Difference	4	3	3	2	2	-	-	5	6	6
PolarBase	20	20	20	19	19	-	-	25	25	25
Improvement	6	5	5	3	3	-	-	12	12	12

Four locations are chosen as optimal, and all locations are necessary in order to fulfill the stated requirements. For period 6 and 7, no possible feasible solution is found. For the feasible solutions, the hub solution gives a minimum improvement of 3 hours and a maximum improvement of 12 hours compared to a conventional solution.

9.4 COMBINATION OF PURPOSES FOR THE HUB

When the purposes for the hub are combined in the extended base case, four tables and one figure for each of the scenarios are presented.

- The first table presents the results for supply and emergency assets
- The second table presents the results for supply only
- The third table presents the response time with a conventional solution
- The last table presents the cost for conventional supply
- The figure illustrates the hub locations for the combined model

9.4.1 Presentation of Results for Scenario 1

Table 26 presents the results for scenario 1, when the purposes for the hub are combined. Table 27 presents the results if emergency response is excluded. Table 28 presents the response time to the installations in scenario 1 from the onshore base. Table 29 presents the result if no hub is utilized for supplying installations. Figure 18 illustrates the location of the hub when purposes are combined.

Table 26 Results when total cost is minimized for scenario 1

Period	Total Cost [10³ NOK]	Hub location	Hub location [lat long]	Inst 1 [hours]	Inst 2 [hours]	Inst 3 [hours]	Inst 4 [hours]
1	7073	116	[72.5, 24.0]	18	13	17	18
2	7073	89	[73.0, 22.0]	17	16	16	18
3	7073	89	[73.0, 22.0]	17	16	16	18
4	7073	82	[73.0, 21.5]	16	16	16	19
5	7073	82	[73.0, 21.5]	16	16	16	19
6	7073	102	[72.5, 23.0]	17	14	18	19
7	7073	102	[72.5, 23.0]	17	14	18	19
8	7073	102	[72.5, 23.0]	17	14	18	19
9	7073	102	[72.5, 23.0]	17	14	18	19
10	7073	102	[72.5, 23.0]	17	14	18	19
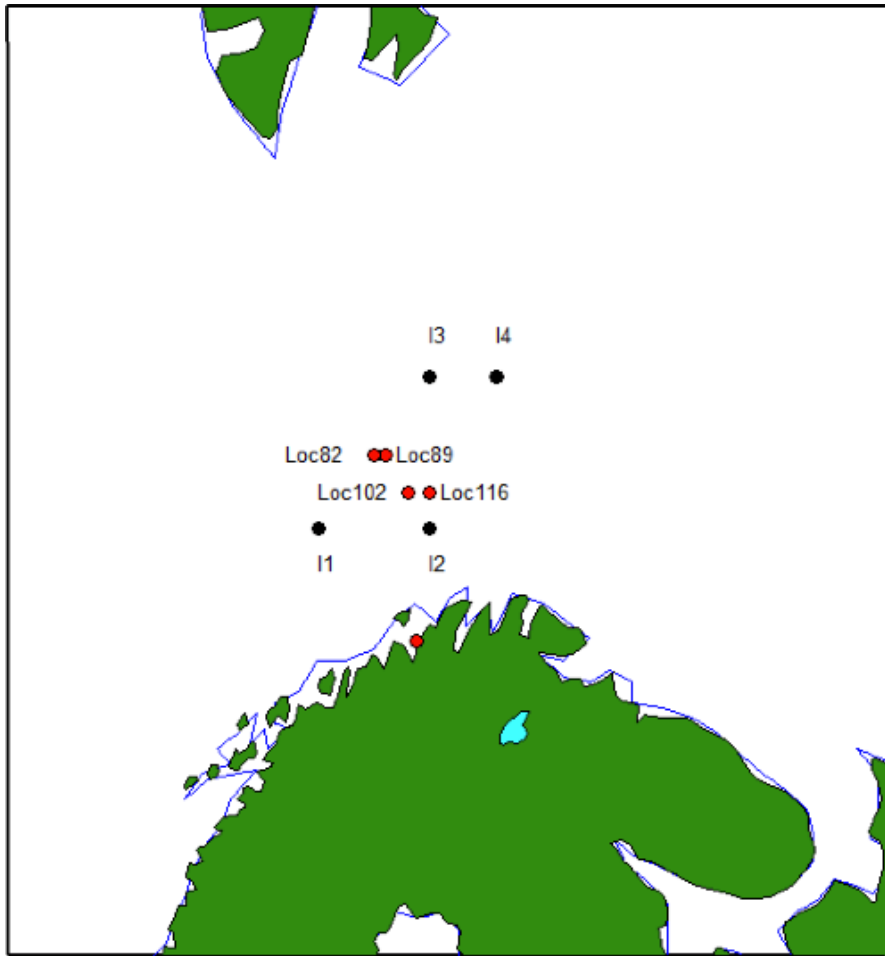
Figure 18 Optimal hub locations for minimized total cost in scenario 1

Table 27 Results when emergency response assets is excluded

Hub location	Hub location [Lat Long]	Total cost [10^3 NOK]	Number of PSVs
117	[73.5, 24.0]	7073	1

Table 28 Response time from base to each installation

Installation	Response time from base [Hours]
Inst 1	20
Inst 2	18
Inst 3	27
Inst 4	27

Table 29 Results for supply with a conventional solution

Hub location	Hub location [Lat Long]	Total cost [10^3 NOK]	Number of PSVs
PolarBase	[70.38, 23.40]	3996	2

For the allocation of the hub when both supply and emergency assets is considered, four locations are chosen as optimal. Location 82, 89 and 116 all located closer to the installations than the requirement for critical level 3. Thus, one of these locations could be chosen for all periods. The locations chosen does not consider the durations between the hub and the installations, as the model only in concerned with minimizing the supply cost. Cost for storing emergency assets is not included in the model. The results indicates that storing emergency assets on the hub, does not impact the results for the supply. The hub solution for supply, is significantly more expensive than the conventional solution.

9.4.2   Presentation of Results for Scenario 2

Table 30 presents the results for the scenario 1, when purposes for the hub are combined. Table 31 presents the hub location if emergency response is excluded. Table 32 present the response time from the onshore base in scenario 1. Table 33 presents the result if no hub us utilized for supplying installations. Figure 19 illustrates the location of the hub when purposes are combined.

Table 30 Results when total cost is minimized for scenario 2

Period	Total Cost [10³ NOK]	Hub location	Hub location [lat long]	Inst 1 [hours]	Inst 2 [hours]	Inst 3 [hours]	Inst 4 [hours]
1	8611	60	[72.5, 20.0]	19	19	21	16
2	8611	60	[72.5, 20.0]	19	19	21	16
3	8611	74	[72.5, 21.0]	18	20	20	17
4	8611	74	[72.5, 21.0]	18	20	20	17
5	8611	74	[72.5, 21.0]	18	20	20	17
6	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-
8	8611	89	[73.0, 22.0]	18	19	18	19
9	8611	89	[73.0, 22.0]	18	19	18	19
10	8611	89	[73.0, 22.0]	18	19	18	19
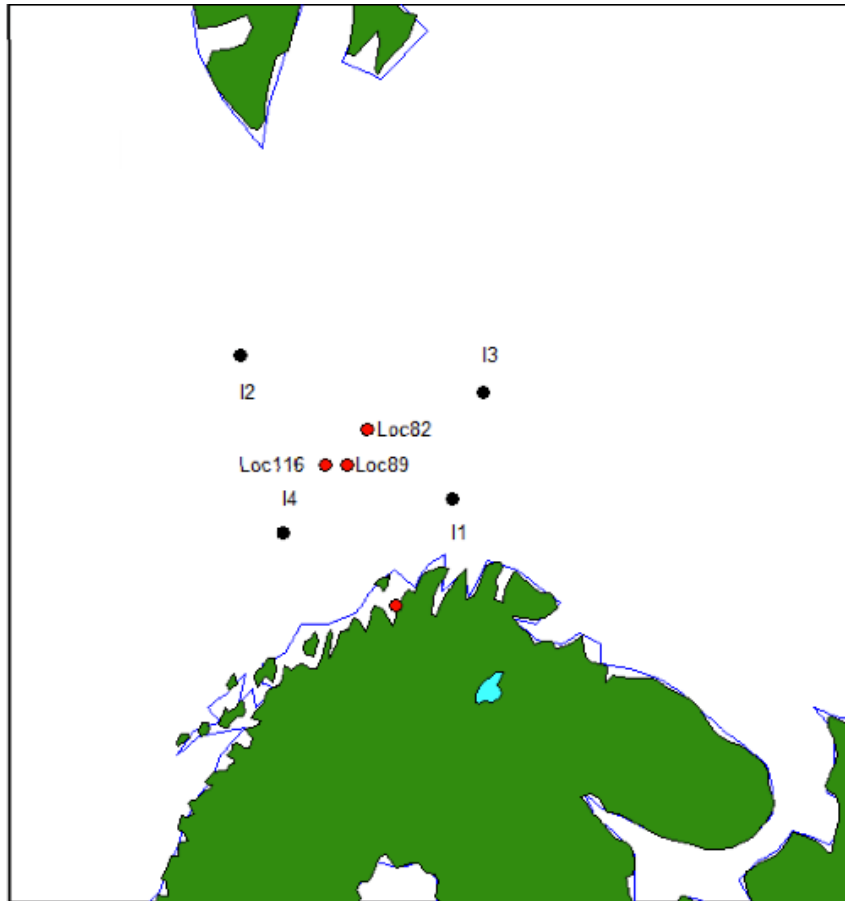
Figure 19 Optimal hub locations for minimized total cost in scenario 2

Table 31 Results when emergency assets is excluded

Hub location	Hub location [Lat Long]	Total cost [10^3 NOK]	Number of PSVs
1	[71.00, 16.00]	8611	2

Table 32 Response time from base to each installation

Installation	Response time from base [Hours]
Inst 1	19
Inst 2	29
Inst 3	25
Inst 4	20

Table 33 Results for supply with a conventional solution

Hub location	Hub location [Lat Long]	Total cost [10^3 NOK]	Number of PSVs
PolarBase	[70.38, 23.40]	3996	2

Three locations are chosen as optimal for scenario 2. They are all necessary in order to fulfill requirements. The cost for supply is not affected when storing emergency assets, but a conventional solution is significantly cheaper than a hub solution. The number of PSVs represent the number of required vessels in order to fulfill supply demands from the installations. It is the yearly charter cost for both the hub vessel and the PSV that dominates the total cost.

CHAPTER 10

DISCUSSION

In this part of the report, the results from Chapter 9 are discussed. Ideas and observations are considered, and elements of the mathematical model are discussed before conclusions are stated in Chapter 11.

With the assumptions made in this report and the limitations to the problem, the preparedness system will be more robust by decreasing the expected response time to an accident site. By using a hub solution, a response can happen faster than with a conventional solution. The optimization model is used to find the optimal location for the hub, and evaluate the hub solution.

The obtained results in this report can be utilized as an indication of where the hub should be placed in order to minimize response time to operating installations. Further, they indicate that emergency response assets can be placed at a hub functioning for other purposes as well. In this report, the hub is used for assets in combination with supply, but there are a wide range of uses. In the introduction, the range for helicopters was mentioned. In addition to supply, the hub could also be used as a stop over for helicopters on their way to operating installations. Utilizing the hub for SAR related operations is also a possibility.

10.1 AVERAGE DISTANCE AND RESPONSE TIME

In this report, the average distance from the hub has been minimized to illustrate how the use of distances between a hub and the installations can be utilized as restrictions. However, in Chapter 3, Literature Review, it was stated that according to Owen & Daskin (1998) selecting locations that minimize the average traveling distance might not be appropriate. A maximum allowed distance between the hub and the installations has been stated and the key issue is to cover the requirements within these specified demands. The cost is excluded from the model, therefore, the distances between the hub and the installations is used as requirements for placing the hub. It is assumed that it is unknown where an accident might occur, and thus the traveling distance to all installations should be as short as possible. Utilizing distance in the calculations can be a good basis, as the response time varies with the vessels availability and speed. However, utilizing response time in the calculations, gives a clear indication of how fast a response to an accident site can be expected.

After allocating the hub when the average travelling distance is minimized, the response time is used as requirements for allocating the hub throughout the rest of this report. The installations operate in four different phases, with critical levels bound to each phase. The highest level of criticality occurs when installations are drilling in oil producing layers. It is desired that the emergency response assets are placed as near as possible to the installation operating in the most critical phase at the same time as the allocation meet requirements for the other installations. Therefore, the response time

for the installation operating in the highest critical level is minimized. The response time is however only minimized for one of the operating installations, even though other installations might operate in the same phase. This is done in order to indicate how close to an installation the hub could be placed and still fulfill stated requirements for other operating installations.

In order to minimize the response time to all the installations operating at the most critical phase, all relevant installations should be included in the calculations. This can be done by minimizing the total response time, or the average response time for the relevant installations.

10.2   MAXIMUM ALLOWABLE DURATION

The assumption made in order to state the maximum allowable response time for the critical levels are debatable. The distance between the onshore base and the north east corner, the point furthest from the onshore base in the possible area for operation, is divided by two. However, the result is in correspondence with the NOFO requirements for tugboats. The NOFO requirement for tugboats is 24 hours if they are less than 120 nm from the base PolarBase (NOFO e, 2014). Both the OR vessel and the tug vessel is required for oil recovery, as described in Chapter 4.1. As it is assumed that the tugboats always will be ready on site when the OR vessel is, it is considered reasonable to assume that the OR vessel also is ready on site after 24 hours. Thus, the stated maximum allowable response time for the lowest criticality level in this report, is not far from todays requirement within this distance. If the distance increase however, the new requirement is set to 36 hours. This incensement might not be necessary with the use of a hub solution.

The difference in maximum allowable response time for the lowest critical level and the highest critical level could also be discussed. The critical levels are stated as low and high, but the difference in required response only states three hours. This might be considered as an insignificant difference compared to the stated criticality levels, and would possibly not make necessary improvements for the preparedness.

The main strategy for oil spill preparedness is to oppose the spill as close as possible to its source. If oil spill occurs, the main focus is to prevent diffusion by collecting the spilled oil close to its source as possible. This requires quick response time. In the most critical operational stage for the installations, it is assumed higher risk and bigger consequences, the response time should be considerably lower to the installations operating in this phase.

Earlier in the discussion, it was mentioned that the response time was minimized for one of the installations operating at the most critical level. The results from this part of the report can be an indication of how much the requirement for maximum allowable response time can be reduced with the use of a hub solution. However, from the results in Chapter 9, it appears that the maximum allowable response time for the different critical levels are too strict in order to cover the entire Barents Sea with only one hub included in the preparedness system. The results make it clear that it is not possible to

reduce the requirements for response time further, without generating infeasible solutions for the some scenarios.

10.3   INFEASIBLE SOLUTIONS

In this report, all stated requirements are met for all installations in all phases, except for scenario 2 in phase 6 and 7 where there are no feasible solutions. This is a consequence of the installations in scenario 2 is having larger distances between each other than for the installations in scenario 1. From Figure 20, it appears that all circles illustrating demands intersect, but there is no potential facility site located in the overlap.
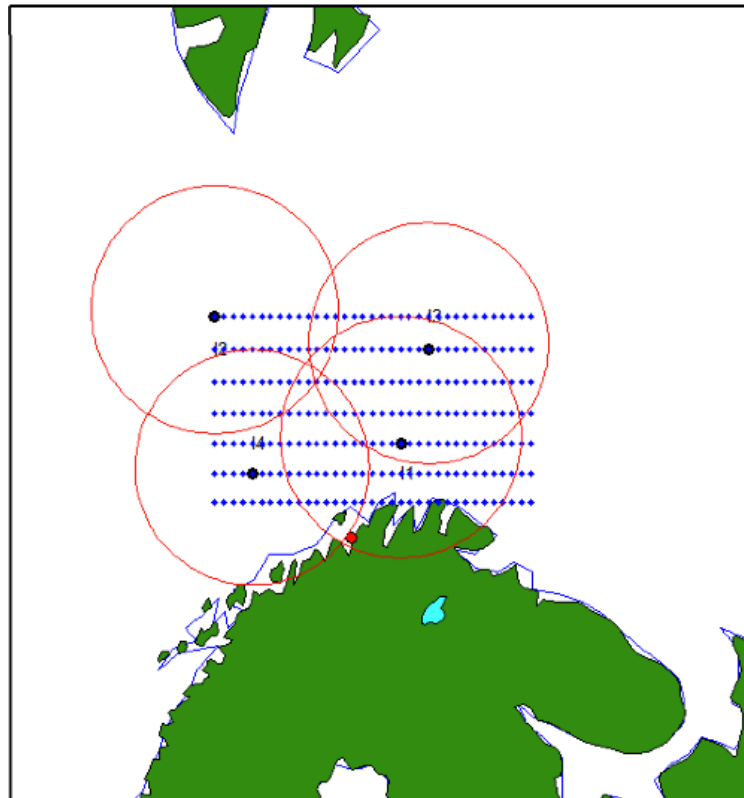
Figure 20 Intersection over possible hub locations for phase 6 and 7 for scenario 2

The missing potential hub location in the circle overlap is a result of the generated hub grid. By generating more possible hub locations in the hub grid, a feasible solution might have been found. It is likely that missing feasible solutions will appear from other installation combinations as well.

10.4   LOCATION OF OR VESSELS

The location of the OR vessel when an accident occur, is not taken into account in this report. In the general formulation of the problem, a set of OR vessels is stated, but only a release time in hours is given as a parameter. This means that the OR vessels transit time from its location when an accident occurs to the location where a hub is placed. In addition, the duration to load necessary equipment is assumed to be equal for all

possible hub locations. In the simplified version and solved problem in this report, the release time is set to 10 hours. The response time in this report, is based on the NOFO requirement that the first system should be ready to transit to an accident with operating crew 10 hours after an accident has occurred. By including the OR vessels location the release time would be affected, thus also the response time.

10.5   EXTENSION OF THE BASE CASE

When the total cost for supplying operating installations, an existing model is used and stated restrictions in this report are implemented into this model. The existing model uses a hub solution to handle supply to installations. The cost only considers supply and charter of the hub vessels and the PSVs, additional cost for storing emergency response assets are not considered in this report.

Utilizing a hub solution for supply are much more expensive that conventional supply. In this report, the cost is not affected by including the emergency assets. Due to the requirements for the allocation of emergency assets, the total supply cost could be affected if an extra hub is required in order to operate at all times. The distance between the hub and the installations are only placed within the stated requirements for response assets. It is not included that the installations ideally should be placed as close as possible to all installations. This means that when a result is found, there are no better solutions for total cost, even though it exist better solutions with regard to response time.

The idea behind combining the two purposes has a basis in operating companies sharing costs, as more functionalities results in lower cost. However, in this analysis, the hub solution is more expensive than the conventional solution. The cost of environmental pollution is therefore an important aspect of further analysis.

In the part where the hub solutions are in use for both supply and allocation of emergency response assets, there are a lot of elements that is included in the model, but not further assessed in this report. In this report, only the main elements of the already existing model is taken into account, with the total cost of utilizing a hub system for supply, and the required number of PSVs in order to fulfill the supply demand for the operating installations. The purpose of this combination is used as an example for how the developed requirements and constraints for emergency preparedness can be included when other purposes for the hub is investigated.

10.6   COST

The results found in this report, indicates that allocating emergency response assets at an offshore location instead of at a land base, can drastically reduce the response time to possible emergency sites. However, there are a lot of parameters that are excluded from the solution approach. For example where the OR vessels are located at a time of an accident, their location would affect the response time. The cost of utilization is not assessed in this report, and it is therefore not taken into consideration whether this solution is a realistic solution with regards to cost. An assumption of a cost for

chartering and drifting a hub, could be taken from Akselsen (2014), where the yearly charter cost of one hub is 120 000 000 NOK.

As the cost for chartering and drifting a hub is so expensive, a cheaper solution might be that the hub has a function as standing emergency. This solution requires a smaller and cheaper vessel. With standing emergency, the necessary equipment is placed on board the OR vessels at all times. This means that the release time for the OR vessel can be reduced to a minimum, and unless the OR vessel has other requirements and tasks transit to the accident site immediately. By operating with standing emergency, the response time is reduced, and the OR vessel can possibly cover a wider range of the Barents Sea. This implies that the tugboats, that are excluded from this report, can respond to an emergency as quickly as the OR vessel.

In order to consider the cost aspect of the preparedness system. A new model could be developed, in order to minimize the total cost of the preparedness system. In the cost analysis the hub solution, standing emergency and allocation of assets could be assessed.

CHAPTER 11

CONCLUSION

In this part of the report, a general conclusion is stated followed by proposals for further work in regards to utilizing a hub solution to allocate emergency response assets.

Different locations of installations and formulations of the objective function have been assessed when the emergency response assets are allocated in the Barents Sea. The optimal location is decided, based on stated requirements for maximum distances and durations between the hub and operating installations.

By utilizing a hub solution for allocation of emergency response assets, the assets are placed closer to the operating installations compared to allocating the assets at the onshore base in Hammerfest. The placement is measured both in distance and duration.

In some cases, a response to an accident at some installations can be possible after only 13 hours, compared to 27 hours if the assets where placed at the onshore installation. This is an improvement 14 hours in response time. While for the distance, an average distance between the assets and the installations can be improved by 91.25 nm from 168 nm to 76.75 nm.

In addition, the extended base has been allocated in order to minimize total cost for supplying installation when emergency assets was stored on the hub. Table 34 below presents all the optimal locations for the hub. The results from this analysis, indicate that the hub solution for a combination of purposes is a possibility.

Table 34 Optimal locations for the extended base

Minimize	Scenario 1		Scenario 2	
	Optimal Location	Result	Optimal Location	Result
Average distance [nm]	[73.5, 24.5]	76.5	[72.5, 22.0]	106.25
	[73.5, 24.0]	76.5	[73.0, 22.0]	107.25
	[73.0, 24.0]	76.75	-	-
Response time [Hours]	[73.5, 25.0]	14	[72.5, 20.5]	16
	[73.5, 24.5]	15	[72.5, 21.0]	17
	[72.5, 22.5]	16	[72.5, 21.5]	17
	[73.5, 23.0]	13	[73.0, 22.0]	18
Total cost [10³ NOK]	[72.5, 24.0]	7073	[72.5, 20.0]	8611
	[73.0, 22.0]	7073	[72.5, 21.0]	8611
	[73.0, 21.5]	7073	[73.0, 22.0]	8611
	[72.5, 23.0]	7073	-	-

11.6   FURTHER WORK

In Chapter 10, it was discussed that allocating one single hub is not sufficient in order to cover the stated requirements for response time for all scenarios. Therefore, it could be an advantage to develop a model that minimizes the required number of hubs to be located, in order to fulfill the stated requirements. In addition to minimize the total number of hubs, the onshore base should be included as possible locations for placing emergency response assets. The possible base locations could be included in the set of potential hub locations. Thus, no new set of decision variables has to be stated. The new objective function could be:

$$minimize \sum_j x_j$$

As the extended base is an extension of an onshore base, the onshore base could always be used. This requires a new constraint. If the base is located at potential site 1, the new constraint could be:

$$x_1 = 1$$

It is also a possibility to add a new set of onshore locations. Then new parameters, decision variables and restrictions must be added. In addition, a new objective function must be generated. The decision variable for the onshore bases should be included in this function.

Further, the locations for the OR vessels are not taken into account. In the solved problem in this report, it is assumed that the release time for the OR vessel is equal for all hub locations. It is not taken into consideration where the vessel is actually located, nor is the OR vessels transit time to the hub location before it is ready to load equipment onboard evaluated. For future work the location of the OR vessel could be taken into account. In the general model presented in this report, a set of vessels is included. This set could state the locations for the OR vessels, equal as for the set of installations and the set of possible hub locations, with the latitudinal and longitudinal coordinates. The parameter that is not included in the general formulation of the problem, the traveling distance between the vessels location and all possible hub locations should be calculated. In order to get the final release time, the duration anticipated to load the vessel must be included. In the current general model, this is covered by the parameter release time for vessel v, F_v.

In the discussion, it was also debated whether or not the required response time for each critical level represents the criticality in a proper way. From the results, it appears that in some cases, the response time could be reduced for the critical levels, or at least stronger requirements for the most critical level could be stated. Thus, a proposal for further work is to stress test the required response time for the different critical levels, with a focus on critical level 3 and decide reasonable required response times in the emergency preparedness system.

Except for the part where a hub is allocated in order to both serve the installations with supply and emergency response assets, costs are excluded when allocating the emergency response assets in this case. These cost only represents the supply to installations, and not the emergency response assets. Cost of the emergency response system could be included in the model in order to investigate if the solution is feasible in an economic perspective. Minimizing total cost of the emergency response preparedness could include the cost perspective of utilizing a hub system, standing emergency and onshore bases. Decision variables for all these parameters should be generated together with parameters for cost of each system.

Finally, the hub solution for allocating emergency response assets requires further research. In this report, only the location of a hub is examined. This report is based on assumptions only, and is not bound in any realistic scenarios. A study on whether or not the described system is realistic, should be specified. In addition, a study on how the risk picture would change and the improvement of the overall preparedness could be performed.

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APPENDIX

APPENDIX A – MSC – THESIS DESCRIPTION

NTNU – Trondheim
Norwegian University of
Science and Technology

MSc - THESIS
Stud. techn. Marina Myhrvold Riple
Spring 2015

Allocation of Emergency Response Assets in the Barents Sea

Background
The main strategy for oil spill preparedness is to oppose the spill as close as possible to its source. Therefore it is desired to respond as quickly as possible in case of an accident. A hub solution is introduced in order to allocate required assets for emergency response as near as possible to operating installations. The hub will operate as an extension to the onshore base in order to reduce the response time and possibly strengthen the overall preparedness system.

Overall Objective
The overall objective in this thesis is to develop an optimization model in order to locate the optimal location for emergency response assets when minimizing response time.

The Specific Tasks for this Thesis Include
1) A state of the art literature review
2) A brief description of the existing emergency preparedness system
3) Generation of a general mathematical model
4) Collection of essential data necessary to run the mathematical model
5) Solve a simplified version of the problem
6) Solve a problem where the hub is used for both allocation of emergency response assets and supply
7) Presentation of the results and aspects to the model

Implementation
At NTNU, Professor Stein Ove Erikstad is the responsible supervisor. The work shall be in accordance with 30 ECTS, corresponding to 100% of one semester.

Stein Ove Erikstad
Professor / Responsible Supervisor

APPENDIX B – MATLAB SCRIPT FOR BASE CASE

Appendix B contains the MatLab script for allocating the hub when only emergency response assets are considered.

```
clear all
close all

%% INPUT----------------------------------------------------------
-----

% STATED VALUES--------------------------------------------------
-----

%Number of installations i, Ni
Ni = 4;

%Current Period, p
%Set of Periods P
%Np = 10;
p = 1;

% Schedule for the different installations
% 0 = Arrival at drilling site
% 1 = Drilling through rocks
% 2 = Production
% 3 = Drilling through oil producing layers
Schedule = [0 1 1 3 3 2 2 2 2 2; 0 0 0 1 1 3 3 2 2 2; 0 0 1 1 1 3 3 3
2 2;3 3 3 2 2 2 2 2 2 2;];

%Maximum allowable response time for critical level k, Rk [Hours]
Rk= [21 20 19 18];

%Maximum allowable distance for critical level k, Dk [nm]
% Dk = [140 130 120 110];

%Service speed for OR vessel, Sv [knot]
Sv=14;

%Release time for OR vessel, Fv [Hours]
Fv=10;

%Deployment time, Tv [Hours]
Tv= 1;

% Random location of installations in a given area
% Set of installations, I
% Instlat=transpose(randi([71.00 74.00], 1, nInst));
% Instlong=transpose(randi([16.00 33.00], 1, nInst));

%Result: Scenario 1
% Instlat= transpose([72.00 72.00 74.00 74.00]);
%    Instlong    =    transpose([19.00    24.00    24.00    27.00]);
```

```matlab
%Result: Scenario 2
Instlat= transpose([72.00 74.00 73.50 71.50]);
Instlong = transpose([26.00 16.00 27.50 18.00]);


InstLocation=[Instlat, Instlong];

%Hub-grid size
nLong = 35;
nLat = 7;
SW = [70.5, 15.5];


%-END-INPUT----------------------------------------------------
-----

%% CALCULATED VALUES ------------------------------------------
-----

% Create potential hub locations as grid
% Set of potential facility sites, J
hg = zeros (nLat, nLong,2);

StepLat = 0.5;
StepLong= 0.5;

for i= 1:nLat;
    for j=1:nLong;
        hg(i,j,1) = SW(1) + StepLat*i;
        hg(i,j,2) = SW(2) + StepLong*j;
    end
end

HubLocations = reshape( hg, nLat*nLong,2);

Nh = size(HubLocations, 1);

% Calculate the distance from hub h to installation i, Dij [nm]
% Dij = zeros(Ni, Nh);
% for i=1:Ni;
%     for j=1:Nh;
%                                                 Dij(i,j)      =
round(deg2nm(distance('gc',[InstLocation(i,1),InstLocation(i,2)],...
%               [HubLocations(j,1),HubLocations(j,2)])));
%     end
% end

% Calculate response time from hub h to installation i, Rij [hours]
Rij = zeros(Ni,Nh);
for i=1:Ni;
    for j=1:Nh;
        Rij        (i,j)        =        Fv        +        Tv        +
round(deg2nm(distance('gc',[InstLocation(i,1),InstLocation(i,2)],...
               [HubLocations(j,1),HubLocations(j,2)]))/Sv);
    end
end

% Maximum allowable distance for installation i, DiMAX
```

```matlab
% DiMAX = zeros (Ni,1);
%
% Period = Schedule(:,p);
%
% for i = 1:Ni;
%     for j = 1;
%         if Period(i)== 0
%             DiMAX(i)= Dk(1);
%         else if Period(i)== 1
%                 DiMAX(i)= Dk(2);
%             else if Period (i)== 2
%                     DiMAX(i)= Dk(3);
%                 else if Period(i) == 3
%                         DiMAX(i) = Dk(4);
%                     end
%                 end
%             end
%         end
%     end
% end

% Maximum allowable response time for installation i, DiMAX
RiMAX = zeros (Ni,1);

Period = Schedule(:,p);

for i = 1:Ni;
    for j = 1;
        if Period(i)== 0
            RiMAX(i)= Rk(1);
        else if Period(i)== 1
                RiMAX(i)= Rk(2);
            else if Period (i)== 2
                    RiMAX(i)= Rk(3);
                else if Period(i) == 3
                        RiMAX(i) = Rk(4);
                    end
                end
            end
        end
    end
end


%% Map -----------------------------------------------------------
-----

%Draw  map  with  all  positions  and  lines
figure;
ha = axesm('mapproj','mercator', 'maplatlim',[65,78], 'maplonlim',
[5,45]);
setm(ha, 'MLineLocation', 5, 'PLineLocation', 5);
axis on, gridm off, framem on;

load('coast');
gc = geoshow(lat,long, 'displaytype', 'line', 'color', 'b');
geoshow('landareas.shp', 'Facecolor', [0.15 0.55 0.15]);
geoshow('worldlakes.shp', 'Facecolor', 'cyan');

textm(InstLocation(1,1)+0.5, InstLocation(1,2),'I1');
```

```matlab
textm(InstLocation(2,1)+0.5, InstLocation(2,2),'I2');
textm(InstLocation(3,1)+0.5, InstLocation(3,2),'I3');
textm(InstLocation(4,1)+0.5, InstLocation(4,2),'I4');


%Draw base
geoshow(70.38,23.40,                'DisplayType',              'point',
'markeredgecolor','k',...
    'markerfacecolor','r','marker','o');


%Draw plattforms
for i=1:Ni;
    geoshow(InstLocation(i,1),                      InstLocation(i,2),
'DisplayType','point', 'markeredgecolor','k',...
        'markerfacecolor','k','marker','o');
end



%Draw gridded hubs
for i=1:Nh;
      geoshow(HubLocations(i,1), HubLocations(i,2), 'DisplayType',
'point', 'markeredgecolor', 'b',...
            'markerfacecolor', 'b', 'marker', '.');
end


%Draw Circles to define maximum distance from installations
for i=1:Ni;
    [lat, long] = scircle1(InstLocation(i,1), InstLocation(i,2),
DiMAX(i), [], earthRadius('nm'));
    plotm(lat, long, 'r')
end

%Draw Circles to define maximum response time from installations
for i=1:Ni;
    [lat, long] = scircle1(InstLocation(i,1), InstLocation(i,2),
RiMAX(i), [], earthRadius('nm'));
    plotm(lat, long, 'r')
end



%% Write to tab delimited file----------------------------------------
-----

fid = fopen('InputHUB.dat', 'w');
fprintf(fid, '\n\n!Input file for Xpress IVE, generated in MATLAB
R2014a \n\n');
fprintf(fid, '\n\n!Master Thesis, NTNU, Marine Technology by Marina
Riple\n\n');
fprintf(fid, '\n\n!"Allocation of emergancy response assets in the
Barents Sea"\n\n');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!All durations given in [hours]\n\n');
fprintf(fid, '\n\n!All distances given in [nm]\n\n');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!Inst : [');
fprintf(fid,'%3.0f\t', InstLocation);
fprintf(fid, ']');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!Period: [');
fprintf(fid, '%3.0f\t', p);
```

```
fprintf(fid, ']');
fprintf(fid, '\n\n \n\n');


%Number of installations and potential facility sites
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\nNh : ');
fprintf(fid,'%3.0f\t', Nh);
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\nNi : ');
fprintf(fid,'%3.0f\t', Ni);
fprintf(fid, '\n\n \n\n');


% Schedule for operations at installation i
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n Schedule: [');
fprintf(fid, '%3.0f\t', transpose(Schedule));
fprintf(fid, ']');
fprintf(fid, '\n\n \n\n');


%Distance between potential facility site j and installation i
% fprintf(fid, '\n\nDij : [ \n\n');
% fprintf(fid,'%3.0f\t', transpose(Dij));
% fprintf(fid, '\n');
% fprintf(fid, '\n\n] \n\n');
% fprintf(fid, '\n\n \n\n');


%Response time between potential facility site j and installation i
fprintf(fid, '\n\nRij : [ \n\n');
fprintf(fid,'%3.0f\t', transpose(Rij));
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Maximum allowable distance for installation i, DiMAX
% fprintf(fid, '\n\nDiMAX : [ \n\n');
% fprintf(fid,'%3.0f\t', DiMAX);
% fprintf(fid, '\n');
% fprintf(fid, '\n\n] \n\n');
% fprintf(fid, '\n\n \n\n');


%Maximum allowable response time for installation i, RiMAX
fprintf(fid, '\n\nRiMAX : [ \n\n');
fprintf(fid,'%3.0f\t', RiMAX);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');

fclose(fid);
```

APPENDIX C – MATLAB SCRIPT FOR EXTENDED CASE

Appendix C contains the MatLab script for allocating the hub when supply and emergency response assets are considered.

```matlab
clear all
close all

%% INPUT-------------------------------------------------------------
-----

% STATED VALUES----------------------------------------------------
-----

%Number of installations i, Ni
Ni = 4;

%Current period p
%Set of periods P
%Np = 10;
p = 1;

% Schedule for the different installations
% 0 = Arrival at drilling site
% 1 = Drilling through rocks
% 2 = Production
% 3 = Drilling through oil producing layers
Schedule = [0 1 1 3 3 2 2 2 2 2; 0 0 0 1 1 3 3 2 2 2; 0 0 1 1 1 3 3 3
2 2;3 3 3 2 2 2 2 2 2 2;];

%Maximum allowable response time for critical level k, Rk [Hours]
Rk= [21 20 19 18];

%Service speed on vessels [knot]
vHub=12;
vPSV=15;
Sv=14;

%Release time for OR vessel, Fv [Hours]
Fv=10;

%Deployment time, Tv [Hours]
Tv= 1;

%Geographical coordinates for supply bases at Hammerfest
BaseLocation = [70.38, 23.40];
nBases = size(BaseLocation,1);

% Random location of installations in a given area
% Set of installations, I
% Instlat=transpose(randi([71.00 74.00], 1, nInst));
% Instlong=transpose(randi([16.00 33.00], 1, nInst));

%Result: Scenario 1
% Instlat= transpose([72.00 72.00 74.00 74.00]);
% Instlong = transpose([19.00 24.00 24.00 27.00]);
```

```matlab
%Result: Scenario 2
Instlat= transpose([72.00 74.00 73.50 71.50]);
Instlong = transpose([26.00 16.00 27.50 18.00]);


InstLocation=[Instlat, Instlong];

%Demand per installation [ton]
Di=repmat(230, 1, Ni);

%Required number of services per installation per week
Si=repmat(3,1,Ni);

%Yearly cost for chartering one vessel [10^3 NOK]
CYearEO = 120000;          %Hub Vessel
CYearET = 80000;           % PSV

%Cost for making use of supply base per ton cargo transported from
base [10^3 NOK / ton]
Cb=1.0;

%Capacity per vessel [ton]
qHub=750;                  %Hub Vessel
qPSV=450;                  %PSV

%Number of PSVs in the fleet
nPSV = 10;

%Period [weeks]:
W = 1;

%Hub-grid
%Hub-grid size
nLong = 35;
nLat = 7;
SW = [70.5, 15.5];

%-END-INPUT--------------------------------------------------------
-----

%% CALCULATED VALUES-----------------------------------------------
-----

% Create potential hub locations as grid
% Set of potential facility sites, H
hg = zeros (nLat, nLong,2);

StepLat = 0.5;
StepLong= 0.5;

for i= 1:nLat;
    for j=1:nLong;
        hg(i,j,1) = SW(1) + StepLat*i;
        hg(i,j,2) = SW(2) + StepLong*j;
    end
end

HubLocations = reshape( hg, nLat*nLong,2);
```

```matlab
Nh = size(HubLocations, 1);

%Calculate number of possible routes, generate Air - matrix
v = 1:Ni;
nRoutes = 0;
for i=1:Ni
    nRoutes = nRoutes + nchoosek(Ni,i);
end

A = zeros(nRoutes, Ni);         %Create the platform visits matrix
(routes in rows, platforms in
                                %columns, 1 if platform p is visited on
route r

r = 0;
for k=1:Ni                  %First visit one platform, then two, then
three, etc.
   C = nchoosek(v,k);   %Find the possible combinations when choosing
k from n
   for i=1:size(C,1)
       r = r+1;
       for j=1:k
           A(r,C(i,j))=1;
       end
   end

end

%Calculate the duration from base b to hub h (one way)[hours]
% 8 hours extra duration
bhDuration = zeros(nBases,Nh);
for i=1:nBases
    for j=1:Nh
        bhDuration(i,j)     =8      +     round(deg2nm(distance('gc',
[BaseLocation(i,1),BaseLocation(i,2)],...
                [HubLocations(j,1),HubLocations(j,2)]))/vHub);
    end
end

%Calculate the duration from hub h to installation i for PSVs [hours]
% 4 hours exprected duration at installation
PSVDuration = zeros(Ni, Nh);
for i=1:Ni
    for j=1:Nh;
        PSVDuration(i,j)                =             4            +
round(deg2nm(distance('gc',[InstLocation(i,1),InstLocation(i,2)],...
                [HubLocations(j,1),HubLocations(j,2)])/vPSV));
    end
end

%Response time for the OR vessel between hub h and installation i
[hours]
ThiOR = zeros(Ni, Nh);
for i=1:Ni
    for j=1:Nh;
        ThiOR(i,j)           =          Fv          +         Tv        +
round(deg2nm(distance('gc',[InstLocation(i,1),InstLocation(i,2)],...
                [HubLocations(j,1),HubLocations(j,2)])/Sv));
    end
```

```matlab
    end

%Calculate the duration between the platforms [hours]
% 4 hours expected duration at installation
earthRadiusInMeters=6371000;
ppDuration = zeros(Ni,1);
    for i=1:Ni
        for j=1:Ni
            if i==j;
                ppDuration(i,j)=round((rad2nm(distance('gc',
InstLocation(i,1),         InstLocation(i,2),         InstLocation(j,1),
InstLocation(j,2),earthRadiusInMeters)/earthRadiusInMeters)/vPSV));
            else
                ppDuration(i,j)=4   +   round((rad2nm(distance('gc',
InstLocation(i,1),         InstLocation(i,2),         InstLocation(j,1),
InstLocation(j,2),earthRadiusInMeters)/earthRadiusInMeters)/vPSV));
            end
        end
    end


% Duration  of  each  route  from  all  possible  hub  locations  to
instllations [hours]
Thr = zeros(Nh,nRoutes);

for j= 1:Nh;
    for i=1:nRoutes;
        Inst=zeros(Ni);
        ni=1;
        for k=1:Ni;
            if A(i,k)==1;
                Inst(ni)=k;
                ni=ni+1;
            end;
        end;

        Inst=Inst(Inst~=0);

        %Find shortest path
        Permutations = perms (Inst);

        BestDuration=Inf;

        for k = 1:length(Permutations);
            ThisDuration=0;
            for ni=2:length(Inst);
                ThisDuration=            ThisDuration            +
ppDuration(Permutations(k,ni-1), Permutations(k,ni));
            end

            ThisDuration=ThisDuration                               +
PSVDuration(Permutations(k,1),j);

            ThisDuration=ThisDuration  +  PSVDuration(Permutations(k,
size(Permutations,2)),j);

            if ThisDuration < BestDuration
                BestDuration = ThisDuration;
            end
```

```matlab
            end
        Thr(j, i)= BestDuration;
    end
end


% Maximum response time for the OR vessel to installation i
TiMAX = zeros (Ni,1);


Period = Schedule(:,p);

for i = 1:Ni;
    for j = 1;
        if Period(i)== 0
            TiMAX(i)= Rk(1);
        else if Period(i)== 1
                TiMAX(i)= Rk(2);
            else if Period (i)== 2
                    TiMAX(i)= Rk(3);
                else if Period(i) == 3
                        TiMAX(i) = Rk(4);
                    end
                end
            end
        end
    end
end

%Period in [hours], no slack
periodHours = W * 24 * 7;
nTimes = floor(periodHours/min(min(Thr)));

%Number of vessels needed to serve each hub from each base
nVessel= zeros(nBases, Nh);

for i = 1:nBases
    for j = 1:Nh
        nVessel(i,j)= nVessel(i,j)+2;
    end
end

%Total demand from all installations
DiTot=sum(Di);

%No of round trips per hub-vessel per period, echelon 1
nTrips=ones(nBases, Nh);

%Total delivery capacity per hub-location per period
CapEO = zeros(nBases, Nh);
for i = 1:nBases
    for j = 1:Nh
        CapEO(i,j)=(nVessel(i,j)*nTrips(i,j))*qHub;
    end
end

for i = 1:nBases
    for j = 1:Nh
        if ( (2*bhDuration(i,j) > (periodHours/(2*nTrips(i,j)))) &&
(nVessel(i,j)* qHub < DiTot) )
```

```matlab
            nVessel(i,j) = nVessel(i,j) + 1;
        elseif ((nVessel(i,j)* qHub >= DiTot) && (2*bhDuration(i,j) >
(periodHours/(2*(nTrips(i,j)+1)))))
                nVessel(i,j) = nVessel(i,j) + 1;
                nTrips(i,j)=nTrips(i,j)+1;
        end
    end
end


%Unit cost for chartering & operating one PSV p per period, echelon 2
CET = ( CYearET / 52 ) * W ;

%Unit cost for chartering & operating the fleet of hub-vessels per
period, echelon 1
CbhEO = zeros(nBases, Nh);
for i = 1:nBases
    for j = 1:Nh
        CbhEO(i,j) = nVessel(i,j)* ((CYearEO / 52) * W);
    end
end


SiW=Si*W;


Q_PSVW=qPSV*W;


%Big M: M_p
M_p = ceil(periodHours / min(min(Thr)));

%Big M: M_r
M_r = max(Di);



%% Write to tab delimited file---------------------------------------
-----

fid = fopen('InputHUB.dat', 'w');
fprintf(fid, '\n\n!Input file for Xpress IVE, generated in MATLAB
R2014a \n\n');
fprintf(fid, '\n\n!Master Thesis, NTNU, Marine Technology by Marina
Riple\n\n');
fprintf(fid, '\n\n!"Allocation of emergency response assets in the
Barents Sea"\n\n');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!All durations given in [hours]\n\n');
fprintf(fid, '\n\n!All distances given in [nm]\n\n');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!Inst : [');
fprintf(fid,'%3.0f\t', InstLocation);
fprintf(fid, ']');
fprintf(fid, '\n\n \n\n');
fprintf(fid, '\n\n!Period: [');
fprintf(fid, '%3.0f\t', p);
fprintf(fid, ']');
fprintf(fid, '\n\n \n\n');


%Number of installations, potential facility sites, routes and bases
fprintf(fid, '\n');
fprintf(fid, '\n\nnHubs : ');
fprintf(fid,'%3.0f\t', Nh);
```

```matlab
fprintf(fid, '\n\nnBases : ');
fprintf(fid,'%3.0f\t', nBases);
fprintf(fid, '\n\nnRoutes : ');
fprintf(fid,'%3.0f\t', nRoutes);
fprintf(fid, '\n\nnPsv : ');
fprintf(fid,'%3.0f\t', nPSV);
fprintf(fid, '\n\nnInst : ');
fprintf(fid,'%3.0f\t', Ni);


%Period in [hours], no slack
fprintf(fid, '\n\nnTimes : ');
fprintf(fid,'%3.0f\t', nTimes);
fprintf(fid, '\n\n \n\n');


%Duration of each route from every possible hub location
fprintf(fid, '\n\nThr : [ \n\n');
fprintf(fid,'%3.0f\t', transpose(Thr));
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Response time between potential facility site j and installation i
fprintf(fid, '\n\nThrOR : [ \n\n');
fprintf(fid,'%3.0f\t', transpose(ThiOR));
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Maximum distance between hub and installation for installation i
fprintf(fid, '\n\nTiMAX : [ \n\n');
fprintf(fid,'%3.0f\t', TiMAX);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Unit cost for chartering & operating one PSV p per period
fprintf(fid, '\n\nCET : ');
fprintf(fid,'%3.0f\t', CET);
fprintf(fid, '\n\n \n\n');


%Unit cost for chartering & operating the fleet of hub-vessels per
period
fprintf(fid, '\n\nCbhEO : [ \n\n');
fprintf(fid,'%3.0f\t', CbhEO);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Base costs, Cb
fprintf(fid, '\n\n\nCb : [ \n\n');
fprintf(fid,'%3.0f\t', Cb);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Period, W [weeks]
fprintf(fid, '\n\n\nW : ');
fprintf(fid,'%3.0f\t', periodHours);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');
```

```
%Number of services at installations, Si
fprintf(fid, '\n\n\nSi : [ \n\n');
fprintf(fid,'%3.0f\t', SiW);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Air-matrix (fixed due to predefined routes & nInstallations)
fprintf(fid, '\n\n\nAir : [ \n\n');
fprintf(fid,'%3.0f\t', A);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Capacity PSV, echelon 2, Qp
fprintf(fid, '\n\n\nQp : ');
fprintf(fid,'%3.0f\t', Q_PSVW);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');


%Demand at installations, Di
fprintf(fid, '\n\n\nDi : [ \n\n');
fprintf(fid,'%3.0f\t', Di);
fprintf(fid, '\n');
fprintf(fid, '\n\n] \n\n');
fprintf(fid, '\n\n \n\n');


%Big M: M_p
fprintf(fid, '\n\n\nM_p : ');
fprintf(fid,'%3.0f\t', M_p);
fprintf(fid, '\n');
fprintf(fid, '\n\n \n\n');


%Big M: M_r
fprintf(fid, '\n\nM_r : ');
fprintf(fid, '%3.0f\t', M_r);
fprintf(fid, '\n');

fclose(fid);
```

APPENDIX D – INPUT FILE FOR MINIMIZING DISTANCE IN SCENARIO 1

!Input file for Xpress IVE, generated in MATLAB R2014a

   !Master Thesis, NTNU, Marine Technology by Marina Riple

!"Allocation of emergency response assets in the Barents Sea"

  !All durations given in [hours]

  !All distances given in [nm]

  !Inst : [72   72   74   74   19   24   24   27   ]

  !Period: [1]

  Nh : 245

  Ni : 4

Schedule: [

0	1	1	3	3	2	2	2	2	2
0	0	0	1	1	3	3	2	2	2
0	0	1	1	1	3	3	3	2	2
3	3	3	2	2	2	2	2	2	2

]

 Dij : [

83	64	56	63	81	105	131	77	56	46 …
164	153	148	149	156	168	185	155	144	139 …
230	207	185	165	149	138	132	225	201	178 …
230	207	185	165	149	138	132	225	201	178 …

]

  DiMAX : [140   140   140   110]

APPENDIX E – INPUT FILE FOR MINIMIZING RESPONSE TIME IN SCENARIO 1

!Input file for Xpress IVE, generated in MATLAB R2014a
   !Master Thesis, NTNU, Marine Technology by Marina Riple
!"Allocation of emergency response assets in the Barents Sea"

!All durations given in [hours]
   !All distances given in [nm]

   !Inst : [72   72   74   74   19   24   24   27   ]

   !Period: [1   ]

   Nh : 245
   Ni : 4

Schedule: [
0   1   1   3   3   2   2   2   2   2
0   0   0   1   1   3   3   2   2   2
0   0   1   1   1   3   3   3   2   2
3   3   3   2   2   2   2   2   2   2
]

   Rij : [
17   16   15   15   17   18   20   16   15   14 ...
23   22   22   22   22   23   24   22   21   21 ...
27   26   24   23   22   21   20   27   25   24 ...
30   29   27   26   25   24   24   30   28   27 ...
]

   RiMAX :   [21   21   21   18   ]

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APPENDIX F – INPUT FILE FOR MINIMIZING SUPPLY COST IN SCENARIO 1

!Input file for Xpress IVE, generated in MATLAB R2014a
   !Master Thesis, NTNU, Marine Technology by Marina Riple
!"Allocation of emergency response assets in the Barents Sea"

  !All durations given in [hours]
  !All distances given in [nm]

!Inst : [72   72   74   74   19   24   24   27   ]

!Period: [1   ]

   nHubs : 245
  nBases : 1
  nRoutes : 15
  nPsv : 10
 nInst : 4
  nTimes : 21

   Thr : [

20	30	38	44	35	43	48	46	50	48 ...
35	40	40	44	40	43	47	44	48	51 ...
.	.	.	.	.	.	.	.	.	.

.
.
.
]

   ThrOR : [

17	16	15	15	17	18	20	16	15	14 ...
23	22	22	22	22	23	24	22	21	21 ...
27	26	24	23	22	21	20	27	25	24 ...
30	29	27	26	25	24	24	30	28	27 ...

]

  TiMAX : [21   21   21   18   ]

  CET : 1538

CbhEO : [4615   4615 6923 6923 6923 6923 6923 4615 4615...

Cb : [1   ]

   W : 168

Si : [3   3   3   3   ]

   Air : [

1	0	0	0	1	1	1	0	0	0	1	1
	1	0	1								
0	1	0	0	1	0	0	1	1	0	1	1
	0	1	1								

0	0	1	0	0	1	0	1	0	1	1	0
	1	1	1								
0	0	0	1	0	0	1	0	1	1	0	1
	1	1	1								

]

Qp : 450

Di : [230 230 230 230]

M_p : 21

M_r : 230

APPENDIX G – INPUT FILE FOR SUPPLY ONLY IN SCENARIO 1

!Input file for Xpress IVE, generated in MATLAB R2014a
!Master Thesis, NTNU, Marine Technology by Marina Riple
!" Allocation of emergency response assets in the Barents Sea"

   !All durations given in [hours]
   !All costs given in [10^3 NOK]

   !Inst : [72   72   74   74   19   24   24   27   ]

   nHubs : 245
 nBases : 1
nRoutes : 15
nPsv : 10
 nInst : 4
 nTimes : 21

  Thr : [
20   30   38   44   35   43   48   46   50   48 ...
35   40   40   44   40   43   47   44   48   51 ...
42   46   43   44   50   20   26   22   28   33 ...
:
:
]
  CET : 1538

   CbhEO : [4615   4615   6923   6923   6923   6923   6923   4615   4615...

Cb : [1   ]

W : 168

   Si : [3   3   3   3   ]

Air : [
1   0   0   0   1   1   1   0   0   0   1   1
       1   0   1
0   1   0   0   1   0   0   1   1   0   1   1
       0   1   1
0   0   1   0   0   1   0   1   0   1   1   0
       1   1   1
0   0   0   1   0   0   1   0   1   1   0   1
       1   1   1
]

Qp : 450

   Di : [230   230   230   230   ]

M_p : 21

  M_r : 230

APPENDIX H – INPUT FILE FOR CONVENTIONAL SUPPLY IN SCENARIO 1

!Input file for Xpress IVE, generated in MATLAB R2014a
  !Master Thesis, NTNU, Marine Technology by Marina Riple
  !" Allocation of emergency response assets in the Barents Sea"

!All durations given in [hours]
  !All costs given in [10^3 NOK]

!Inst : [72   72   74   74   19   24   24   27   ]

   nHubs : 1
nBases : 1
nRoutes : 15
nPsv : 10
nInst : 4
 nTimes : 7

  Thr : [
26   22   38   38   34   46   48   42   43   45   50   53
        53   49   58   ]

CET : 1538

   CbhEO : [0   ]

Cb : [1   ]

W : 168   Si : [3   3   3   3   ]

Air : [
1   0   0   0   1   1   1   0   0   0   1   1
         1   0   1
0   1   0   0   1   0   0   1   1   0   1   1
         0   1   1
0   0   1   0   0   1   0   1   0   1   1   0
         1   1   1
0   0   0   1   0   0   1   0   1   1   0   1
         1   1   1
]

Qp : 450

   Di : [230   230   230   230   ]

   M_p : 8

   M_r   :   230

APPENDIX I – XPRESS IVE SCRIPT FOR BASE CASE

Appendix I contains the Xpress IVE script for allocating the hub when only emergency response assets are considered.

```
model HubLocation
uses "mmxprs";
!gain access to the Xpress-Optimizer solver

! Line break is not an expressio separator. All commands must end
with a ;
options explterm
! Everything except indices must be declared before it is used
options noimplicit

parameters
    DataFile = 'Scenario2R9.txt';
end-parameters
! Get the data file

declarations
    Nh      :   integer;
    Ni      :   integer;
end-declarations
! Data describing the size of the problem:

initializations from DataFile
    Nh;
    Ni;
end-initializations
! The data is read from the file DataFile

declarations
    Hubs        :   set of integer;
    Inst        :   set of integer;
end-declarations
! Defines the sets

Hubs := 1 .. Nh;
Inst := 1.. Ni;
! Define the sets based on the number of facilities

finalize(Hubs);
finalize(Inst);
! All sets are finalized. It is no longer possible to add or remove
elements from the sets

writeln('Hubs : ', Hubs);
writeln('Inst : ', Inst);
! Write to screen

declarations
    Rij     :   array(Inst, Hubs)               of integer;
    RiMAX   :     array(Inst)                     of integer;
    !Dij            :    array(Inst, Hubs)              of integer;
    !DiMAX      :    array(Inst)                  of integer;
end-declarations
! Data describing the rest of the problem

initializations from DataFile
```

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```
    Rij;
    RiMAX;
    !Dij;
    !DiMAX;
end-initializations
! The data is read from the file DataFile

declarations
    Xj            :    dynamic array(Hubs)            of mpvar;
end-declarations
! Declare all variables

forall (hh in Hubs) do
    create(Xj(hh));
end-do
! Generate all variables

declarations
    ResponseTime       :
linctr;
    Duration           :
linctr;
    !AverageDistance       :
linctr;
    !Distance          :        dynamic array(Inst, Hubs )
of linctr;
    HubLocation        :
linctr;
end-declarations
! Declare the objective function (6.12) in the report
! Declare the constraint (6.13) in the report
! Declare the constraint (6.14) in the report
! Declare the constraint (6.15) in the report


ResponseTime:=
    sum(hh in Hubs) (Rij(3,hh)*Xj(hh));
! Defines the objective function (6.12) when response time is
minimized

!AverageDistance:=
!   sum(ii in Inst, hh in Hubs) (Dij(ii,hh) * Xj(hh))/Ni;
! Defines the objective function (6.12) when the average distance is
minimized

HubLocation :=
    sum(hh in Hubs) Xj(hh) = 1;
! Defines constraints (6.13) in the report

forall(hh in Hubs) do
    Rij(1,hh)* Xj(hh) <= RiMAX(1);
    Rij(2,hh)* Xj(hh) <= RiMAX(2);
    Rij(3,hh)* Xj(hh) <= RiMAX(3);
    Rij(4,hh)* Xj(hh) <= RiMAX(4);
end-do
!Defines constraint (6.14)in the report when the response time is
minimized

!forall(ii in Inst,hh in Hubs) do
    !Dij(1,hh)* Xj(hh) <= DiMAX(1);
```

```
    !Dij(2,hh)* Xj(hh) <= DiMAX(2);
    !Dij(3,hh)* Xj(hh) <= DiMAX(3);
!Dij(4,hh)* Xj(hh) <= DiMAX(4);
!end-do
! Defines constraint (6.14) in the report when the average distance
is minimized

forall(hh in Hubs) Xj(hh) is_binary;
! Defines binary restriction on variable. Constraints (6.15) in the
report

minimize(ResponseTime);

!minimize(AverageDistance);

writeln;
writeln('-----------------------------------------');
writeln('"Optimal objective value : " ');
!writeln(' ');
!writeln(getobjval);

writeln;
writeln('deltaH is 1 if hub location h is used, o otherwise');
!writeln(' ');
forall(hh in Hubs) do
writeln('Xj(',hh,') :');
!writeln(getsol(Xj(hh)));
end-do

end-model
```

APPENDIX J – XPRESS IVE SCRIPT FOR EXTENDED CASE

Appendix J contains the MatLab script for allocating the hub when supply and emergency response assets are considered.

```
model HubNetwork
uses "mmxprs";
!gain access to the Xpress-Optimizer solver

! Line break is not an expressio separator. All commands must end
with a ;
options explterm
! Everything except indices must be declared before it is used
options noimplicit

parameters
    DataFile = 'TEST.txt';
end-parameters
! Get the data file

declarations
    nHubs        :   integer;
    nBases       :   integer;
    nRoutes      :   integer;
    nPsv         :   integer;
    nInst        :   integer;
    nTimes       :   integer;
end-declarations
! Data describing the size of the problem:

initializations from DataFile
    nHubs;
    nBases;
    nRoutes;
    nPsv;
    nInst;
    nTimes;
end-initializations
! The data is read from the file DataFile

declarations
    Hubs         :   set of integer;
    Bases        :   set of integer;
    Routes       :   set of integer;
    Psv          :   set of integer;
    Inst         :   set of integer;
    Times        :   set of integer;
end-declarations
! Defines the sets

Hubs := 1 .. nHubs;
Bases := 1 .. nBases;
Routes := 1 .. nRoutes;
Psv := 1 .. nPsv;
Inst := 1 .. nInst;
Times := 1 .. nTimes;
! Define the sets based on the number of facilities

finalize(Hubs);
finalize(Bases);
```

```
finalize(Routes);
finalize(Psv);
finalize(Inst);
finalize(Times);
! All sets are finalized. It is no longer possible to add or remove
elements from the sets

writeln('Hubs : ', Hubs);
writeln('Bases : ', Bases);
writeln('Routes : ', Routes);
writeln('PSV : ', Psv);
writeln('Inst : ', Inst);
writeln('Times : ', Times);
! Write to screen

declarations
    Thr             :   array(Hubs, Routes)         of integer;
    ThrOR           :   array(Inst, Hubs)           of integer;
    CET             :                               integer;
    CbhEO           :   array(Bases, Hubs)          of integer;
    Cb              :   array(Bases)                of integer;
    W               :                               integer;
    Si              :   array(Inst)                 of integer;
    Air             :   array(Inst, Routes)         of integer;
    Qp              :   array(Psv)                  of integer;
    Di              :   array(Inst)                 of integer;
    M_p             :                               integer;
    M_r             :                               integer;
    TiMAX           :   array(Inst)                 of integer;

end-declarations
! Data describing the rest of the problem

initializations from DataFile
    Thr;
    ThrOR;
    CET;
    CbhEO;
    Cb;
    W;
    Si;
    Air;
    Qp;
    Di;
    M_p;
    M_r;
    TiMAX;

end-initializations
! The data is read from the file DataFile

declarations
    deltaH  :   dynamic array(Hubs)                         of
mpvar;
    gammaB  :   dynamic array(Bases)                        of
mpvar;
    alphaP  :   dynamic array(Psv)                          of
mpvar;
    rhoBH   :   dynamic array(Bases, Hubs)                  of
mpvar;
```

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```
    xPRH    :    dynamic array(Psv, Routes, Hubs)                    of
mpvar;
    qIPRK   :    dynamic array(Inst, Psv, Routes, Times)             of
mpvar;
    betaPRK :    dynamic array(Psv, Routes, Times)                   of
mpvar;
end-declarations
! Declare all variables

forall (hh in Hubs) do
    create(deltaH(hh));
end-do

forall (bb in Bases) do
    create(gammaB(bb));
end-do

forall (pp in Psv) do
    create(alphaP(pp));
end-do

forall (bb in Bases, hh in Hubs) do
    create(rhoBH(bb,hh));
end-do

forall (pp in Psv, rr in Routes, hh in Hubs) do
    create(xPRH(pp, rr, hh));
end-do

forall (ii in Inst, pp in Psv, rr in Routes, kk in Times) do
    create(qIPRK(ii,pp,rr,kk));
end-do

forall (pp in Psv, rr in Routes, kk in Times) do
    create(betaPRK(pp,rr,kk));
end-do
! Generate all variables

declarations
    TotalCost       :
linctr;
    Service         :    dynamic array(Inst)                         of
linctr;
    HubLocation     :
linctr;
    BaseLocation    :
linctr;
    MaxResponsetime :    dynamic array(Inst, Hubs)                   of
linctr;
    CouplingA       :    dynamic array(Psv)                          of
linctr;
    CouplingB       :    dynamic array(Bases)                        of
linctr;
    CouplingC       :    dynamic array(Psv, Hubs)                    of
linctr;
    ExistBase       :    dynamic array(Bases)                        of
linctr;
    ExistHub        :    dynamic array(Hubs)                         of
linctr;
```

```
    Duration          :    dynamic array(Psv)                          of
linctr;
    Delivery          :    dynamic array(Inst)                         of
linctr;
    CouplingD         :    dynamic array(Inst, Routes, Psv, Times)  of
linctr;
    CouplingE         :    dynamic array(Routes, Psv)                  of
linctr;
    CapacityVessel    :    dynamic array(Routes, Psv)                  of
linctr;
    AntiSym_p         :    dynamic array(Inst, Psv, Routes, Times)   of
linctr;
    AntiSym_b         :    dynamic array(Psv, Routes, Times)           of
linctr;
end-declarations
! Declare the objective function (8.1) in the report
! Declare constraint (8.2) in the report
! Declare constraint (8.3) in the report
! Declare constraint (8.4) in the report
! Declare constraint (5.23) in the report
! Declare constraint (8.5) in the report
! Declare constraint (8.6) in the report
! Declare constraint (8.7) in the report
! Declare constraint (8.8) in the report
! Declare constraint (8.9) in the report
! Declare constraint (8.10) in the report
! Declare constraint (8.11) in the report
! Declare constraint (8.12) in the report
! Declare constraint (8.13) in the report
! Declare constraint (8.14) in the report
! Declare constraint (8.15) in the report
! Declare constraint (8.16) in the report

TotalCost:=
    sum(pp in Psv) CET * alphaP(pp) +
    sum(bb in Bases, hh in Hubs) CbhEO(bb,hh) * rhoBH(bb,hh) +
    sum(bb in Bases, ii in Inst) Cb(bb) * Di(ii) * gammaB(bb);
! Defines the objective function (8.1) in the report

forall(ii in Inst) do
    sum(hh in Hubs, pp in Psv, rr in Routes) Air(ii,rr) *
xPRH(pp,rr,hh) >= Si(ii);
end-do
! Defines constraint (8.2) in the report

HubLocation :=
    sum(hh in Hubs) deltaH(hh) = 1;
! Defines constraint (8.3) in the report

BaseLocation :=
    sum(bb in Bases) gammaB(bb) = 1;
! Defines constraint (8.4) in the report

forall(ii in Inst,hh in Hubs) do
    ThrOR(1,hh)* deltaH(hh) <= TiMAX(1);
    ThrOR(2,hh)* deltaH(hh) <= TiMAX(2);
    ThrOR(3,hh)* deltaH(hh) <= TiMAX(3);
    ThrOR(4,hh)* deltaH(hh) <= TiMAX(4);
end-do
!Defines constraint (8.23) in the report
```

```
forall(pp in Psv, rr in Routes) do
    sum(hh in Hubs) xPRH(pp, rr, hh) - (M_p * alphaP(pp)) <= 0;
end-do
! Defines constraints (8.5) in the report

forall (pp in Psv, hh in Hubs) do
    sum(rr in Routes) xPRH(pp, rr, hh) - (M_p * deltaH(hh)) <= 0;
end-do
! Defines constraints (8.6) in the report

forall(bb in Bases) do
    gammaB(bb) = sum(hh in Hubs) rhoBH(bb,hh);
end-do
! Defines constraints (8.7) in the report

forall(hh in Hubs) do
    deltaH(hh) = sum(bb in Bases) rhoBH(bb,hh);
end-do
! Defines constraints (8.8) in the report

forall(pp in Psv, hh in Hubs) do
    sum(rr in Routes) Thr(hh,rr) * xPRH(pp,rr,hh) <= W;
end-do
! Defines constraints (8.9) in the report

forall(ii in Inst) do
    sum(pp in Psv, rr in Routes, kk in Times) qIPRK(ii,pp,rr,kk) >=
Di(ii);
end-do
! Defines constraints (8.10) in the report

forall(ii in Inst, rr in Routes, pp in Psv, kk in Times) do
    qIPRK(ii,pp,rr,kk) - M_r * betaPRK(pp,rr,kk) <= 0;
end-do
! Defines constraints (8.11) in the report

forall(rr in Routes, pp in Psv) do
    sum(kk in Times) betaPRK(pp,rr,kk) = sum(hh in Hubs)
xPRH(pp,rr,hh);
end-do
! Defines constraints (8.12) in the report

forall(rr in Routes, pp in Psv) do
    Qp(pp) >= sum(ii in Inst, kk in Times) qIPRK(ii,pp,rr,kk);
end-do
! Defines constraints (8.13) in the report

forall(ii in Inst, pp in Psv, rr in Routes, kk in Times | kk <=
(nTimes-1) ) do
    qIPRK(ii, pp, rr, kk+1) <= qIPRK(ii, pp, rr, kk);
end-do
! Defines constraints (8.14) in the report

forall(pp in Psv, rr in Routes, kk in Times | kk <= (nTimes-1) ) do
    betaPRK(pp, rr, kk+1) <= betaPRK(pp, rr, kk);
end-do
! Defines constraints (8.15) in the report

forall(hh in Hubs) deltaH(hh) is_binary;
! Defines binary restriction on variable. Constraints (5.16) in the
report
```

```
forall(bb in Bases) gammaB(bb) is_binary;
! Defines binary restriction on variable. Constraints (8.17) in the
report

forall(pp in Psv) alphaP(pp) is_binary;
! Defines binary restriction on variable. Constraints (8.18) in the
report

forall(bb in Bases, hh in Hubs) rhoBH(bb,hh) is_binary;
! Defines binary restriction on variable. Constraints (8.19) in the
report

forall(pp in Psv, rr in Routes, hh in Hubs) xPRH(pp,rr,hh)
is_integer;
! Defines integer restriction on variable. Constraints (8.20) in the
report

forall(ii in Inst, pp in Psv, rr in Routes, kk in Times)
qIPRK(ii,pp,rr,kk) is_integer;
! Defines integer restriction on variable. Constraints (8.21) in the
report

forall(pp in Psv, rr in Routes, kk in Times) betaPRK(pp,rr,kk)
is_binary;
! Defines binary restriction on variable. Constraints (8.22) in the
report

minimize(TotalCost);

writeln;
writeln('------------------------------------------');
writeln('"Optimal objective value : " ');
!writeln(' ');
!writeln(getobjval);

writeln;
writeln('deltaH is 1 if hub location h is used, o otherwise');
!writeln(' ');
forall(hh in Hubs) do
writeln('deltaH(',hh,') :');
!writeln(getsol(deltaH(hh)));
end-do

writeln;
writeln('gammaB is 1 if base b is used, 0 otherwise');
!writeln(' ');
forall(bb in Bases) do
writeln('gamaB(',bb,') : ');
!writeln(getsol(gammaB(bb)));
end-do

writeln;
writeln('alphaP');
!writeln(' ');
forall(pp in Psv) do
writeln('alphaP(',pp,') : ');
!writeln(getsol(alphaP(pp)));
end-do

writeln;
```

```
writeln('betaPRK');
!writeln(' ');
forall(pp in Psv, rr in Routes ,kk in Times) do
writeln('betaPRK(',pp,',', rr,',', kk,') : ');
!writeln(getsol(betaPRK(pp, rr, kk)));
end-do

writeln;
writeln('qIPRK');
!writeln(' ');
forall(ii in Inst, pp in Psv, rr in Routes ,kk in Times) do
writeln('qIPRK(',ii,',',pp,',', rr,',', kk,') : ');
!writeln(getsol(qIPRK(ii,pp, rr, kk)));
end-do

writeln;
writeln('rhoBH');
!writeln(' ');
forall(bb in Bases, hh in Hubs) do
writeln('rhoBH(',bb,',', hh,') : ');
!writeln(getsol(rhoBH(bb,hh)));
end-do

writeln;
writeln('xPRH');
!writeln(' ');
forall(pp in Psv, rr in Routes ,hh in Hubs) do
writeln('xPRH(',pp,',', rr,',', hh,') : ');
!writeln(getsol(xPRH(pp, rr, hh)));
end-do


end-model
```

APPENDIX K – POTENTIAL HUB LOCATIONS

All possible potential hub locations.

Location	Latitude°N	Longitude°E	Location	Latitude°N	Longitude°E
1	71	16	42	74	19
2	71,5	16	43	71	19,5
3	72	16	44	71,5	19,5
4	72,5	16	45	72	19,5
5	73	16	46	72,5	19,5
6	73,5	16	47	73	19,5
7	74	16	48	73,5	19,5
8	71	16,5	49	74	19,5
9	71,5	16,5	50	71	20
10	72	16,5	51	71,5	20
11	72,5	16,5	52	72	20
12	73	16,5	53	72,5	20
13	73,5	16,5	54	73	20
14	74	16,5	55	73,5	20
15	71	17	56	74	20
16	71,5	17	57	71	20,5
17	72	17	58	71,5	20,5
18	72,5	17	59	72	20,5
19	73	17	60	72,5	20,5
20	73,5	17	61	73	20,5
21	74	17	62	73,5	20,5
22	71	17,5	63	74	20,5
23	71,5	17,5	64	71	21
24	72	17,5	65	71,5	21
25	72,5	17,5	66	72	21
26	73	17,5	67	72,5	21
27	73,5	17,5	68	73	21
28	74	17,5	69	73,5	21
29	71	18	70	74	21
30	71,5	18	71	71	21,5
31	72	18	72	71,5	21,5
32	72,5	18	73	72	21,5
33	73	18	74	72,5	21,5
34	73,5	18	75	73	21,5
35	74	18	76	73,5	21,5
36	71	18,5	77	74	21,5
37	71,5	18,5	78	71	22
38	72	18,5	79	71,5	22
39	72,5	18,5	80	72	22
40	73	18,5	81	72,5	22
41	73,5	18,5	82	73	22

Location	Latitude°N	Longitude°E	Location	Latitude°N	Longitude°E
83	73,5	21,5	124	73	24,5
84	74	21,5	125	73,5	24,5
85	71	22	126	74	24,5
86	71,5	22	127	71	25
87	72	22	128	71,5	25
88	72,5	22	129	72	25
89	73	22	130	72,5	25
90	73,5	22	131	73	25
91	74	22	132	73,5	25
92	71	22,5	133	74	25
93	71,5	22,5	134	71	25,5
94	72	22,5	135	71,5	25,5
95	72,5	22,5	136	72	25,5
96	73	22,5	137	72,5	25,5
97	73,5	22,5	138	73	25,5
98	74	22,5	139	73,5	25,5
99	71	23	140	74	25,5
100	71,5	23	141	71	26
101	72	23	142	71,5	26
102	72,5	23	143	72	26
103	73	23	144	72,5	26
104	73,5	23	145	73	26
105	74	23	146	73,5	26
106	71	23,5	147	74	26
107	71,5	23,5	148	71	26,5
108	72	23,5	149	71,5	26,5
109	72,5	23,5	150	72	26,5
110	73	23,5	151	72,5	26,5
111	73,5	23,5	152	73	26,5
112	74	23,5	153	73,5	26,5
113	71	24	154	74	26,5
114	71,5	24	155	71	27
115	72	24	156	71,5	27
116	72,5	24	157	72	27
117	73	24	158	72,5	27
118	73,5	24	159	73	27
119	74	24	160	73,5	27
120	71	24,5	161	74	27
121	71,5	24,5	162	71	27,5
122	72	24,5	163	71,5	27,5
123	72,5	24,5	164	72	27,5

Location	Latitude°N	Longitude °E	Location	Latitude°N	Longitude°E
165	72,5	27,5	206	72	30,5
166	73	27,5	207	72,5	30,5
167	73,5	27,5	208	73	30,5
168	74	27,5	209	73,5	30,5
169	71	28	210	74	30,5
170	71,5	28	211	71	31
171	72	28	212	71,5	31
172	72,5	28	213	72	31
173	73	28	214	72,5	31
174	73,5	28	215	73	31
175	74	28	216	73,5	31
176	71	28,5	217	74	31
177	71,5	28,5	218	71	31,5
178	72	28,5	219	71,5	31,5
179	72,5	28,5	220	72	31,5
180	73	28,5	221	72,5	31,5
181	73,5	28,5	222	73	31,5
182	74	28,5	223	73,5	31,5
183	71	29	224	74	31,5
184	71,5	29	225	71	32
185	72	29	226	71,5	32
186	72,5	29	227	72	32
187	73	29	228	72,5	32
188	73,5	29	229	73	32
189	74	29	230	73,5	32
190	71	29,5	231	74	32
191	71,5	29,5	232	71	32,5
192	72	29,5	233	71,5	32,5
193	72,5	29,5	234	72	32,5
194	73	29,5	235	72,5	32,5
195	73,5	29,5	236	73	32,5
196	74	29,5	237	73,5	32,5
197	71	30	238	74	32,5
198	71,5	30	239	71	33
199	72	30	240	71,5	33
200	72,5	30	241	72	33
201	73	30	242	72,5	33
202	73,5	30	243	73	33
203	74	30	244	73,5	33
204	71	30,5	245	74	33
205	71,5	30,5			

APPENDIX L – DISTANCES FOR SCENARIO 1

Distances between all possible hub locations and installations for scenario 1.

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
1	83	164	230	267	42	120	154	91	141
2	64	153	207	246	43	60	113	201	230
3	56	148	185	227	44	30	99	174	207
4	63	149	165	210	45	0	93	149	185
5	81	156	149	197	46	30	96	125	165
6	105	168	138	187	47	60	108	104	149
7	131	185	132	182	48	90	127	89	138
8	77	155	225	261	49	120	149	83	132
9	56	144	201	239	50	61	105	197	225
10	46	139	178	220	51	31	90	170	201
11	55	140	158	202	52	9	83	144	178
12	75	148	141	189	53	31	88	119	158
13	100	161	129	179	54	61	101	97	141
14	128	178	124	174	55	90	120	81	129
15	71	146	220	254	56	120	144	74	124
16	48	135	195	232	57	63	97	194	220
17	37	130	172	212	58	35	81	166	195
18	47	132	151	195	59	19	74	139	172
19	70	140	134	181	60	35	79	114	151
20	97	154	121	170	61	63	94	91	134
21	125	172	116	165	62	92	115	74	121
22	66	138	215	248	63	121	139	66	116
23	41	126	189	226	64	66	90	191	215
24	28	121	165	205	65	41	72	162	189
25	41	123	144	187	66	28	65	135	165
26	66	132	126	173	67	41	71	108	144
27	94	147	113	162	68	66	87	85	126
28	123	165	108	157	69	94	109	66	113
29	63	129	210	242	70	123	135	58	108
30	35	117	184	219	71	71	83	188	210
31	19	111	160	198	72	48	64	159	184
32	35	114	137	180	73	37	56	131	160
33	63	124	119	165	74	47	63	104	137
34	92	140	105	154	75	70	81	79	119
35	121	160	99	149	76	97	105	59	105
36	61	121	205	236	77	125	131	50	99
37	31	108	179	213	78	77	77	186	205
38	9	102	154	191	79	56	56	157	179
39	31	105	131	172	80	46	46	128	154
40	61	116	111	157	81	55	55	100	131
41	90	133	97	146	82	75	75	74	111

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
83	100	100	52	97	**124**	116	61	61	74
84	128	128	41	91	**125**	133	90	31	52
85	83	71	184	201	**126**	154	120	8	41
86	64	48	154	174	**127**	129	63	181	184
87	56	37	125	149	**128**	117	35	151	154
88	63	47	96	125	**129**	111	19	121	125
89	81	70	69	104	**130**	114	35	92	96
90	105	97	45	89	**131**	124	63	62	69
91	131	125	33	83	**132**	140	92	34	45
92	90	66	182	197	**133**	160	121	17	33
93	72	41	152	170	**134**	138	66	182	182
94	65	28	123	144	**135**	126	41	152	152
95	71	41	94	119	**136**	121	28	123	123
96	87	66	65	97	**137**	123	41	94	94
97	109	94	39	81	**138**	132	66	65	65
98	135	123	25	74	**139**	147	94	39	39
99	97	63	181	194	**140**	165	123	25	25
100	81	35	151	166	**141**	146	71	184	181
101	74	19	121	139	**142**	135	48	154	151
102	79	35	92	114	**143**	130	37	125	121
103	94	63	62	91	**144**	132	47	96	92
104	115	92	34	74	**145**	140	70	69	62
105	139	121	17	66	**146**	154	97	45	34
106	105	61	180	191	**147**	172	125	33	17
107	90	31	150	162	**148**	155	77	186	180
108	83	9	120	135	**149**	144	56	157	150
109	88	31	90	108	**150**	139	46	128	120
110	101	61	61	85	**151**	140	55	100	90
111	120	90	31	66	**152**	148	75	74	61
112	144	120	8	58	**153**	161	100	52	31
113	113	60	180	188	**154**	178	128	41	8
114	99	30	150	159	**155**	164	83	188	180
115	93	0	120	131	**156**	153	64	159	150
116	96	30	90	104	**157**	148	56	131	120
117	108	60	60	79	**158**	149	63	104	90
118	127	90	30	59	**159**	156	81	79	60
119	149	120	0	50	**160**	168	105	59	30
120	121	61	180	186	**161**	185	131	50	0
121	108	31	150	157	**162**	173	90	191	180
122	102	9	120	128	**163**	162	72	162	150
123	105	31	90	100	**164**	158	65	135	120

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
165	158	71	108	90	**206**	213	121	165	135
166	165	87	85	61	**207**	212	123	144	108
167	176	109	66	31	**208**	216	132	126	85
168	191	135	58	8	**209**	223	147	113	66
169	181	97	194	181	**210**	234	165	108	58
170	172	81	166	151	**211**	236	146	220	194
171	167	74	139	121	**212**	227	135	195	166
172	167	79	114	92	**213**	222	130	172	139
173	173	94	91	62	**214**	221	132	151	114
174	184	115	74	34	**215**	224	140	134	91
175	198	139	66	17	**216**	231	154	121	74
176	190	105	197	182	**217**	242	172	116	66
177	181	90	170	152	**218**	245	155	225	197
178	176	83	144	123	**219**	237	144	201	170
179	176	88	119	94	**220**	232	139	178	144
180	181	101	97	65	**221**	230	140	158	119
181	191	120	81	39	**222**	233	148	141	97
182	205	144	74	25	**223**	240	161	129	81
183	199	113	201	184	**224**	249	178	124	74
184	190	99	174	154	**225**	254	164	230	201
185	185	93	149	125	**226**	246	153	207	174
186	185	96	125	96	**227**	241	148	185	149
187	190	108	104	69	**228**	239	149	165	125
188	199	127	89	45	**229**	242	156	149	104
189	212	149	83	33	**230**	248	168	138	89
190	209	121	205	186	**231**	257	185	132	83
191	199	108	179	157	**232**	263	173	236	205
192	195	102	154	128	**233**	255	162	213	179
193	194	105	131	100	**234**	250	158	191	154
194	199	116	111	74	**235**	248	158	172	131
195	207	133	97	52	**236**	250	165	157	111
196	220	154	91	41	**237**	256	176	146	97
197	218	129	210	188	**238**	265	191	141	91
198	209	117	184	159	**239**	273	181	242	210
199	204	111	160	131	**240**	264	172	219	184
200	203	114	137	104	**241**	259	167	198	160
201	207	124	119	79	**242**	257	167	180	137
202	215	140	105	59	**243**	259	173	165	119
203	227	160	99	50	**244**	264	184	154	105
204	227	138	215	191	**245**	273	198	149	99
205	218	126	189	162					

APPENDIX M – DISTANCES FOR SCENARIO 2

Distances between all possible hub locations and installations for scenario 2.

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
1	199	180	258	49	42	178	41	154	150
2	190	150	239	38	43	146	188	216	36
3	185	120	223	48	44	135	159	195	19
4	185	90	210	71	45	130	131	176	35
5	190	60	201	97	46	132	104	161	63
6	199	30	196	125	47	140	79	150	92
7	212	0	195	154	48	154	59	145	121
8	190	180	251	42	49	172	50	146	151
9	181	150	232	29	50	138	191	209	42
10	176	120	215	41	51	126	162	188	29
11	176	90	202	66	52	121	135	168	41
12	181	61	192	94	53	123	108	153	66
13	191	31	187	123	54	132	85	142	94
14	205	8	187	152	55	147	66	136	123
15	181	181	243	36	56	165	58	138	152
16	172	151	224	19	57	129	194	203	49
17	167	121	207	35	58	117	166	181	38
18	167	92	194	63	59	111	139	161	48
19	173	62	184	92	60	114	114	145	71
20	184	34	179	121	61	124	91	133	97
21	198	17	179	151	62	140	74	128	125
22	173	182	236	32	63	160	66	129	154
23	162	152	216	10	64	121	197	197	57
24	158	123	199	31	65	108	170	174	48
25	158	94	185	61	66	102	144	154	56
26	165	65	175	91	67	105	119	137	76
27	176	39	170	120	68	116	97	125	101
28	191	25	170	150	69	133	81	119	128
29	164	184	229	30	70	154	74	121	157
30	153	154	209	0	71	113	201	191	65
31	148	125	191	30	72	99	174	168	57
32	149	96	177	60	73	93	149	147	64
33	156	69	167	90	74	96	125	129	82
34	168	45	162	120	75	108	104	116	105
35	185	33	162	150	76	127	89	111	132
36	155	186	222	32	77	149	83	113	159
37	144	157	202	10	78	105	205	186	74
38	139	128	184	31	79	90	179	162	67
39	140	100	169	61	80	83	154	140	72
40	148	74	158	91	81	88	131	121	88
41	161	52	153	120	82	101	111	108	110

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
83	120	97	102	136	124	66	157	60	149
84	144	91	105	162	125	94	146	51	168
85	97	210	181	83	126	123	141	59	189
86	81	184	156	76	127	63	242	157	138
87	74	160	133	81	128	35	219	128	133
88	79	137	114	95	129	19	198	100	135
89	94	119	100	116	130	35	180	74	143
90	115	105	94	140	131	63	165	53	156
91	139	99	97	166	132	92	154	43	174
92	90	215	176	92	133	121	149	52	195
93	72	189	150	86	134	61	248	154	148
94	65	165	127	90	135	31	226	125	143
95	71	144	106	103	136	9	205	97	144
96	87	126	92	122	137	31	187	70	151
97	109	113	85	145	138	61	173	46	164
98	135	108	89	170	139	90	162	34	181
99	83	220	171	101	140	120	157	45	201
100	64	195	145	95	141	60	254	153	157
101	56	172	120	99	142	30	232	123	152
102	63	151	99	110	143	0	212	94	153
103	81	134	83	128	144	30	195	66	160
104	105	121	77	150	145	60	181	40	172
105	131	116	81	174	146	90	170	26	188
106	77	225	167	110	147	120	165	39	207
107	56	201	140	105	148	61	261	151	167
108	46	178	115	108	149	31	239	121	162
109	55	158	92	118	150	9	220	92	162
110	75	141	75	135	151	31	202	63	169
111	100	129	68	156	152	61	189	35	180
112	128	124	74	179	153	90	179	17	195
113	71	230	163	120	154	120	174	34	213
114	48	207	136	114	155	63	267	150	176
115	37	185	109	117	156	35	246	120	171
116	47	165	86	126	157	19	227	90	172
117	70	149	68	142	158	35	210	61	177
118	97	138	60	162	159	63	197	31	187
119	125	132	66	184	160	92	187	9	202
120	66	236	160	129	161	121	182	31	219
121	41	213	132	124	162	66	274	150	186
122	28	191	105	126	163	41	253	120	181
123	41	172	80	135	164	28	234	90	181

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
165	41	218	60	186	**206**	83	280	105	237
166	66	205	30	196	**207**	88	266	80	239
167	94	195	0	209	**208**	101	254	60	245
168	123	190	30	226	**209**	120	245	51	255
169	71	281	150	195	**210**	144	239	59	268
170	48	260	120	190	**211**	113	324	163	252
171	37	242	90	190	**212**	99	305	136	247
172	47	226	61	195	**213**	93	288	109	246
173	70	213	31	204	**214**	96	274	86	248
174	97	203	9	216	**215**	108	262	68	254
175	125	198	31	232	**216**	127	253	60	263
176	77	288	151	205	**217**	149	248	66	275
177	56	268	121	200	**218**	121	331	167	262
178	46	249	92	199	**219**	108	313	140	257
179	55	234	63	204	**220**	102	296	115	255
180	75	221	35	212	**221**	105	282	92	257
181	100	212	17	224	**222**	116	270	75	262
182	128	206	34	239	**223**	133	261	68	271
183	83	295	153	214	**224**	154	256	74	282
184	64	275	123	209	**225**	129	339	171	271
185	56	257	94	209	**226**	117	321	145	266
186	63	242	66	212	**227**	111	304	120	264
187	81	229	40	220	**228**	114	290	99	266
188	105	220	26	232	**229**	124	278	83	271
189	131	215	39	246	**230**	140	270	77	279
190	90	302	154	224	**231**	160	264	81	290
191	72	282	125	219	**232**	138	346	176	281
192	65	265	97	218	**233**	126	328	150	276
193	71	250	70	221	**234**	121	312	127	274
194	87	237	46	228	**235**	123	298	106	275
195	109	228	34	239	**236**	132	287	92	279
196	135	223	45	253	**237**	147	278	85	287
197	97	309	157	233	**238**	165	272	89	298
198	81	290	128	228	**239**	146	354	181	290
199	74	273	100	227	**240**	135	336	156	285
200	79	258	74	230	**241**	130	320	133	283
201	94	246	53	237	**242**	132	306	114	284
202	115	237	43	247	**243**	140	295	100	288
203	139	231	52	260	**244**	154	286	94	295
204	105	316	160	243	**245**	172	280	97	305
205	90	298	132	238	**246**				

APPENDIX N – RESPONSE TIME FOR SCENARIO 1

Response time between all possible hub locations and installations for scenario 1.

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
1	17	23	27	30	42	20	22	17	21
2	16	22	26	29	43	15	19	25	27
3	15	22	24	27	44	13	18	23	26
4	15	22	23	26	45	11	18	22	24
5	17	22	22	25	46	13	18	20	23
6	18	23	21	24	47	15	19	18	22
7	20	24	20	24	48	17	20	17	21
8	16	22	27	30	49	20	22	17	20
9	15	21	25	28	50	15	18	25	27
10	14	21	24	27	51	13	17	23	25
11	15	21	22	25	52	12	17	21	24
12	16	22	21	24	53	13	17	19	22
13	18	22	20	24	54	15	18	18	21
14	20	24	20	23	55	17	20	17	20
15	16	21	27	29	56	20	21	16	20
16	14	21	25	28	57	15	18	25	27
17	14	20	23	26	58	14	17	23	25
18	14	20	22	25	59	12	16	21	23
19	16	21	21	24	60	14	17	19	22
20	18	22	20	23	61	15	18	17	21
21	20	23	19	23	62	18	19	16	20
22	16	21	26	29	63	20	21	16	19
23	14	20	25	27	64	16	17	25	26
24	13	20	23	26	65	14	16	23	25
25	14	20	21	24	66	13	16	21	23
26	16	20	20	23	67	14	16	19	21
27	18	21	19	23	68	16	17	17	20
28	20	23	19	22	69	18	19	16	19
29	15	20	26	28	70	20	21	15	19
30	14	19	24	27	71	16	17	24	26
31	12	19	22	25	72	14	16	22	24
32	14	19	21	24	73	14	15	20	22
33	15	20	19	23	74	14	15	18	21
34	18	21	19	22	75	16	17	17	19
35	20	22	18	22	76	18	18	15	19
36	15	20	26	28	77	20	20	15	18
37	13	19	24	26	78	16	16	24	26
38	12	18	22	25	79	15	15	22	24
39	13	19	20	23	80	14	14	20	22
40	15	19	19	22	81	15	15	18	20
41	17	20	18	21	82	16	16	16	19

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
83	18	18	15	18	124	19	15	15	16
84	20	20	14	17	125	20	17	13	15
85	17	16	24	25	126	22	20	12	14
86	16	14	22	23	127	20	15	24	24
87	15	14	20	22	128	19	14	22	22
88	15	14	18	20	129	19	12	20	20
89	17	16	16	18	130	19	14	18	18
90	18	18	14	17	131	20	15	15	16
91	20	20	13	17	132	21	18	13	14
92	17	16	24	25	133	22	20	12	13
93	16	14	22	23	134	21	16	24	24
94	16	13	20	21	135	20	14	22	22
95	16	14	18	19	136	20	13	20	20
96	17	16	16	18	137	20	14	18	18
97	19	18	14	17	138	20	16	16	16
98	21	20	13	16	139	21	18	14	14
99	18	15	24	25	140	23	20	13	13
100	17	14	22	23	141	21	16	24	24
101	16	12	20	21	142	21	14	22	22
102	17	14	18	19	143	20	14	20	20
103	18	15	15	17	144	20	14	18	18
104	19	18	13	16	145	21	16	16	15
105	21	20	12	16	146	22	18	14	13
106	18	15	24	25	147	23	20	13	12
107	17	13	22	23	148	22	16	24	24
108	17	12	20	21	149	21	15	22	22
109	17	13	17	19	150	21	14	20	20
110	18	15	15	17	151	21	15	18	17
111	20	17	13	16	152	22	16	16	15
112	21	20	12	15	153	22	18	15	13
113	19	15	24	24	154	24	20	14	12
114	18	13	22	22	155	23	17	24	24
115	18	11	20	20	156	22	16	22	22
116	18	13	17	18	157	22	15	20	20
117	19	15	15	17	158	22	15	18	17
118	20	17	13	15	159	22	17	17	15
119	22	20	11	15	160	23	18	15	13
120	20	15	24	24	161	24	20	15	11
121	19	13	22	22	162	23	17	25	24
122	18	12	20	20	163	23	16	23	22
123	19	13	17	18	164	22	16	21	20

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
165	22	16	19	17	206	26	20	23	21
166	23	17	17	15	207	26	20	21	19
167	24	19	16	13	208	26	20	20	17
168	25	21	15	12	209	27	21	19	16
169	24	18	25	24	210	28	23	19	15
170	23	17	23	22	211	28	21	27	25
171	23	16	21	20	212	27	21	25	23
172	23	17	19	18	213	27	20	23	21
173	23	18	17	15	214	27	20	22	19
174	24	19	16	13	215	27	21	21	17
175	25	21	16	12	216	28	22	20	16
176	25	18	25	24	217	28	23	19	16
177	24	17	23	22	218	29	22	27	25
178	24	17	21	20	219	28	21	25	23
179	24	17	19	18	220	28	21	24	21
180	24	18	18	16	221	27	21	22	19
181	25	20	17	14	222	28	22	21	18
182	26	21	16	13	223	28	22	20	17
183	25	19	25	24	224	29	24	20	16
184	25	18	23	22	225	29	23	27	25
185	24	18	22	20	226	29	22	26	23
186	24	18	20	18	227	28	22	24	22
187	25	19	18	16	228	28	22	23	20
188	25	20	17	14	229	28	22	22	18
189	26	22	17	13	230	29	23	21	17
190	26	20	26	24	231	29	24	20	17
191	25	19	24	22	232	30	23	28	26
192	25	18	22	20	233	29	23	26	24
193	25	19	20	18	234	29	22	25	22
194	25	19	19	16	235	29	22	23	20
195	26	20	18	15	236	29	23	22	19
196	27	22	17	14	237	29	24	21	18
197	27	20	26	24	238	30	25	21	17
198	26	19	24	22	239	30	24	28	26
199	26	19	22	20	240	30	23	27	24
200	26	19	21	18	241	30	23	25	22
201	26	20	19	17	242	29	23	24	21
202	26	21	19	15	243	30	23	23	19
203	27	22	18	15	244	30	24	22	19
204	27	21	26	25	245	30	25	22	18
205	27	20	25	23					

APPENDIX O – RESPONSE TIME FOR SCENARIO 2

Response time between all possible hub locations and installations for scenario 2.

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
1	25	24	29	14	42	24	14	22	22
2	25	22	28	14	43	21	24	26	14
3	24	20	27	14	44	21	22	25	12
4	24	17	26	16	45	20	20	24	14
5	25	15	25	18	46	20	18	22	15
6	25	13	25	20	47	21	17	22	18
7	26	11	25	22	48	22	15	21	20
8	25	24	29	14	49	23	15	21	22
9	24	22	28	13	50	21	25	26	14
10	24	20	26	14	51	20	23	24	13
11	24	17	25	16	52	20	21	23	14
12	24	15	25	18	53	20	19	22	16
13	25	13	24	20	54	20	17	21	18
14	26	12	24	22	55	21	16	21	20
15	24	24	28	14	56	23	15	21	22
16	23	22	27	12	57	20	25	26	14
17	23	20	26	14	58	19	23	24	14
18	23	18	25	15	59	19	21	22	14
19	23	15	24	18	60	19	19	21	16
20	24	13	24	20	61	20	17	21	18
21	25	12	24	22	62	21	16	20	20
22	23	24	28	13	63	22	16	20	22
23	23	22	26	12	64	20	25	25	15
24	22	20	25	13	65	19	23	23	14
25	22	18	24	15	66	18	21	22	15
26	23	16	24	17	67	19	19	21	16
27	24	14	23	20	68	19	18	20	18
28	25	13	23	22	69	20	17	20	20
29	23	24	27	13	70	22	16	20	22
30	22	22	26	11	71	19	25	25	16
31	22	20	25	13	72	18	23	23	15
32	22	18	24	15	73	18	22	21	16
33	22	16	23	17	74	18	20	20	17
34	23	14	23	20	75	19	18	19	19
35	24	13	23	22	76	20	17	19	20
36	22	24	27	13	77	22	17	19	22
37	21	22	25	12	78	18	26	24	16
38	21	20	24	13	79	17	24	23	16
39	21	18	23	15	80	17	22	21	16
40	22	16	22	17	81	17	20	20	17
41	22	15	22	20	82	18	19	19	19

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
83	20	18	18	21	**124**	16	22	15	22
84	21	17	19	23	**125**	18	21	15	23
85	18	26	24	17	**126**	20	21	15	25
86	17	24	22	16	**127**	15	28	22	21
87	16	22	20	17	**128**	14	27	20	21
88	17	21	19	18	**129**	12	25	18	21
89	18	19	18	19	**130**	14	24	16	21
90	19	19	18	21	**131**	15	23	15	22
91	21	18	18	23	**132**	18	22	14	23
92	17	26	24	18	**133**	20	22	15	25
93	16	25	22	17	**134**	15	29	22	22
94	16	23	20	17	**135**	13	27	20	21
95	16	21	19	18	**136**	12	26	18	21
96	17	20	18	20	**137**	13	24	16	22
97	19	19	17	21	**138**	15	23	14	23
98	21	19	17	23	**139**	17	23	13	24
99	17	27	23	18	**140**	20	22	14	25
100	16	25	21	18	**141**	15	29	22	22
101	15	23	20	18	**142**	13	28	20	22
102	15	22	18	19	**143**	11	26	18	22
103	17	21	17	20	**144**	13	25	16	22
104	18	20	16	22	**145**	15	24	14	23
105	20	19	17	23	**146**	17	23	13	24
106	16	27	23	19	**147**	20	23	14	26
107	15	25	21	18	**148**	15	30	22	23
108	14	24	19	19	**149**	13	28	20	23
109	15	22	18	19	**150**	12	27	18	23
110	16	21	16	21	**151**	13	25	15	23
111	18	20	16	22	**152**	15	24	13	24
112	20	20	16	24	**153**	17	24	12	25
113	16	27	23	20	**154**	20	23	13	26
114	14	26	21	19	**155**	15	30	22	24
115	14	24	19	19	**156**	14	29	20	23
116	14	23	17	20	**157**	12	27	17	23
117	16	22	16	21	**158**	14	26	15	24
118	18	21	15	23	**159**	15	25	13	24
119	20	20	16	24	**160**	18	24	12	25
120	16	28	22	20	**161**	20	24	13	27
121	14	26	20	20	**162**	16	31	22	24
122	13	25	18	20	**163**	14	29	20	24
123	14	23	17	21	**164**	13	28	17	24

Location	Inst 1	Inst 2	Inst 3	Inst 4	Location	Inst 1	Inst 2	Inst 3	Inst 4
165	14	27	15	24	206	17	31	18	28
166	16	26	13	25	207	17	30	17	28
167	18	25	11	26	208	18	29	15	29
168	20	25	13	27	209	20	28	15	29
169	16	31	22	25	210	21	28	15	30
170	14	30	20	25	211	19	34	23	29
171	14	28	17	25	212	18	33	21	29
172	14	27	15	25	213	18	32	19	29
173	16	26	13	26	214	18	31	17	29
174	18	26	12	26	215	19	30	16	29
175	20	25	13	28	216	20	29	15	30
176	16	32	22	26	217	22	29	16	31
177	15	30	20	25	218	20	35	23	30
178	14	29	18	25	219	19	33	21	29
179	15	28	15	26	220	18	32	19	29
180	16	27	13	26	221	19	31	18	29
181	18	26	12	27	222	19	30	16	30
182	20	26	13	28	223	20	30	16	30
183	17	32	22	26	224	22	29	16	31
184	16	31	20	26	225	20	35	23	30
185	15	29	18	26	226	19	34	21	30
186	15	28	16	26	227	19	33	20	30
187	17	27	14	27	228	19	32	18	30
188	18	27	13	28	229	20	31	17	30
189	20	26	14	29	230	21	30	16	31
190	17	33	22	27	231	22	30	17	32
191	16	31	20	27	232	21	36	24	31
192	16	30	18	27	233	20	34	22	31
193	16	29	16	27	234	20	33	20	31
194	17	28	14	27	235	20	32	19	31
195	19	27	13	28	236	20	31	18	31
196	21	27	14	29	237	21	31	17	32
197	18	33	22	28	238	23	30	17	32
198	17	32	20	27	239	21	36	24	32
199	16	30	18	27	240	21	35	22	31
200	17	29	16	27	241	20	34	20	31
201	18	29	15	28	242	20	33	19	31
202	19	28	14	29	243	21	32	18	32
203	21	28	15	30	244	22	31	18	32
204	18	34	22	28	245	23	31	18	33
205	17	32	20	28					

APPENDIX P – MATLAB SCRIPT FOR DISTANCES AND RESPONSE TIME

Matlab script for calculating distances and response time from the onshore base.

```matlab
clear all
close all

%% Calculate Distances---------------------------------------------
-----

BaseLocation = [70.39, 23.40];

% Installation Location Scenario 1
% Instlat= transpose([72.00 72.00 74.00 74.00]);
% Instlong = transpose([19.00 24.00 24.00 27.00]);

% Installation Location Scenario 2
Instlat= transpose([72.00 74.00 73.50 71.50]);
Instlong = transpose([26.00 16.00 27.50 18.00]);


InstLocation=[Instlat, Instlong];

% Number of installations
Ni = 4;

% Service speed for OR vessel, Sv [knot]
Sv=14;

% Release time for OR vessel, Fv [Hours]
Fv=10;

% Deployment time, Tv [Hours]
Tv= 1;

% Calculate the distance from Onshore Base to installation i, Dij
[nm]
Dij = zeros(Ni, 1);
for i=1:Ni;
    for j=1;
        Dij(i,j)                                              =
round(deg2nm(distance('gc',[InstLocation(i,1),InstLocation(i,2)],...
                [BaseLocation(j,1),BaseLocation(j,2)])));
    end
end

% Calculate response time from Onshore Base to installation i, Rij
[hours]
Rij = zeros(Ni,1);
for i=1:Ni;
    for j=1;
        Rij       (i,j)      =      Fv      +      Tv      +
round(deg2nm(distance('gc',[InstLocation(i,1),InstLocation(i,2)],...
                [BaseLocation(j,1),BaseLocation(j,2)]))/Sv);
    end
end
```

APPENDIX Q – DISTANCES AND RESPONSE TIME FROM ONSHORE BASE

Scenario 1

Installation	Distance [nm]	Response Time [Hours]
1	129	20
2	97	18
3	217	27
4	227	27

Scenario 2

Installation	Distance [nm]	Response Time [Hours]
1	109	19
2	255	29
3	202	25
4	125	20

APPENDIX Q – DISTANCES AND RESPONSE TIME FROM ONSHORE BASE