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Optimal Positioning of Emergency Preparedness Assets based on Dynamic Traffic Situation

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Marine Technology
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Master Thesis in Marine Systems
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Background
Vessel traffic along the Norwegian coastline poses a constant threat to the environment. At any given time, a vessel could lose maneuverability and start drifting towards the mainland, threatening to spill its tanks full of oil into the water, where it will be disastrous for wildlife and the cleanup costs will be huge. Because of this, the Norwegian government through the Ministry of Transport and Communications, task and fund the Norwegian Coastal Administration to efficiently control maritime traffic along the Norwegian coast. Reducing the risk of maritime accidents is one of their tasks. It is therefore interesting to see how the current emergency preparedness assets could be utilized to its potential.

Primary Objective
The objective of this thesis is to develop a model that can be used by operators at Vessel Traffic Service (VTS) centers to assess risk and allocate resources efficiently to meet the threats to the environment posed by the merchant traffic along the Norwegian coast.

Scope of work
The candidate should presumably cover the following main points:

1. A brief description capturing the relevant background
2. Provide an in-depth literature study related to optimization models covering emergency asset location and emergency preparedness
3. Create models that find the optimal position of emergency assets from a tactical point of view as well as from a strategic point of view based on vessel type, position, speed and bearing of vessels in the vicinity and for different planning horizons
4. Develop a measure for quantifying emergency preparedness
5. Develop a scenario to compare and analyze the model(s) with
6. Implement the models and record the solutions
7. Visualize the solutions and show the relative dangers in an a way that clearly shows the differences between areas
8. Analyze the solutions, compare the models and comment on the emergency preparedness measure

Modus operandi
Professor Stein Ove Erikstad will be the main supervisor and Professor Bjørn Egil Asbjørnslett will be the co supervisor from NTNU. The work shall follow the guidelines made by NTNU for thesis work. The workload shall correspond to 30 credits.

Stein Ove Erikstad
Professor/Main Supervisor

Preface

This master thesis was written during the spring of 2015 at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU).

The objective of this thesis is to create a method that uses mathematical models and tools to measure the threat posed to the environment by the merchant traffic along the Norwegian coast. This is done so that operators at Vessel Traffic Service(VTS) centers in Norway can assess dangers by using information from several sources and allocate resources to the correct areas so that the existing assets are utilized to their potential.

Working on the thesis has been very rewarding, although sometimes frustrating. I have enjoyed gaining insights in the topics of operations analysis and emergency preparedness.

I would like to thank my supervisors, Professor Stein Ove Erikstad and Professor Bjørn Egil Asbjørnslett for invaluable advice during the preparation.

Trondheim, June 10, 2015

Knut Skaseth Støwer

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Abstract

The objective of this thesis is to create a method that utilizes mathematical models and tools to measure the threat posed to the environment by the merchant traffic along the Norwegian coast. This is done so that operators at Vessel Traffic Service(VTS) centers in Norway can assess dangers and allocate emergency assets to the correct areas so that the existing assets are utilized to their potential. If the existing emergency assets are utilized fully, the risk of catastrophic accidents is minimized.

The thesis looks specifically at merchant vessel positions along the Norwegian coast at a given point in time. Using this information I calculate a criticality value for different areas so that they can be prioritized according to this value. The criticality takes into account the merchant vessels positions and other characteristics like its type and position relative to regional characteristics such as like currents or skerries. Merchant vessels are grouped together in zones so that the operators can see where they need to pay closer attention or allocate emergency assets to reduce the total risk of any incident leading to catastrophic accident.

An optimization model is then developed to find the optimal position of one or more emergency assets based on the criticality that gets used as a demand or a weight for each zone. Five potential sites for home port for the emergency assets were selected and the optimization model found the optimal location based on the calculated criticalities.

A second formulation was created to better support the location of several emergency assets, and this was used to find the optimal location for two emergency assets based on the distance to all the zones and the zones criticality.

The optimal solutions were analyzed using two methods for quantifying the preparedness. These methods takes into account the criticality of each zone and the location of an emergency asset as well as the speed of the emergency assets. This is used to find what zones are covered by the different assets and a comparison is done between the zones and between the methods on the solution found by the optimization model.

The analysis shows that the methods show good promise and the visualization is helpful in determining critical areas. However, there are many opportunities for improving on the methods which is discussed in the discussion and further work chapters.

Sammendrag

Formålet med denne oppgaven er å lage en metode som utnytter matematiske modeller og verktøy slik at man kan måle trusselen som kommersiell trafikk langs norskekysten stiller. Dette gjøres slik at operatører på norske sjøtrafikksentraler kan vurdere faremomenter og anvise beredskapsressurser til områder slik at risikoen totalt sett minimeres.

Denne oppgaven ser mer spesifikt på posisjonen til kommersielle fartøy langs norskekysten på gitte tidspunkt. Denne informasjonen brukes til å beregne kritikalitet for ulike områder slik at disse områdene kan prioriteres med tanke på denne kritikalitetsverdien. Kritikalitet beregnes med hensyn til fartøysposisjoner og andre karakteristikker som fartøystype og posisjon relativt til ulike faremomenter i området som sterk strøm og grunt vann. Kommersielle fartøy grupperes sammen i soner slik at operatøren på sjøtrafikksentralen kan se hvor de må rette oppmerksomheten eller anvise beredskapsressurser i et forsøk på å redusere den totale risikoen.

En optimeringsmodell blir så utviklet for å finne den optimale posisjonen for en eller flere beredskapsressurser basert på kritikalitetsverdien. Kritikaliteten brukes som en vekt eller en type etterspørsel for hver sone. Fem potensielle lokasjoner for hjemmehavn for beredskapsfartøy blir presentert og optimeringsmodellen velger den beste lokasjonen.

En annen matematisk modell blir utviklet for å gjøre det mulig å finne optimal posisjon for et ukjent antall beredskapsressurser. Modellen brukes til å finne optimal posisjon for to beredskapsfartøy basert på de tidligere beregnede kritikalitetsverdiene.

Den optimale løsningen blir analysert ved hjelp av to ulike formler som prøver å kvantifisere beredskapen. Metodene tar hensyn til beregnet kritikalitet i hver sone i tillegg til posisjonen til beredskapsressursene. Denne kvantifiseringsmetoden brukes for å identifisere hvilke soner som har god eller dårlig beredskap i et forsøk på å analysere godheten av løsningen til optimeringsmodellen.

Analysen viser at den overordnede metoden gir gode hjelpemidler for å visualisere kritiske områder. Det er derimot mange områder hvor metoden kan forbedres, som blir diskutert i diskusjonskapitlene.

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Equations and Formulae

Glossary

AHTS Anchor handling and tug supply vessels are built mainly to handle anchors, towing and supply duties. They differ from regular platform supply vessels in that they are fitted with winches for towing and anchor handling. 1

Automatic Identification System Is an automatic tracking system used on ships and by vessel traffic services. IX

Facility Location Problem Facility location problems a problem where the choise of a set of facilities are chosen to best support a setof customers. 13

FICO Xpress-IVE Optimization software that allows for solving large optimization problems. 19, 48

Matlab Developed by MathWorks, Matlab is a numerical computing environment that allows for easy calculations and plotting. 19, 48

NCA The Norwegian Coastal Administration is user and state financed. Tasks are assigned through the state budget and an annual allocation letter is received from the Norwegian Ministry of Transport and Communications. 1

TSS Is a traffic management system where vessels sail in indicated corridors or lanes with an indicated direction. Additionally, rules indicating how to cross these corridors are imposed. All this is done to reduce the risk of collisions. 7

VTS Vessel traffic services use radar, AIS and other systems to monitor vessel traffic in a specified area to provide navigational safety and allocate emergency response assets when it is required. 2, 9

Acronyms

AHTS Anchor Handling and Tug Supply. *Glossary:* AHTS, 1, 7, 8

AIS Automatic Identification System. *Glossary:* Automatic Identification System, IX, 8, 9, 10, 17, 18, 39, 41, 63

FLP Facility Location Problem. *Glossary:* Facility Location Problem, 13

NCA Norwegian Coastal Administration. *Glossary:* NCA, 1, 6, 7, 9, 39, 41, 63

TSS Traffic Separation Scheme. *Glossary:* TSS, 7, 58

VTS Vessel Traffic Service. *Glossary:* VTS, 2, 8, 9, 18, 42, 65

1 Introduction

Vessel traffic along the Norwegian coastline poses a constant threat to the environment. At any time, a vessel could lose manoueverability and start drifting towards the mainland, threatening to spill its tanks full of oil into the water where it will be disastrous for wildlife and the cleanup costs will be huge.

Because of this, the Norwegian government, through the Ministry of Transport and Communications, task and fund the Norwegian Coastal Administration (NCA) to efficiently control all maritime traffic. In that lies also the partial objective to reduce the risk of maritime accidents and more specifically, the risk of oil spills. (Det Kongelige Samferdselsdepartement, 2014) (Kystverket, 2014)

Det Kongelige Samferdselsdepartement (2014) states that the current situation with two emergency preparedness vessels for the northern areas should continue. These two vessels are the Anchor Handling and Tug Supply (AHTS) Beta and the AHTS NSO Crusader. Having a way of making sure these vessels reduce the risk as efficiently as possible on a day to day basis becomes important.

How can we do this? By using a system to categorize vessels sailing along the Norwegian coast according to some common criteria it is possible to find areas with higher probability of some unwanted incident happening. These areas need to be monitored closely and emergency preparedness vessels need to be positioned so that they can react when something does happen.

As of February 2015, the oil prices have decreased to a level where many offshore projects are put on hold until new technology lowers the investment costs. This means that the activity in these areas will stay low. However, if the oil price increases to earlier levels again, or new technology allows for new projects with the current prices, the activity could go up again.

Even if the traffic along the coast doesn't increase as it is expected to, utilizing the state chartered AHTS vessels optimally is of great interest as it could lower risk for oil spills damaging vulnerable areas along the coast or simply lower the cost of operating emergency response vessels.

In the event of a vessel losing engine power or propulsion for some reason, the wind and currents will determine its drift pattern. If the vessel grounds a shore there is a risk of damaging some of the tanks on board the vessel, potentially leaking oil into the water.

In the event of a grounding of a vessel with oil as cargo or as bunker, large quantities of oil and other types of cargo can spill out into the ocean. Depending on wind and currents in the area, the oil will move to shore. How much damage is done, and how much the cost of cleaning will be depends on the type of oil, temperature and the vulnerability of the area. (Eide, Endresen, Røang & Ervik, n.d.)

Operators at Vessel Traffic Service (VTS) have to consider the locations of hundreds of vessels and information about weather, currents and future events from many different sources. Even experienced operators can be overwhelmed by the amount of data available, and it might be impossible to consider all of it at once. Models that utilize this information and present it in a clear and concise way could be of great assistance as decision support tools. (Eide, Endresen, Brett, Ervik & Røang, 2007)

According to Kristiansen (2005), the general trend in accident rates is declining due to risk reduction measures. However, as the potential for further improvements becomes smaller the relative achievement by each measure becomes smaller.

This thesis attempts to look at a general situation with an unknown number of emergency assets. It assesses the traffic picture by using information from several sources. Further, it uses this information to find the optimal location for emergency assets. This is done by first attempting to quantify the criticality by dividing the region into a grid of zones. Each zones criticaility is then calculated by combining the risk contribution from each vessel and its position relative to known areas that have characteristics that could be problematic.

This thesis is structured as follows: Chapter 2 gives a brief introduction to the background information that is needed to understand the context of the thesis. An overview of relevant and state of the art research is given in chapter 3. Chapter 4 introduces and explains the solution methods. The test case where the methods are used is presented in chapter 5. The results are presented and discussed in chapter 6. The conclusion is presented in chapter 7, followed by further work in chapter 8.

2 Background

This chapter will introduce a few concepts such as emergency preparedness and risk, and the actors that work to keep the oceans safer, their tools and working conditions. It will also introduce some of the technology used and explain how to find hotspots for use in a model later.

The reason for researching this is to reduce the probability of incidents where the environment will suffer as a consequence. The scope is limited to looking at accidents that occur as vessels are drifting (i.e. vessel has lost control over manoeuvring and is drifting at the whims of wind and currents).

2.1 Emergency Preparedness

According to Standards Norway (2010), emergency preparedness is defined as "technical, operational and organisational measures, including necessary equipment that are planned to be used under the management of the emergency organisation in case hazardous or accidental situations occur, in order to protect human and environmental resources and assets".

Perhaps more colloquially, emergency preparedness can be described as the systems and equipment prepared before an unwanted event, to prevent or mitigate the unwanted consequences of that event. In any case, emergency preparedness is about preparing for the unwanted, as it is not possible to avoid it altogether.

Good preparedness could possibly be achieved by having the correct assets within adequate distance so that they can intervene when needed.

Kristiansen (2005) states that "emergency preparedness requires that one makes the necessary planning and training proactively, i.e. before something undesirable happens".

The lack of emergency preparedness was one of the reasons that the Exxon Valdez grounding ended up as one of the worst man-made environmental disasters in maritime history. (Kristiansen, 2005)

2.2 Risk

There are several definitions of risk, and they differ mostly between fields of study. Within project management, risk is defined as "an uncertain event that, if it occurs, has a positive or negative effect on a project's objective". (Project Management Institute, 2004)

Within economics the consequence could be a positive or negative event, for example the cost of some commodity going up or down. Within health and safety, it is often assumed that the consequences are negative.

According to Standards Norway (2010) the definition of risk is "a combination of the probability of occurrence of harm and the severity of that harm". Additionally, an accidental event is defined as "an event or chain of events that may cause loss of life or damage to health, assets or the environment".

Historically, there have been many catastrophic accidents at sea, leading to loss of life, and large scale pollution. One example is the Exxon Valdez that ran aground in Alaska, resulting in an oil spill of 10.8 million gallons of crude oil in 1989. (Alaska Oil Spill Commission, 1990)

However, large-scale accidents normally represent a small part of accident occurrences and therefore their contribution to the total risk picture may be relatively low. (Kristiansen, 2005)

Naturally, we want to avoid all types of accidents from happening, but that is not always possible. A simple way to avoid shipping accidents would be to stop sending vessels on the oceans. Obviously, that is not feasible nor is it wanted, but it shows that it is possible to influence the number of accidents that can occur.

Since we do not want to accept that all accidents are going to happen, we want to mitigate the risk by reducing either the likelihood or consequence. To do this, there are a number of possible actions to take. In the next few chapters I will go through some of the things that are done to reduce risks and increase the efficiency of ship traffic in Norwegian territorial waters.

2.3 Norwegian Coastal Administration

The NCA is an agency in the Norwegian Ministry of Transport and Communications, and is the executive body in matters pertaining to the administration of ports and seaways.

According to Kystverket (2014), one of the secondary objectives of the NCA is that no collisions or groundings is to take place as a result of failure in the NCAs sea safety services.

To reduce the risk of collisions along the Norwegian coast a Traffic Separation Scheme (TSS) was set up. This forces tankers and other vessels of 5000 gross tonnes or more further away from the Norwegian Coast. This reduces the immediate risk of pollution. Figure 1 shows where the TSS is imposed in the northern areas. (Forskrift om sjøtrafikk i bestemte farvann, 2009) The reason for using a TSS is to separate the traffic from each other by assigning fixed lanes for the northbound and southbound traffic so that they seldom, if ever, are at a collision course. This means that if they loose control over the vessel, they will have a lower probabilty of drifting into other vessels.

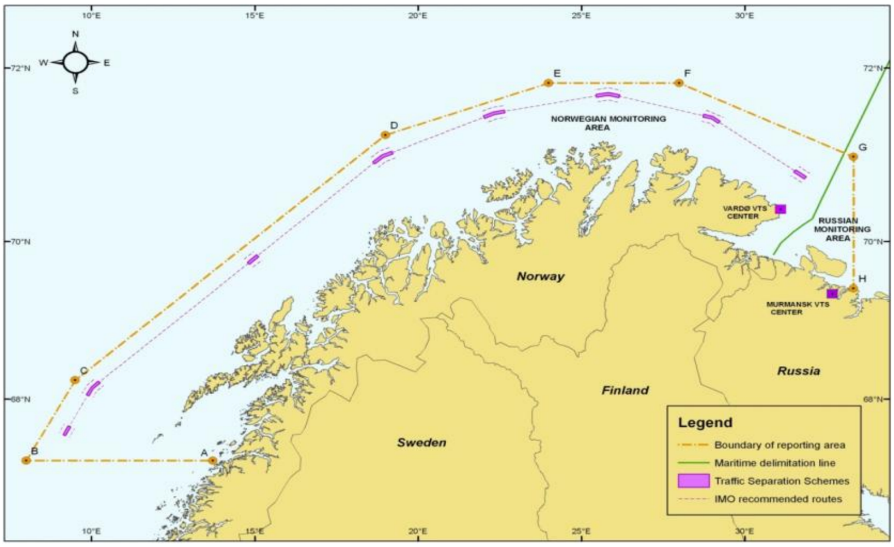

Figure 1: Map showing traffic separation scheme along the coast of northern parts of Norway and towards the Russian border. The purple line drawn shows the location of the corridors. (Forskrift om sjøtrafikk i bestemte farvann, 2009)

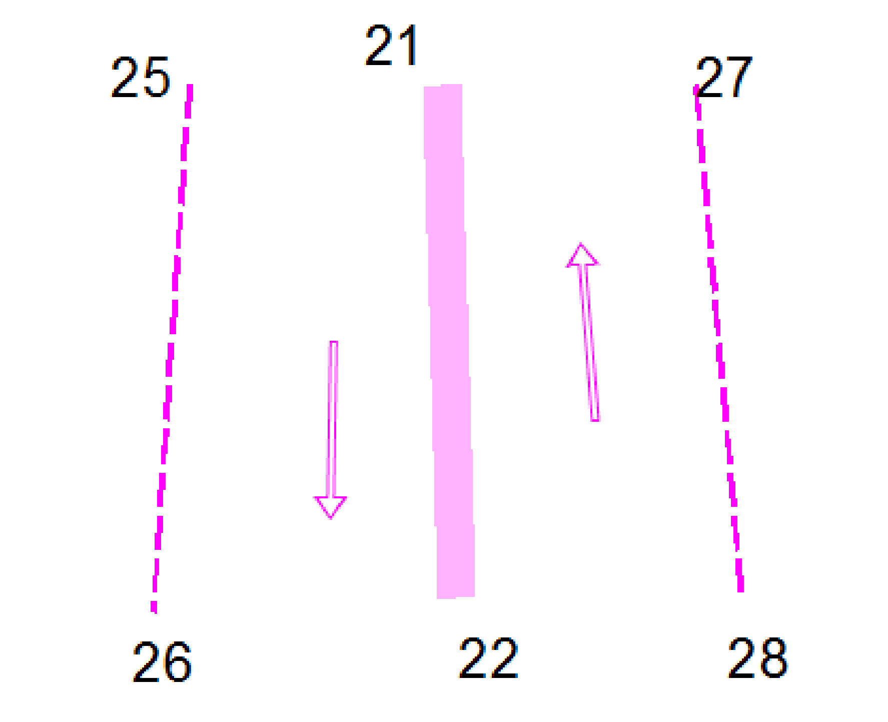

Figure 2: Figure showing the traffic separation scheme south in Karmsundet. The lanes are shown with the direction assigned by the arrow. The thick line in the middle is there to show where no vessel should sail. (Forskrift om sjøtrafikk i bestemte farvann, 2009)

In Norway, the NCA has been delegated the responsibility for the emergency tug readiness. According to Det Kongelige Samferdselsdepartement (2014) the NCA should charter 2 vessels for the northern areas, 1 for western Norway and 1 for southern Norway. That means that the NCA has to charter in these vessels and station them in areas with the highest environmental risks and where fewer commercial actors are present. The two vessels covering the northern areas are the AHTS Beta and the AHTS NSO Crusader.

The current vessels used for the northern areas are AHTS vessels that, in addition to tug capabilities, have extra equipment for oil spill recovery, assisting damaged vessels, a sick bay and ROV equipment. According to Kystverket (2012) it is important that the vessels used for emergency preparedness have extra capabilities, so that they can handle different incidents. This will in turn lead to a better utilization, instead of just waiting for one type of incident.

2.4 Vessel Traffic Services

VTS are similar to air traffic control for aircraft, in that they monitor the traffic at sea by use of radar, radio communications and other technologies such as AIS to keep track of where vessels inside the area they are monitoring are moving. This is done to provide safety in the region they monitor.

In Norway the mandate of the Vessel Traffic Services is given by the NCA. According to Forskrift om sjøtrafikk i bestemte farvann (2009) and Kystverket (2011) the VTS is tasked with working for reducing the risk of any vessel accidents and contribute to efficient traffic management.

The tasks of the VTS are divided into three parts.

- Information Services
- Navigational assistance services
- Traffic regulation

The VTS performs several tasks to assist and guide vessels. This lists mentions some of these.

- Provide vessels with information about weather conditions, relevant events or activity
- In areas where needed, they give permission for sailing in to a port
- In situations with regulatory misconduct they can intervene and instruct the parties
- When observing unexpected behaviour, such as a vessel suddenly drifting off course, they can set in motion actions that can prevent further unwanted consequences

2.5 AIS

AIS is a system developed and put in use to be able to provide information about vessels to other vessels and coastal authorities automatically. As of December

31st 2004, *all ships of 300 gross tonnage and upwards on international international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size* are required to fit AIS systems on board. (International Maritime Organization, n.d.)

- Identity (MMSI ID)
- Vessel type
- Coordinates
- Course over ground
- Speed over ground

There are many different types of messages that are sent out depending on where the vessel is and its status. (International Telecommunication Union, 2010, table 43) shows the different message types available with AIS. The list above gives an overview of what message type 1 and 5 contain. There are more message types than these two, but they are irrelevant for the purpose of this thesis. See International Telecommunication Union (2010) for detailed information.

Message type 1 is a "position report" and contains a scheduled position report. It is typically sent at a constant interval. Message type 5 contains some more information, it is names "static and voyage related data" and contains "scheduled static and voyage related vessel data report". With these two combined, the position of the vessel is given and the vessel type, size and general cargo information is found.

2.6 Hotspots

A hotspot is a point, intersection or area that has a higher density of some measurable quantity. In the literature it can be mentioned as hotspots or black spots, sites with promise or high risk locations. (Cheng & Washington, 2005) Hotspots are points or areas that have a higher density of some activity, risk or vessels. This leads to the need for a higher attention with regards to emergency preparedness. This need stems from the different contributions that will increase the risk in any given area. Things that one wants to avoid includes collisions, power grounding, grounding, drifting (which could lead to grounding) and loss of life.

The category of a hotspot is given by its criticality which will be calculated in chapter 4.2.

To find these hotspots I need to look at what factors influence this risk for unwanted incidents. There are several factors, where some are dynamic (i.e. they change over time) and some are more or less constant. As hotspots are a combination of both dynamic and constant factors, the hotspots themselves are dynamic. In other words they will have a different risk of unwanted incidents for different times of day, week or year.

By looking at density maps over an area, we can see that the traffic typically moves in a set pattern. This is in part due to established shipping routes and these areas will typically have many close encounters of vessels of many different types. An example of this is shown in figure 3.

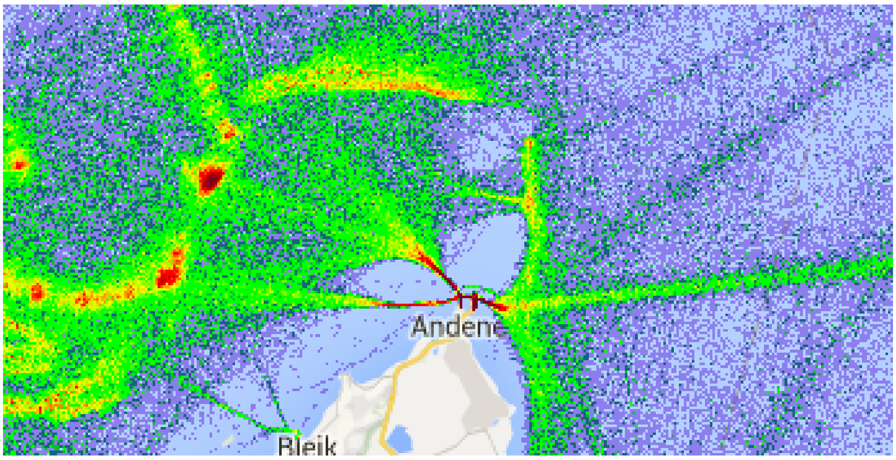

Figure 3: Map showing the area around Andøya with density maps. Coloured areas show statistical density map, where green is on the lower end of the scale and red is high density. Source: marinetraffic.com

As many vessels follow somewhat similar sailing routes, there are lanes and areas with a higher traffic density than others. These areas obviously have some increased risk of collision occurring. This is because when many vessels tries to access the same area, the density increases, and any loss of control will have a higher probability of colliding into something. These areas are often near ports, where vessels sail in and out through the same area, but then go in different directions, much like a traffic intersection.

Even though there are common sailing lanes or routes for traffic, these are based on a statistical view and the actual hour-by-hour outlook is much more dynamic. An example of this is Hurtigruta, which arrives and leaves daily. Due to its many passengers it is important that emergency response assets are positioned properly in case something happens, like it did in 2011 when a fire broke out on the vessel MS Nordlys. (Kvilesjø et al., 2011)

In the case of Hurtigruta, one might consider keeping tug vessels closer to this vessel when it is close to shore, due to the fact that it has many passengers, and any incident could quickly become dangerous.

Other traffic of both regular and irregular nature contribute to this dynamic picture and underlines the need for proper positioning of emergency response vessels.

In addition to these factors, the age, cargo, how often the vessel sails and length of sailing leg for the vessels sailing also influence the risk they pose.

The time it takes for a vessel in drift to ground ashore is affected by distance to shore, winds and currents. Obviously, under the same wind and current conditions, a vessel closer to shore will reach it earlier than a vessel further out. Consequently, the probability of an unwanted incident increases with decreasing distance to shore, due to the fact that the response time required decreases.

As was already mentioned, winds and currents vary along the coast, but simulation models used by Eide, Endresen, Brett et al. (2007) show that it is possible to predict where vessels in drift will end up. Combining these simulations with information about the vulnerability of certain coastal areas, we get a picture of what areas along the coast that are more crucial to patrol than others.

3 State of the art research

This chapter presents research within the field of operational analysis that is relevant for this thesis. The problem introduced in the background chapter is about location of emergency assets given a known demand. In relation to this problem, several topics are relevant for analysis. These will be presented in this chapter. This includes model building for optimal positioning of fire stations, emergency logistics including organisation of emergency assets (private and public) and hotspot identification.

There is a lot of research available on Facility Location Problem (FLP)s, which is not very surprising as it is one of the more profitable areas of applied operations research. (Krarup & Pruzan, 1983)

Başar, Çatay and Ünlüyurt (2012) review emergency service station location problems and conclude that "emergency medical stations and fire station location problems have been extensively studied whereas hospital and police station location problems have been rather neglected".

Lundgren, Rönnqvist and Värbrand (2010) define a facility location problem as "the problem of choosing a set of facilities (terminals, depots or distribution centre) and from these, support a set of customers".

With the set $\mathcal{M}$ of potential facilities and the set $\mathcal{N}$ customers, each facility i has a given capacity S_i and each customer j has a given demand D_j. The costs involved are, F_i for facility i and a unit cost C_{ij} for each unit transported between facility i and customer j.

Variable y_i and x_{ij} are defined as:

$$y_i = \begin{cases} 1, & \text{facility } i \text{ is used} \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ij} = \text{flow from facility } i \text{ to customer } j$$

Thus we get the following formulation for the objective function.

$$\min Z = \sum_{i \in \mathcal{M}} \sum_{j \in \mathcal{N}} C_{ij} x_{ij} + \sum_{i \in \mathcal{M}} F_i y_i \tag{3.1}$$

Subject to the constraints

$$\sum_{j \in \mathcal{N}} D_j x_{ij} \leq S_i y_i \qquad i \in \mathcal{M} \tag{3.2}$$

$$\sum_{i \in \mathcal{M}} x_{ij} = D_j \qquad j \in \mathcal{N} \tag{3.3}$$

$$x_{ij} \geq 0 \qquad i \in \mathcal{M}, j \in \mathcal{N} \tag{3.4}$$

$$y_i \in \{0, 1\} \qquad i \in \mathcal{M} \tag{3.5}$$

Equation (3.1) is the objective function that minimizes the cost of flow from facility to customer and the use of a facility. Equation (3.2) ensures that the flow from a facility does not exceed the supply and that the facility has to be in use. Equation (3.3) ensures that the customers demand is met and (3.4) and (3.5) ensure that the flow from facility to customer is non-negative and that a facility is either in use or not in use, respectively.

Cost of flow from facility to customer can be modelled to be different things. The cost of using a vehicle is an obvious way to model it and so is the distance, but it could also be time or some other measure. What the most useful unit depends on the application of the problem.

Similarly, the demand of a customer can be modelled to be different measurements. The obvious example will be to model the demand as an amount of some type of commodity, and the flow directly translates to the amount of that commodity is transported from the facility to the customer. Another way of modelling would be to model demand as amount of *expected* service calls to an emergency response centre. This way, the facility will be located closest to the customers that are expected to call emergency centres most often.

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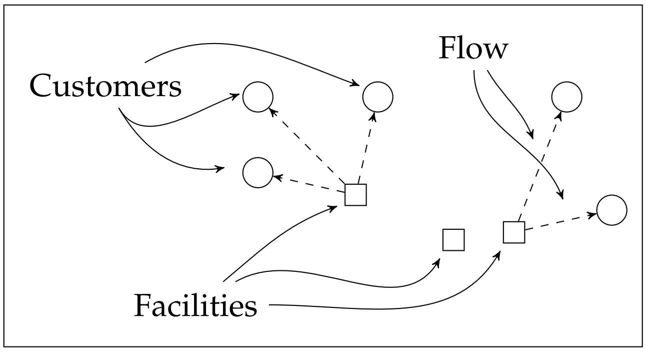


Figure 4: Example figure showing the principle in a facility location problem. Boxes represent facilities and circles represent customers. The lines show the link between the facility and the customer.

Pilemalm, Granberg, Stenberg and Axelsson (2012) investigates emergency preparedness in rural Sweden, where many of the emergency services found in larger cities does not exist. They highlight new ways of organizing local and public assets in a way to make the emergency response more effective.

Andersson and Värbrand (2005) talks about quantifying the preparedness for more efficient ambulance logistics. They do this by first defining three categories that emergency calls fall under and assigning priorities to these. They suggest a quantitative measure that can be used to calculate the preparedness in areas around Stockholm, Sweden. The objective is to use it as a decision support tool for discovering where the preparedness is lacking whenever an ambulance is sent to service a call or is moved to serve some other area. They also mention that the three following things can be used to assess the preparedness in a zone:

1. The number of ambulances that can reach the zone (within a certain time)

2. The time it takes for the ambulances to reach the zone (i.e. travel time)

3. The expected need for ambulances in the zone

Andersson and Värbrand (2007) further develops a decision support tool for dynamic ambulance relocation and automatic ambulance dispatching. Previously, qualitative measures have been used to assess preparedness, but two people do not necessarily agree on what is good or bad preparedness, based on their experience and personality. Therefore, Andersson and Värbrand (2007) introduce a quantifiable measure for preparedness. They do this by dividing the area, e.g. a county or city into zones. Each zone has an expected number of calls to emergency services. Additionally, each zone has a certain number of ambulances that contribute to the preparedness in each zone, and an expected travel time to the zone.

Similar to this is Gustafsson and Granberg (2012) which mention that since the need for assistance from fire-fighters varies throughout the day, the strategy of waiting at the station makes it unlikely that they are optimally located at all times. They also develop a quantitative measure for preparedness that could be used for decision support. They compute the preparedness in an area with equation (3.6).

$$P_{aj} = d_{aj} \frac{\sum_{i \in \mathcal{I}} r_{ij} t_{ij}}{\sum_{i \in \mathcal{I}} r_{ij}}, i \in \mathcal{I}, j \in \mathcal{J}, a \in \mathcal{A} \tag{3.6}$$

Here r_{ij} is the number of requested resources form zone i that contribute to the preparedness in zone j, t_{ij} is the response time from zone i to zone j, and d_{aj} is the expected number of accidents of type a in zone j. A lower value for P_{aj} mirrors improved preparedness. A value of zero, for example, would mean that d_{aj} is zero, meaning that the number of expected accidents of type a in zone j is zero.

Hogg (1968) writes about the optimum siting of r fire stations on n alternative sites with the objective to minimize the total loss from fire. Time spent by appliances journeying to fires is used as a measure of how good a solution is, as implementing an economic comparison wasn't possible in this case. The region that is analysed is divided into as many sub-areas as feasible, only dependent on there being enough historical fire data so that a distribution could be estimated. Topographical features such as canals and railway lines were added as barriers to movement, and as such good places to divide areas. Boundaries were also placed along lines of low fire incidence.

Marianov and ReVelle (1992) presents a model that sites fire stations and other fire fighting assets in such a way that the population or calls covered is maximised. Maximising $\sum_{i \in \mathcal{I}} a_i w_i$ will return the solution that maximizes the number of demand nodes that are covered to the required extent. Here $\mathcal{I}$ is the set of all demand nodes, a_i is the population or expected number of calls at node i and w_i is equal to 1 if i is covered by the required number of assets. Different decision variables can be used in the objective function to maximize different types of coverage.

Keskin, Li, Steil and Spiller (2012) attempts to create a model that determines optimal patrol routes for state troopers for covering highway spots with high crash frequencies (hotspots). As the use of visible law enforcement is believed to have a positive impact on reducing crash frequencies it is useful to maximize time spent in known hotspots. The model has similarities to the orienteering problem (OP) and selective travelling salesman problem (STSP), that tries to maximize profit while keeping travel cost below a pre set limit. Hotspots are assigned time windows that the patrols should maximize time spent in. Which makes the problem similar to the team orienteering problem with time windows (TOPTW).

By maximizing $\sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{K}} (f_{ik} - s_{ik})$, this is achieved. Here, the set of hotspots is $\mathcal{N}$ and $\mathcal{K}$ is the set of storm trooper cars and f_{ik} and s_{ik} are the times the state trooper car k leaves and arrives at hotspot n, respectively.

Espejo, Marín, Puerto and Rodríguez-Chía (2009) considers a facility location problem with an equity criterion. The model minimizes the total *envy* felt by the set of demand points. The problem consists of establishing a fixed number of p plants to M demand points based on the demand points preference orders on the site locations. The goal is to find the location of the facilities minimizing the total envy felt by the entire set of demand points. Each customer ranks the potential sites and the problem then uses this to find the solution with minimum envy.

Eide, Endresen, Brett et al. (2007) describes a model which estimates the risk levels individual ships pose, using AIS data. The goal is to more easily assess how likely a ship is to produce an oil spill and how much it is likely to spill in an attempt

Among other things, the model presented in the previous article mentioned is used in Eide et al. (n.d.) to model dynamic risk for use as a decision support tool for dynamic risk based positioning of tugs used at VTS centres. The model takes into account weather and currents, what tugs are available, the possibility of self repair, the vulnerability of the affected area, spill size and oil type. These parameters are fed into the model and the risk measure is prepared for use in decision support. Most of the data is received by using AIS data received from the vessels.

Kristiansen (2005) covers a broad set of maritime transportation risk topics such as basic introduction and definitions for risk and emergency preparedness. The book covers risk calculations by using statistical methods as well as traffic based methods. It continues with traffic-based models that cover grounding and stranding, loss of navigational control, collision and visibility. Methods for different types of fairways and traffic separation schemes are presented.

4 Methods and models

This section will introduce the methods and mathematical formulations that are needed to fulfill the objective of the thesis.

I will first go through the creation of two optimization models that can be used to find optimal locations for emergency assets. Then I will move on to what contributes to the risk each vessel exposes the environment to and use this to find spots and areas that need to be followed closely with regards to emergency preparedness.

Using these hotspot values I will use the first formulation to find the optimal position of the home port for the emergency assets. Then I will use the second formulation to find the optimal position of the emergency assets based on the same hotspot values.

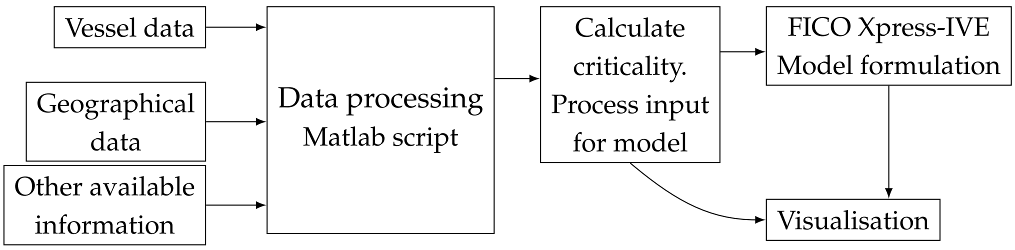


Figure 5: Figure shows the process of how different types of data are combined. From raw data to Matlab, FICO Xpress-IVE and visualisation.

Figure 5 shows the process of how the different types of data are combined and what tools are used and in what order they are used.

4.1 Creating a model to minimize distance to hotspots

With the objective set to minimize distance to hotspots with a set of limited emergency assets the assumptions and definitions need to create a model will be listed. The model should find the optimal position of a set of emergency assets. The goal is make a generic model that can fit any amount of emergency assets, and is easy to extend with new constraints when new needs appear. As the model is supposed to be generic, the term emergency asset is left undefined besides the obvious connotations.

- The risk in an area is lowered by moving emergency assets closer to the critical areas
- The criticality in all areas can be calculated

The first assumption then means that the model will try to minimize the total distance from assets to hotspots based on the hotspot criticality.

In chapter 4.2 I will explain how the region is divided into zones and how to calculate the criticality for all zones.

The first formulation

To model this I need to introduce some notation. Assume that $\mathcal{A}$ is the set of all emergency assets and $\mathcal{Z}$ is the set of all zones. Additionally, the emergency assets has a set of possible locations $\mathcal{L}$. The model will attempt to find the solutions with the emergency assets as close to these zones as possible.

Now I need a decision variable that can decide where emergency asset a is located. That is, in what location ,l, is emergency asset a to be located. This is to avoid confusion between the indices that both indicate a location. The decision variable then becomes x_{al}, which is a binary variable, so that the asset can either be at location l or not.

As we know that the objective should be to locate the assets close to the critical zones, we need a parameter that has the distance between all possible locations. D_{lz} contains the distance from location l to zone z.

In addition I need to know the criticality of each zone, so that the problem will choose the location closest to the most critical zones instead of any zone. C_z is then used to hold the criticality values for each zone.

To account for the distance from the position of the emergency asset to the zone and the zones criticality, both of these need to be in the objective function. The objective function is the product of the distance from location l to zone z and the criticality of zone z if emergency asset a is in location l. This way the distance to and criticality of the zone is accounted for. Since all distances from the asset location to the zones are included multiplied by the zones, this will ensure that the model chooses locations close to the zones with highest criticality.

$$\min z = \sum_{a \in \mathcal{A}} \sum_{l \in \mathcal{L}} \sum_{z \in \mathcal{Z}} D_{lz} C_z x_{al} \tag{4.1}$$

At this point the solution to this problem is that all decision variables are zero. There is nothing that forces the model to choose a location for the emergency assets.

$$\sum_{l \in \mathcal{L}} x_{al} = 1, a \in \mathcal{A} \tag{4.2}$$

Equation (4.2) makes sure that all assets have one, and only one location.

$$x_{al} \in 0, 1, a \in \mathcal{A}, l \in \mathcal{L} \tag{4.3}$$

A constraint ensuring that x_{al} is binary is given in by equation (4.3).

This model will then find the location l for asset a that is closest to the zones with the highest criticality. It does not have a cost for using the asset, and that can be included by introducing a few more aspects.

The cost of using asset a in location l has a fixed cost, F_{al}. We already have a decision variable that is equal to 1 if asset a is using location l, so we only need to add another part to the objective function to include the fixed cost.

$$\min z = \sum_{a \in \mathcal{A}} \sum_{l \in \mathcal{L}} \sum_{z \in \mathcal{Z}} D_{lz} C_z x_{al} + \sum_{a \in \mathcal{A}} \sum_{l \in \mathcal{L}} F_l x_{al} \tag{4.4}$$

The objective function in equation (4.4) includes the fixed cost of using an asset at a location.

This formulation does support numerous assets. However, if two assets were to be located by using this method, the model would put both of them in the same location. To ensure that the assets do not choose the same location, further notation is needed. The second formulation in chapter 4.1 ensures that the assets choose locations that will give better coverage.

The second formulation

Similar to the first formulation, this formulation tries to find locations from a set $\mathcal{L}$ for a set of assets, $\mathcal{A}$, and provide the availability of these assets to a set of zones $\mathcal{Z}$.

As the previous, the objective is to minimize the distance to these zones. However, this time each zone is covered by specific assets. This means that the model *assigns* assets to zones.

The needed parameters are F_{al} which is the cost for asset a to use location l, C_z which is the criticality in zone z, D_{lz} which is the distance from location l to zone z and S_a which is the number of zones asset a is able to cover. In figure 6, the problem notation is explained.

A decision variable to assign assets to locations is needed. This variable will also need to assign coverage from an asset to a zone. Additionally, one variable that keeps track of what location an asset is in is needed.

These are defines as:

$$x_{alz} = \begin{cases} 1, & \text{if asset } a \text{ uses location } l \text{ to cover zone } z \\ 0, & \text{otherwise} \end{cases}$$

$$y_{al} = \begin{cases} 1, & \text{if asset } a \text{ uses location } l \\ 0, & \text{otherwise} \end{cases}$$

We want to minimize the distance from the zones to the locations that assets are in. Thus, the objective function is defined as:

$$\min z = \sum_{a \in \mathcal{A}} \sum_{l \in \mathcal{L}} \sum_{z \in \mathcal{Z}} x_{alz} D_{lz} C_z + \sum_{a \in \mathcal{A}} \sum_{l \in \mathcal{L}} F_{al} y_{al} \tag{4.5}$$

To make sure that assets only use one location we need a constraint that makes sure that the sum of all locations used by any asset is equal to one.

$$\sum_{l \in \mathcal{L}} y_{al} = 1, a \in \mathcal{A} \tag{4.6}$$

To make sure that each zone is covered once, and only once, we need the a constraint that makes sure that for each zone, the sum of coverage from all assets in all locations is equal to one.

$$\sum_{a \in \mathcal{A}} \sum_{l \in \mathcal{L}} x_{alz} = 1, z \in \mathcal{Z} \tag{4.7}$$

The zone coverage capacity also has to be constrained, so that one asset cannot be set to cover more than it is allowed. The sum of all zones covered by all assets in all locations cannot exceed the capacity for asset a in location l.

$$\sum_{z \in \mathcal{Z}} x_{alz} \leq S_a y_{al}, a \in \mathcal{A}, l \in \mathcal{L} \tag{4.8}$$

In addition two binary restrictions for y_{al} and x_{alz} are needed. This is to avoid solutions where the asset is partially one place and partially another. The asset is either in a location, or it is not[1].

[1]There is no try

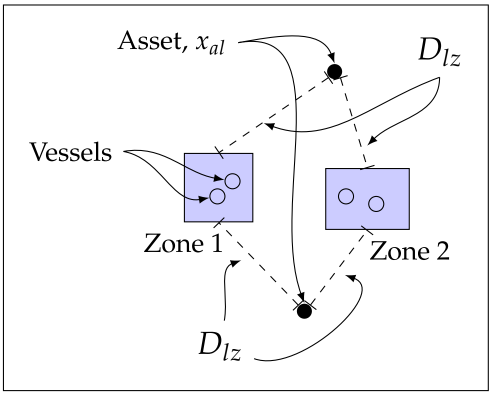


Figure 6: Figure shows the concept of zones with vessels and distance from asset location to zones. The black dots are potential locations for assets.

$$x_{alz} \in \{0,1\}, a \in \mathcal{A}, l \in \mathcal{L}, z \in \mathcal{Z} \tag{4.9}$$

$$y_{al} \in \{0,1\}, a \in \mathcal{A}, l \in \mathcal{L} \tag{4.10}$$

Looking at the formulation in this chapter, it can be seen that it is similar to that of a facility location problem. The facility location problem is introduced in chapter 3. If the parameters for distance and criticality are combined, the only thing separating them is the added index that allows for multiple assets.

4.2 Calculating criticality

Criticality is a number that is higher when there is a higher need for attention in an emergency preparedness context. The purpose of calculating criticality is to have a measure of how much attention is needed in each area of the region so that emergency assets can be allocated accordingly. The models formulated in chapter 4.1 and 4.1 will minimize the product of distance to a zone and the zones criticality value. Therefore, the way the criticality value is found be fundamental to producing a good result.

The calculation of criticality does not consider the current location of emergency assets. It only looks at what vessels are in each zone and what area characteristics they are close to.

Calculation of criticality is done in an attempt to mirror the inherent risk in an area. Formally, the method used does not measure risk in any formal way, but tries to use different sources of information to complete the picture and find areas that need to be prioritized.

In reality, it is impossible to use a minimum criticality measure, as it is not an absolute measure. It is comparable only between the zones in the region that are calculated at the same time.

Dividing the area into zones

To make it easier to find areas with high criticality in a meaningful and coherent way, without using cluster analysis, I divide the area into zones. Hogg (1968) states that as many zones as is feasible is better, but this is dependent on the available data. How many is feasible is limited by computing power and the need for accuracy. Additionally there are a few other concerns that will be discussed later, in chapter 6.

I will set each zone to be of fixed size, using degrees longitude and latitude. This means that the zones total area will have slightly different areas further north. This is because the distance between meridians is smaller further north. However, this makes scripting a lot easier, and the area of the zone doesn't influence the result in the current implementation.

The use of zones means that we reduce the number of points in the region by grouping merchant vessels together. Alternatively, all vessels could be a point in the model. However, this might lead to a model with many decision variables that is harder to solve, due to the added complexity. We use the zones to add together all the factors that contribute to the criticality of the zone.

Factors that contribute to the criticality of the zone are listed below.

- Vessels of all types are weighted according to their size and cargo
- Specific factors in certain areas

- Skerries or shallow areas
- Known currents that will increase the probability of leading a drifting vessel to vulnerable areas, such as Moskstraumen (Kartverket, 2015, p. 234)
- Biologically vulnerable areas
- Other special factors that are known to cause problems in certain areas

Additionally, there are other factors that can be considered. The only real limit is by what information is available. Presenting more information to the operator means that the operator is, in theory at least, able to make better decisions, as it is easy to be overwhelmed with the amount of data available.

An alternative to dividing the region into zones like this is to use cluster analysis. However, using cluster analysis raises the need for different sorting criteria and does not necessarily mean that the information is represented more accurately in any way. Additionally, by using cluster analysis we will always find some clusters, even if they in reality could be a poor representation of the available information. The distance between centroids could also become quite large, which could remove good solutions from the solution space as the emergency assets might be unable to move between two clusters within the planning horizon. Had there been some location in between the two clusters, it might have provided a better location for the asset. (Hair, Black, Babin & Anderson, 2010)

The size of the zones will also affect how easy it is to spot zones with low preparedness. If the size is very small, many zones will be equally covered, and larger sizes will include several ships in the same zone which will increase the risk. On the other hand, if one large zone is divided into 4 smaller, the risk stays the same, but the way it is identified in the visualisation will differ slightly and the optimization model will stay close or far away from this area either way.

Inside each zone, each vessel is weighted by their risk contribution and the centre of gravity inside the zone is found. This location is used as the centroid for the zone. This is similar to how Hogg (1968) divided the county into sub-areas,

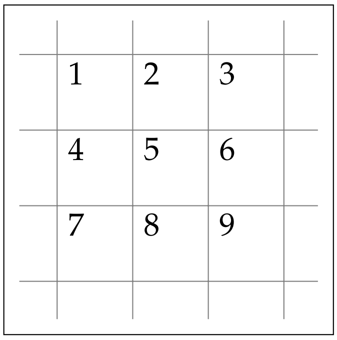


Figure 7: The figure shows a grid that is used as an overlay over a map with the numbering. The index used to number the zones, is, as can be seen in the figure, spanning over all the rows.

but on the ocean I don't need to divide them because of rivers or roads.

Figure 8 shows the position of three vessels that pose different risk and how the centre of gravity is found. For smaller zone sizes, this distinction becomes less important as the distance between each zone is relatively small. Additionally, when zone sizes are small, the distance between the vessels is also relatively small. The direction of travel is not taken into consideration. Each risk picture is taken at one given moment in time. So for the next time period, their new position is estimated and their heading and speed is used only for estimating their new position.

Estimating vessel positions

Sources that provide live data or historic snapshots of vessel information can be used to calculate the current risk picture. However, if one is to make an attempt to assess future risk pictures, some method for estimating vessel positions is needed.

Assuming live data on vessel locations, bearing and speed to be available, their position in some amount of time can be calculated if it is assumed that they will keep the speed and course for the time period.

This is obviously not true for longer periods of time, but could for a span of a

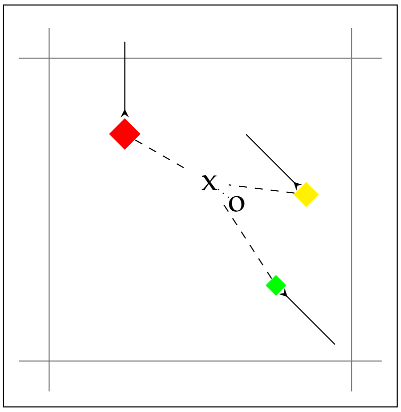


Figure 8: The figure shows how the centre of gravity for each zone is calculated. Each vessel poses a different risk. The red, yellow and green vessels are weighted 2.5, 1.5 *and* 1.0 *respectively. Their heading is drawn, but is not used in the weighting. The x marks the centre of gravity. The circle(o) marks the centre of gravity if all the vessels posed equal risk.*

few hours predict the dynamics of the criticality, even if this means that some vessels will be estimated to be on shore. If live data is available, new predictions can be made whenever an update arrives so that the accuracy increases, but estimates a set hours ahead of time will always have this uncertainty.

Figure 9 shows an example from *MarineTraffic* (2015) where the vessels position is predicted by drawing a line that follows the heading the ship has reported.

Using equation (4.12) and (4.13) found on Veness (2015), it is possible to find the new position with fair accuracy. According to Veness (2015), using a earth radius of $6,371km$, assuming spherical geometry, the error in using this method is never above 0.55%(i.e. $5.5m$ on $1km$), which for this purpose is more than adequate.

Calculating the distance travelled along a great circle in the time span considered is shown in equation (4.12) and (4.13).

$$\text{Distance} = \text{speed} \times \text{sailing time} \tag{4.11}$$

Veness (2015) provides the following formulae for new coordinates.

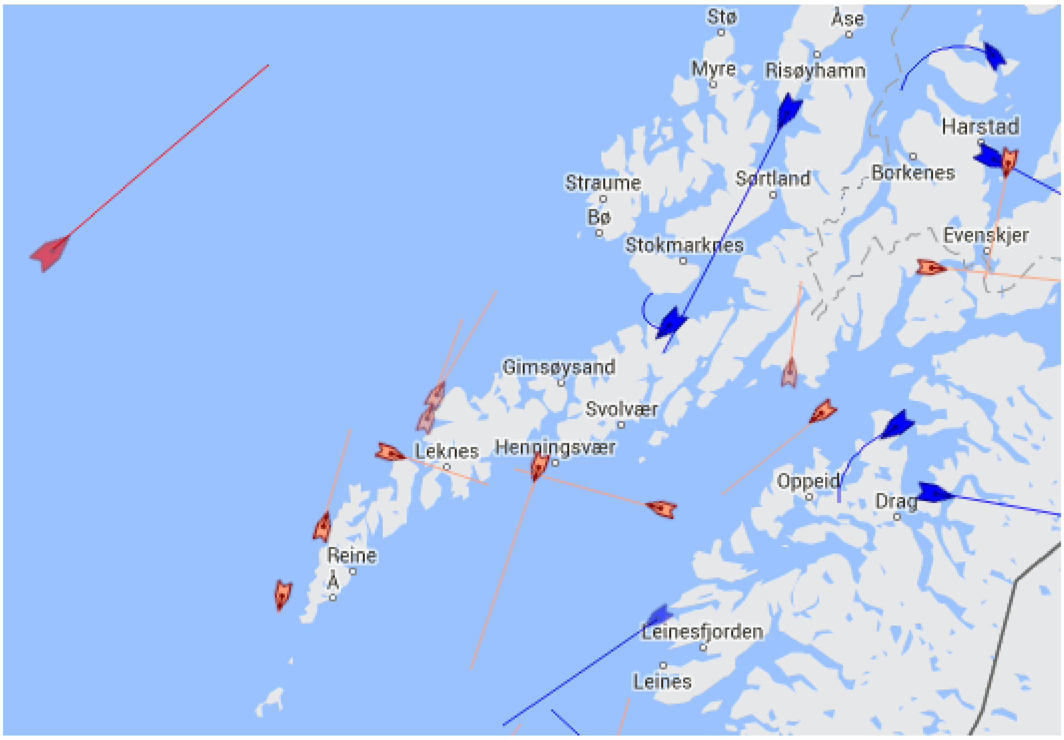


Figure 9: Map showing vessel position, heading and 120 minute projection. Note that some of the vessels are projected to be quite a way inshore. Source: marinetraffic.com

$$\phi_2 = asin(\sin(\phi_1) \cdot \cos(\delta) + \cos(\phi_1) \cdot \sin(\delta) \cdot \cos(\theta) \tag{4.12}$$

$$\lambda_2 = \lambda_1 + atan2(\sin(\theta) \cdot \sin(\delta) \cdot \cos(\phi_1), \cos(\delta) - sin(\phi_1) \cdot \sin(\phi_2) \tag{4.13}$$

Here ϕ_1 is the starting latitude, λ_1 is the starting longitude and δ is the angular distance equal to $\frac{\text{Distance}}{R}$.

Distance is the distance that the vessel sailed in the time span estimated, and R is the radius of the earth. θ is the heading of the vessel, where $0°$ is true north, and $90°$ is east.

Individual vessels contribution to criticality

When calculating the criticality of each zone, a system for categorizing individual vessels needs to be defined.

Instead of analysing the statistical probability of each vessel losing manoeuvrability individually, I am assuming that all vessels have an equal probability of losing manoeuvrability.

Then the categorization can be done according to each vessels cargo type. This information is assumed to be readily available.

By assuming equal probability for loss of manoeuvrability, it is easier to rank different types of vessels so that data mining becomes easier and categorization is possible.

If the vessel is close to an area or point that is defined as a critical factor, the criticality contribution from that vessel will be multiplied by the factor before being added to the zones accumulated criticality. This will be introduced in detail in the next chapter.

Eide, Endresen, Breivik et al. (2007) used simulations to find drift patterns which can be used to find locations that will have a higher probability of leading to vulnerable areas. These locations can be added to a list that increases the criticality of the vessels nearby.

As the main goal of this thesis is to reduce the risk of oil spills into the environment, it becomes clear that any oil tanker must belong to a category of high risk and other vessels, carrying less oil to potentially be spilled, must belong to lower risk categories.

Passenger vessels carry a very valuable cargo, namely passengers. However, in an attempt to reduce oil spills, passenger vessels do not carry enough oil to belong to the high risk category. Also, passenger vessels will be prioritized by many other assets (e.g. nearby vessels and helicopters helicopters), and in this context medium risk seems adequate.

Fishing vessels is the last vessel included in the scenario, are considered low risk category. This is because they carry less oil than an oil tanker, and the personell on board is usually skilled seamen.

Other vessels, such as vessels carrying "general cargo" where excluded from the data mining, simply because they were difficult to categorize without further

Table 1: Table showing different risk weights for different vessels. To simplify data collection for scenario analysis, only three categories are included.

Category	Vessels
High	Oil tankers
Medium	Passenger vessels
Low	Fishing vessels

analysis. This means that many vessels were excluded, and the number of vessels used in the case in chapter 5 is lower than the actual number of vessels along the coast.

Criticality contributions from area characteristics

The location of a vessel when it loses manoeuvrability has an impact on the consequence if one is unable to regain manoeuvrability. Certain locations have elements that increase the probability of certain accidents, such as coastal waters. Distance to shore, skerries or shallow water are only some of the reasons why a vessels criticality should be increased.

Ship transportation risk can be modelled and estimated for a specific seaway. Table 6.1 in Kristiansen (2005) lists the following potential accident situations.

1. Collision with ships on the same course
2. Head-on collision
3. Stranding
4. Collision with crossing traffic
5. Stranding
6. Grounding on shoal in fairway

In this thesis, no formal risk assessment is done to find the contributions from these potential accidents. Instead they are roughly estimated for a few locations along the coast to show how they can contribute to changing the risk picture for some areas with the same traffic density as others if there are special conditions met.

Different areas along the coast are more vulnerable than others or possess some characteristics which increase the probability of collision or simply increase the cost of clean-up if something should happen. The cost could increase in some areas because it is much more difficult to clean-up all the oil.

There is a big difference in the type of accident that occurs for smaller vessels, operating in coastal waters and larger vessels operating mainly in open water. (Kristiansen, 2005)

Some of the different characteristics that will influence the characteristics of an area, and ultimately the criticality of each vessel within range of these follows.

- Areas where the shoreline is of a type that makes it more time and resource consuming to clean up
- Areas where the biodiversity is especially vulnerable to oil spills
- Areas with strong currents leading a drifting vessel towards shore
- Strong winds
- Areas with an abundance of skerries
- Areas with shallow waters
- Other characteristics that are generally deemed as threatening to vessel traffic
- Special wind phenomena

Ideally, all of these will be known, and some factor and range will be set. As a base value, each vessel will have a multiplier of 1, however, each area will have a factor that is added to this base value that is larger than zero. That means if a vessel is within the range of some spot that has a factor of 0.2, the multiplying criticality factor for that asset is 1.2. This product of vessel criticality and area characteristics is the contribution to the zones criticality.

These areas will have some factor attached to them that will be multiplied by the individual vessels criticality when they are inside the area in question so that the criticality value for each vessel reflects the criticality based on the vessel characteristics and the characteristics of the area it is located.

4.3 Identifying hotspots

Identifying hotspots is important as it lies the foundation for any decision made for asset location or movement. Both of the model formulations will use the same hotspot values as input data.

By hotspots, it is meant areas that have a higher than zero criticality value. Hotspots have previously been used to indicate intersections that have a high probability of traffic accidents and use that information to place visible, and thus deterring, police patrols near these locations to reduce the accident prevalence. (Keskin et al., 2012)

Hotspots are identified by combining different types of information in such a way that they represent an area that is posing a threat to the environment and that by positioning emergency assets close to these areas, we are reducing this risk as much as possible.

For simply accumulating the different vessel criticality value it would be sufficient to loop over all zones and check what vessels are in the given zone and record the values. However, since it is needed to also check if the vessels are near other objects or areas that increase their criticality, a slightly more sophisticated approach is explained in the following paragraph.

For each zone the different critical elements are accumulated and form the criticality score. This includes all the vessels in the zone, with the vessels criticality given by what type of vessel it is and where it is located in relation to the different area characteristics are estimated to increase the criticality.

This results in a matrix of values, one value for each zone.

In algorithm 1 I show the outline of how the criticality for each zone is calculated.

Using the criticality values, they are divided into three equal sized bins (like in a histogram), representing their respective criticality category. The categories are high, medium and low. Their criticality values are kept and used in the models, but it could be useful to see how they are graded next to each other. This is to give the decision maker more information about what the current situation looks like with regards to criticality.

In algorithm 1 I don't take into account the estimated locations of merchant vessels. This was due to time constraints, as I was not able to get the implementation to work properly. The idea was to do this in two different ways.

The first method was to simply calculate criticality values for the current time, and then a new set of criticality values for all the zones in the future, with the estimated merchant vessel positions. This would give a dynamic view of the situation. Estimating the vessel positions cannot be done too far into the future, as the positions would be very unrealistic, but as there are many vessels, the criticality values could change a lot, which would give valuable information to an optimization model that is able to handle multiple time steps.

The second method to handle the time dimension, would be to use the estimated vessel positions and use them in the calculation of the current criticality values. That would mean that the estimated position would contribute to the current criticality. An example of this is if a vessel is sailing towards some skerries, but at T_0 is not close enough, but at $T_{5minutes}$ is, the model would include this in the current criticality value. This would then give a sligthly more nuanced criticality picture than just looking at the current picture.

After calculating the criticality values for all zones, what we end up with is a map of varying hotspots index values, where the peaks are the hotspots that will be used for positioning of emergency assets. Andersson and Värbrand (2005) used three categories to prioritize calls made to the emergency call centres based on the severity of the situation. Even though it in that case was used to allocate ambulance resources to critically ill patients first a similar approach can be used here. Three categories will be used according to the consequence, high, medium and low.

```
Data: Vessel coordinates, speed, course and type and criticality contribution
      for each
Data: Area characteristics
Data: Zone coordinates
Result: Calculated criticality for all zones
initialization;
for all zones do
    for all vessels do
        if vessel is in zone z then
            for all known area characteristics do
                if vessel is in range of area risks then
                    Vessel Criticality Factor += area risk factor;
                end
            end
        end
        Zone Criticality += Vessel Criticality * Vessel Criticality Factor;
    end
end
```

Algorithm 1: Pseudo code explaining how the criticality is calculated for each zone

Vessels carrying different types of cargo and amount of cargo will pose a different threat to the environment. Some vessels will therefore, just by their cargo, be labelled high risk, where others might be medium or low risk. An example could be a large oil tanker and a small fishing vessel. The oil tanker is high risk and the fishing vessel is low risk as summarized in table 1.

The specific weights attributed to each vessel type is not set in stone, and can be subject to need some adjusting. As mentioned by Andersson and Värbrand (2005), different operators will categorize the same situation in different ways. By proposing scenarios to experienced operators it is possible to adapt the values of these weights so that the algorithm will more accurately locate the actual threats.

Hotspots can be found dynamically and statistically. Dynamic hotspots are useful for finding the optimal location of emergency vessels or patrol routes for the emergency vessels to sail. Statistical hotspots are useful for finding the optimal location for a home base, but the same method can be used for both.

The dynamic model will use some type of live data, while the statistical model will need to use historical data. This can come from the same source as the live data.

4.4 Quantifying preparedness

In chapter 3 I list the factors that that can be used to assess emergency preparedness in a zone. In the case of Andersson and Värbrand (2005), the preparedness regarding ambulance service in the Stockholm area is considered. In this case I am looking at preparedness along the coast. Using their list as inspiration, I can say that the following factors are important when assessing preparedness.

1. The number of assets that can reach the zone within a certain time
2. How long it takes for the asset to reach the zone
3. The criticality of the zone

Criticality then becomes a sort of analogue to ambulance need, e.g. the expected rate of illness or traffic accidents. In other words a mirror or emergency asset need.

Finding hotspots means that we can find the relative criticality in each zone and compare it to other zones and use that to allocate assets in a meaningful way. However, when using an optimization model, it will give us the location that is best according to the objective function that is used. It does not give us any meaningful information about how well prepared each zone is. This will also rely on information of where the emergency assets are located.

Apart from this, a model for quantifying preparedness can be used without using any criticality measures or optimization models. It also gives a way to objectively compare different scenarios without subjective bias. Of course, there might be some bias in the model, but all scenarios should be possible to compare on an even basis with such a model.

According to Andersson and Värbrand (2005), a qualitative measure of preparedness can be assessed very differently, even by experienced operators at emergency centres.

As shown in chapter 3, Gustafsson and Granberg (2012) develop a quantitative measure for preparedness that can show, objectively, how well the preparedness in a given situation is.

It is interesting then, to see how well each zone is prepared for any given accident and by using this measure it is easy to compare different solutions given by different methods.

Using equation (3.6), but modifying it for only one type of accident type, we get the following formulae:

$$P_j = d_j \frac{\sum_{i \in \mathcal{Z}} r_{ij} t_{ij}}{\sum_{i \in \mathcal{Z}} r_{ij}}, \forall j \in \mathcal{Z} \tag{4.14}$$

Where P_j is the preparedness in zone j, d_j is the accumulated criticality in zone j, r_{ij} is the number of emergency assets in zone i that contribute to the preparedness in zone j, t_{ij} is the response time from zone i to zone j.

Essentially, this formulae takes the criticality value, which is a measure of the priority when compared to other zones and multiplies it by the ratio of the product of the number assets and their response time by the number of assets. The parameters in equation (4.14) and (4.15) are weights and do not have any specific unit. Therefore the values obtained do not tell us anything in themselves. (Andersson & Värbrand, 2005)

A lower value for preparedness means that the preparedness in the zone is better. Obviously, if there are no ships in the zone, the value is zero. If no emergency assets are available, it also drops to zero, but in this case, it is obvious that the preparedness is not necessarily adequate, so a special case has to be made for the case where $d_j > 0$ and $r_{ij} = 0$. In the implementation in this thesis, I have decided to set the emergency preparedness value for the zones that have a criticality larger than zero and no assets close enough, equal to the maximum value set in any zone.

If the emergency asset is in an active operation, i.e. not contributing to the preparedness in any other zones, the preparedness value will also increase rapidly when this point where the asset is busy occurs.

The response times are very different from ambulance logistics. According to Andersson and Värbrand (2005) the goal in Stockholm is to answer 75% of priority 1 calls within 10 minutes. The national standby readiness is two emergency response vessels for the northern region. It is obvious that the response time will be different from the situation in Stockholm as reported in Andersson and Värbrand (2005).

Another way of quantifying this is by using the method introduced by Andersson and Värbrand (2007) which is similar to equation (4.14). The main difference is that it also takes into consideration the contribution factor an asset has on a given accident. One vessel of the same size and many similar capabilities, may have a different ability to assist in certain scenarios. This could be related to equipment on board, fire fighting equipment, bollard pull or helicopter carrying capacity.

$$B_j = \frac{1}{c_j} \sum_{a \in \mathcal{A}} \frac{\gamma_a}{t_{aj}} \tag{4.15}$$

Here p_j is the preparedness of zone j, c_j is the criticality in zone j, γ_a is the contribution from asset a and t_{aj} is the time asset a needs to move to zone j. $\mathcal{A}$ is the set of assets that are considered.

We see that the assets contribution will decrease as the distance to the zone increases. An asset that has the best equipment available on the other side of the earth, will contribute very little to the emergency preparedness.

To compare the different quantification methods, a way of subjectively assessing the emergency preparedness is set up.

Table 2: Subjective evaluation of the emergency preparedness in all zones

Category	Value(Lower is better)
OK	0.1
OK -	0.3
Low	0.5
Low -	0.8

By using the same criteria as in the other models, namely criticality value in the zone and distance to the closest emergency assets, the emergency preparedness can be assessed. Table 2 shows the rating and the corresponding values.

4.5 Data availability

AIS is gathered directly from ships using a radio receiver and a decoder that can translate the coded message into useful information. There are many free software alternatives available that can be used for this purpose. This does however require a receiver somewhere along the coast, or preferably several places, to gather data directly from vessels. It is possible to contact the NCA for access to historical AIS data, which could be useful in the situation for this thesis.

On the internet, there are several sites offering services with AIS data for large areas, combining terrestrial and satellite coverage, both live and historical. (*MarineTraffic*, 2015) offers a map view with current positions for vessels, but no way to extract data without paying for it.

5 Test case

This chapter uses the methods introduced in chapter 4 on the data that is gather from different sources. First, the scenario is developed, explaining where the data is collected. Then the methods from chapter 4 are used on the data and results are presented.

5.1 Scenario development

As I wanted to avoid using large amounts of money gathering data on vessel locations and I did not get access to the AIS data provided by the NCA until June 8th, which for my use was too late.

Because of this I went to (*MarineTraffic*, 2015) and filtered away vessel types that I had previously decided to be outside the scope. Additionally, it could be argued that the need for live data is not needed. Any snapshot from any point in time could be used to test models.

The filter applied only showed vessels of type passenger vessels, tankers and fishing vessels. I then manually noted the location, bearing, speed and type of the vessel. The vessels can be seen plotted as red dots on a map in figure 11.

Vessels that were recorded were inside the area defined by being between 60°–72° North and 5°–31° East. The list of vessels can be found in appendix E.

In addition to vessel data I need to add information of vulnerable areas or areas that have known elements that can be a problem. This is done sporadically and not in any way thoroughly. As I don't have any data available on all areas that are known to have these problems, I added some covering Lofoten and other areas that seemed to be either "sticking out" or very narrow. And I purposely left some of them out. The severity, or contribution from each place was also set to be around 0.1 – 0.2 and are added to a multiplying factor to each vessel within the range of each spot. A spot has a coordinate and a range, so if a vessel is within this range, its criticality is multiplied by this factor.

Setting these spot values to the correct value and range isn't prioritized in this thesis. As the contribution from these spots could be very large, it is important not to set them too high to begin with. Further analysis is needed to adjust these values.

Eide, Endresen, Breivik et al. (2007) show results from simulations and figure 7 in that paper shows the *Time to Shore* distribution. It shows that from 7 hours, vessels in simulated drift have started arriving to shore. Because of this, I am setting 7 hours to be the maximum allowed time to the zone for the asset to be accounted for in the emergency preparedness model. So any asset that is so far away that it cannot reach the zone within 7 hours, does not provide any coverage for that zone. This means that there are some zones that are left uncovered, regardless of position.

5.2 Calculate criticality in zones based on live data

Dividing this region into zones I chose the size to be 2° latitude and 2° longitude. This does not make the zones quadratic, nor does it make them equal size. The distance between the coordinates 72° North 8° East and 72° North 10° East is 37 nautical miles, but between 65° North 8° East and 65° North 10° East the distance is 51 nautical miles, a difference of 14 nautical miles. The result of this zone partitioning can be seen in figure 10.

All latitude lines are parallel to the equator and each other, where longitude lines are perpendicular to the equator and end up in the same point on the geographic north and south pole. That is, following the longitude lines, the distance to the next longitude line becomes shorter as you go north or south of the equator.

In figure 11 I have plotted all the vessels in the data set as red dots on a map of the Norwegian coast. I didn't record any vessels south of approximately 65° North as I was only concerned with the region covered by the VTS in Vardø.

Table 3 shows the distribution of vessels of each vessel type.

Combining the data shown in figure 11 and 12 and utilizing the partition shown

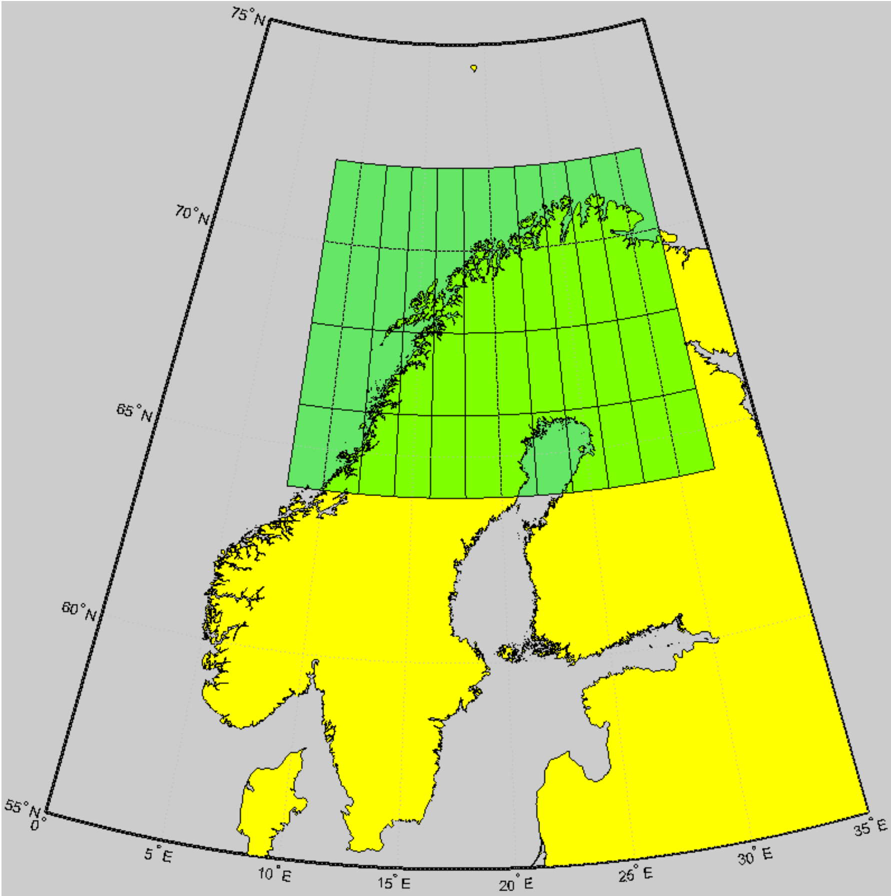


Figure 10: Map showing the zones and their coverage

in figure 10 I can calculate the combined criticality for all the zones by using the method shown in chapter 4.3.

Now that the criticality in each zone is calculated, I can divide the zones into three categories based on the values. Table 5 shows the distribution of zones in each category high, medium and low criticality. There are many zones that are in the low criticality category. This does not mean that the value is zero, just that it is in the third lowest bracket. The values for all zones will be used as data for any models using this calculation later. This is done to categorize them and more easily visualize the zones with higher criticality.

Now that the criticality category for each zone has been found, it can be visualized on a map together with vessel locations, zone grid and area risks. This is done

Table 3: Table with vessel data set statistics

Vessel type	Number of
Tanker	4
Passenger	33
Fishing	86

Table 4: Zone criticality, or hotspot values. Position in table corresponds to the zone in figure 13. Longitude is given in degrees east and latitude in degrees north.

		Longitude°E											
		8–10	10–12	12–14	14–16	16–18	18–20	20–22	22–24	24–26	26–28	28–30	30–32
Latitude°N	70–72	0	0	0	0	0	0	12	15	13	13	21	1
	68–70	0	0	2	9	13	12	7	0	0	0	0	0
	66–68	0	5	22	2	0	0	0	0	0	0	0	0
	64–66	0	13	8	0	0	0	0	0	0	0	0	0

Table 5: Table showing distribution of the number of zones in each criticality category

Category	Number of zones
High	3
Medium	8
Low	37

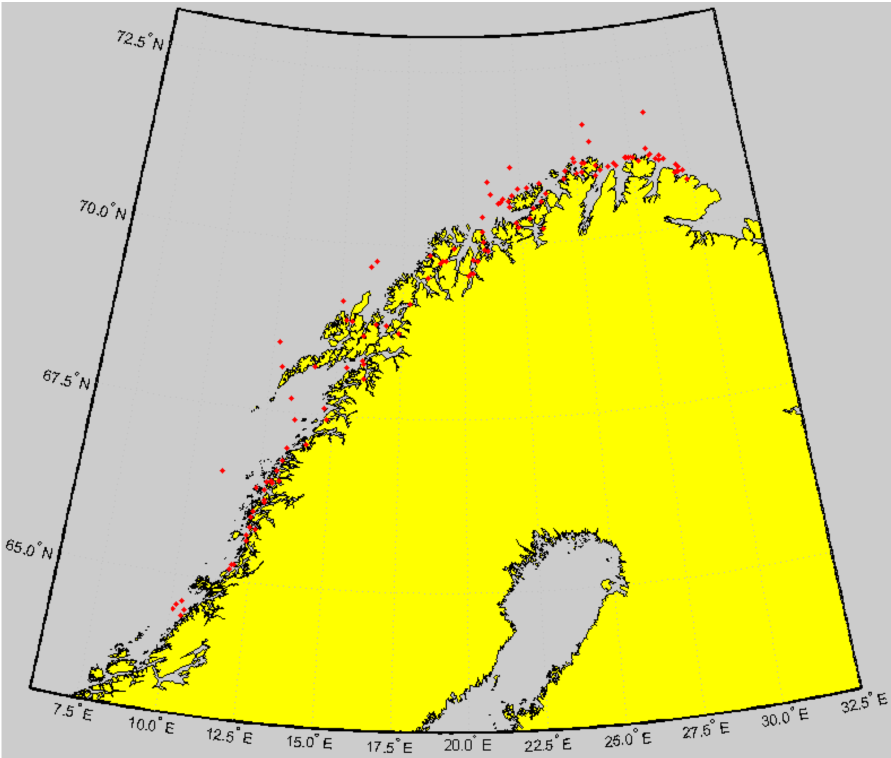


Figure 11: Map showing the Norwegian coast with all the vessels in the data set marked with their position in red.

in figure 13.

Figure 13 shows the region with zones clearly marked and the zone colour corresponds to the calculated risk. Red, yellow and green correspond to high, medium and low, respectively.

Now that the criticality values are found for each zone, I can move on to the next step.

5.3 Finding the best location for a home base

The vessels used for emergency response are usually chartered on year-long contracts. Even if it were to stay on shorter contracts, finding a base location that would minimize travel to and from patrol would both reduce operational

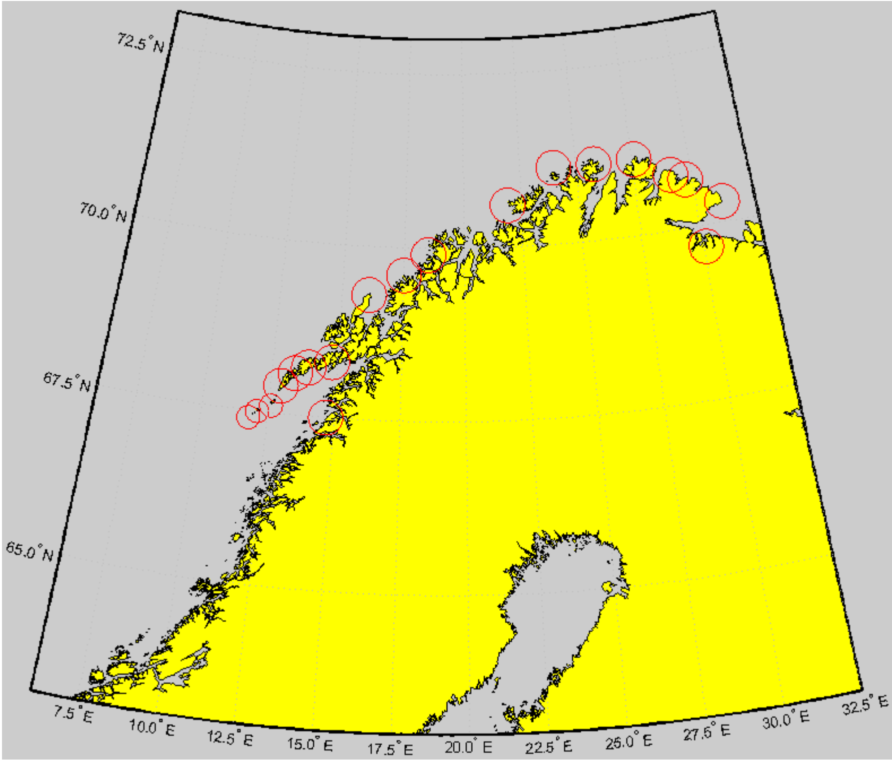


Figure 12: Map illustrating all the areas marked with having a higher criticality than others. When vessels are inside any of the red circles, their criticality is multiplied by that areas factor.

costs for the vessel and increase total preparedness. The total preparedness would increase because the vessel spends less time in port.

In chapter 4.1 I created a model that can be used to locate assets based on their proximity to the hotspots. It makes sense to use this same model for finding an optimal location for the home base. This is where the vessel sails to when it needs to refuel and re-stock supplies and change the crew. The less time spent doing these things means that it can stay close to the critical zones for a larger percentage of time.

To solve this problem I will need some data. In the previous chapter I calculated the zone criticality values to find hotspots. I can now use these values as input for the model. A note to make here is that the hotspot values that are calculated are for a *snapshot*, i.e. a certain point in time. When finding an optimal location

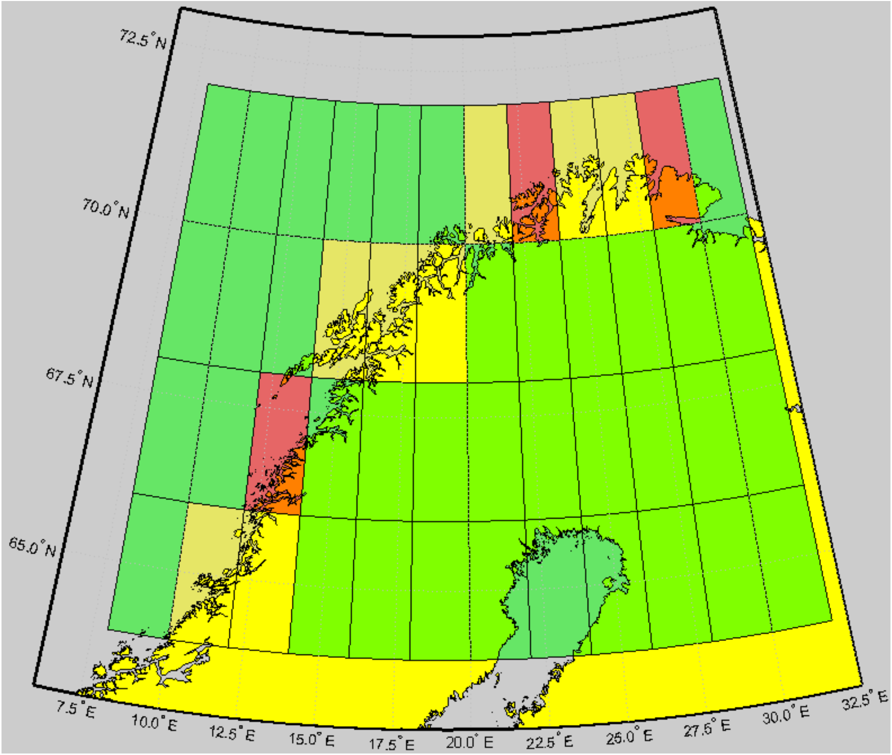


Figure 13: Figure showing all zones marked in red, yellow or green, according to whether they belong to the high, medium or low criticality category

for an onshore installation that is expensive to build, historical data should be used. However, not having this data available, I use the snapshot hotspot values. To the model they are only scalar values, so it will not know the difference.

Additionally, I will need potential locations for a port. I will choose 5 locations that are suitable and find what costs are incurred by using the location.

I will pick the locations near existing ports and use the road standard to set the cost of using the port. If it is a motorway or trunk road, primary road or secondary road, the cost will be 100, 110 and 130, respectively. The costs are estimates made to show how the cost will vary depending on existing infrastructure.

Table 6 then gives us both the costs in F_{al} and the set of locations $l \in \mathcal{L}$.

The calculated hotspot criticality values will be used for C_z. That is, each zone has a criticality value. The distances will be calculated from all $l \in \mathcal{L}$ to all

Table 6: Table with information on the potential port locations

#	Name	Road Standard	Cost	Coordinates
1	Brønnøysund	Secondary road	110	65.4°N 12.1°E
2	Fredvang	Secondary road	110	68.1°N 13.1°E
3	Andenes	Primary road	110	69.3°N 16.1°E
4	Hammerfest	Trunk road	100	70.6°N 23.6°E
5	Vardø	Trunk road	100	70.4°N 31.1°E

$z \in \mathcal{Z}$ to form the parameter D_{lz}.

The Matlab script in appendix A is used to calculate the criticality values and output the data file for the FICO Xpress-IVE model. The FICO Xpress-IVE model is found in appendix B.

The model introduced in chapter 4.1 gives us a solution that indicates option #3 as the best position for a home base. Figure 14 shows the zones with the criticality indicated as well as the alternative locations numbered.

5.4 Finding the best location for emergency vessels

Now that the optimal location for a home base has been found, I can use the same data for hotspot criticality values for optimally localizing a set of emergency vessels. Today, the state charters 2 vessels that are on readiness. (Det Kongelige Samferdselsdepartement, 2014)

The model created in chapter 4.1 supports multiple assets. The locations, l, in $\mathcal{L}$ then become the possible locations that the assets can *move to*. The fixed cost, F_{al} for moving to these locations is the distance the vessel has to travel from its current position.

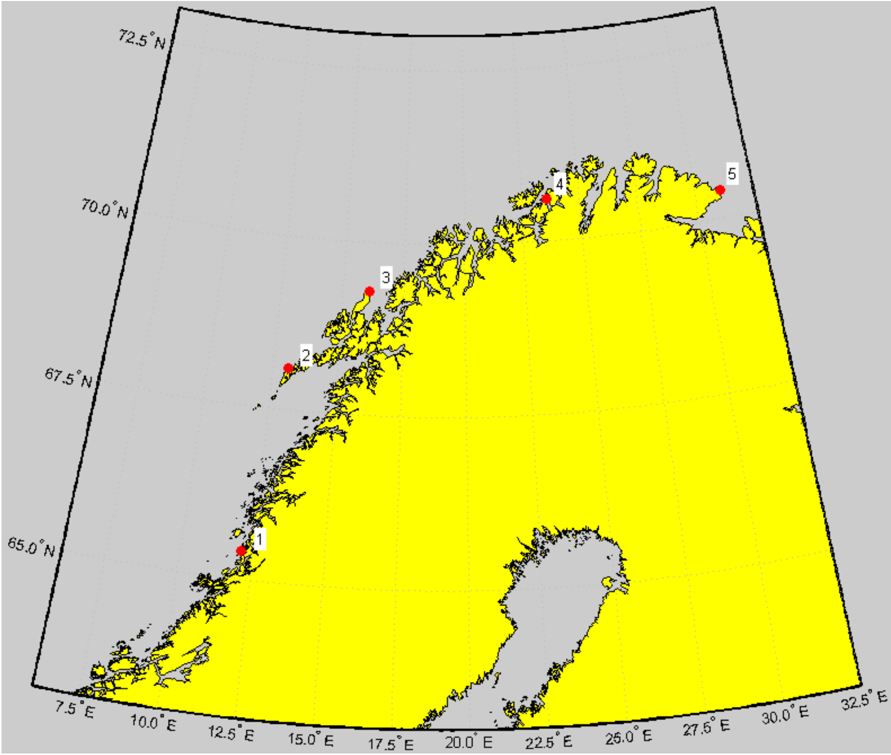


Figure 14: Map showing locations of potential home bases with number

5.5 Measuring preparedness

Using equation (4.14) and (4.15) I can quantify the emergency preparedness for each zone by using the calculated criticality as *requested resource*.

Optimal emergency asset position

Using the model in chapter 4.4, the emergency preparedness is calculated using equation (4.14) and (4.15). The two methods differ and the results are shown in figure 16a and 16b. The values are normalized so that it is easier to compare how the two methods differ between zones. By that I do not mean that it is possible to compare between the methods, but normalizing will show how method 1 and 2 show high and low points, even if method 2 produces somewhat larger numbers.

Figure 15 shows the region with the positions of two assets placed by the second formulation with the rings indicating their 7 hour reach.

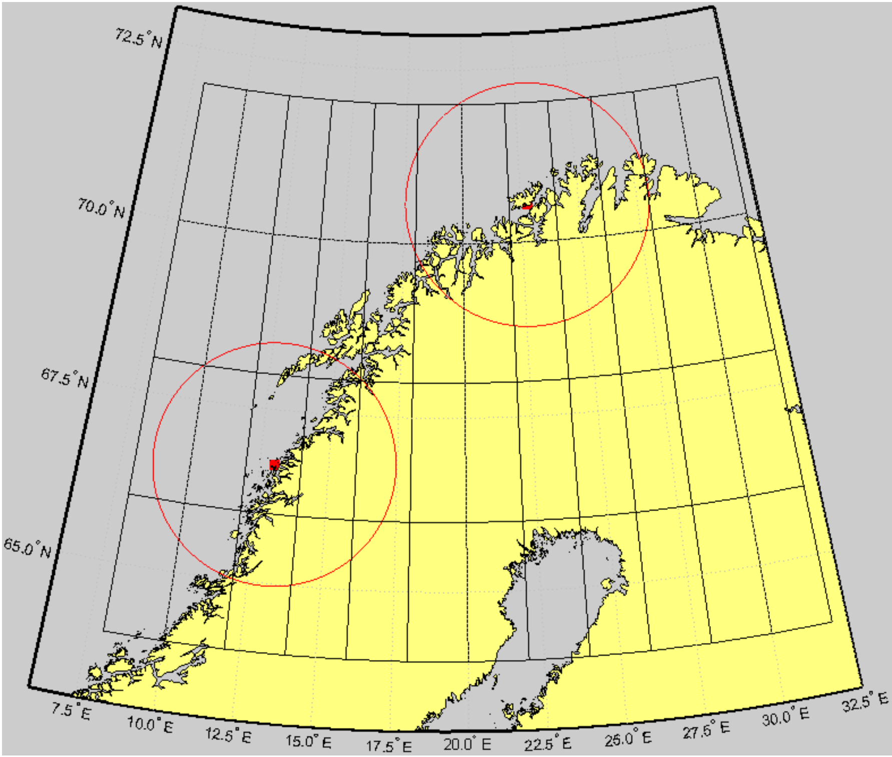


Figure 15: Figure showing the 7 hour reach for two emergency assets in the position found by the second formulation in case 2.

Looking at the numbers in figure 16a and 16b it becomes clear that they both produce different results. The first method calculates worse emergency preparedness north east, whereas the second method calculates worse emergency preparedness further south.

The two blank cells represent the zones where the emergency assets are located, so the preparedness measure either becomes the criticality value here or is just not calculated. I'm assuming that if the emergency asset is in the zone whenever a vessel loses control, the tugging operation can be started immediately. Therefore the value has been omitted in that zone/cell.

Looking at the values in the first figure, 16a, we clearly see that the zones along the coast have non-zero values, which at least indicate that the implementation

0.00	0.00	0.00	0.00	0.00	0.00	0.36		0.44	0.67	1.00	0.05
0.00	0.00	0.05	0.38	0.53	0.58	0.37	0.00	0.00	0.00	0.00	0.00
0.00	0.12		0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.36	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(a) Values obtained using second formulae, equation (4.14)

0.00	0.00	0.00	0.00	0.00	0.00	0.39		0.19	0.12	0.00	0.00
0.00	0.00	0.69	0.13	0.00	0.14	0.31	0.00	0.00	0.00	0.00	0.00
0.00	0.56		1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.10	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(b) Values obtained using second formulae, equation (4.15)

0	0	0	0	0	0	0.1	x	0.1	0.3	0.5	0.8
0	0	0.3	0.5	0.8	0.3	0.1	0	0	0	0	0
0	0.1	x	0.1	0	0	0	0	0	0	0	0
0	0.1	0.3	0	0	0	0	0	0	0	0	0

(c) Values obtained using subjective assessment, using values from table 2

Figure 16: Figure showing the quantified emergency preparedness values using equations (4.14) *and* (4.15) *, normalized. Higher value is worse, so the colours represent the value. Red is worst and green is good, while shades of yellow is in between. Each cell corresponds to the zone in the same relative position.*

works. Further, the zones closest to the emergency assets positions have a better (i.e. lower value) emergency preparedness than the ones further away. Figure 15 shows the map with the asset positions and coverage, which indicate that the coverage for the zones between the two vessels will be low. The values in the figure also indicate that if one travels in a line from one to the other, it decreases before it increases again when it closes in on the location where the asset is.

For the second formulae, shown in figure 16b, we can see that the zones closest to the zone where the asset is, the values are higher than zones further away. This means that the model finds the preparedness to be worse in the zone closest to the asset, than in the zone further away, even for two zones with almost identical criticality. The zones around the location of the first asset have low criticality, and are closest to the asset, but have high emergency preparedness value. This indicates either that the preparedness is bad in that zone or that there are some issues with the implementation.

In figure 16c I have attempted to assess the emergency preparedness in all the zones based on the distance from to the nearest emergency asset and the zones. I mark the asset locations with an x and use four categories that I later assigned values to. Table 2 shows the categories I used and what value they represent.

As the tables in figure 16 and 16c show, the values found by using the first formulae (equation (4.14)), better mirror the actual preparedness in each zone.

6 Results and discussion

This section will briefly present the results for each case and discuss the consequences and different aspects of the results.

6.1 Test case

The problems in the test case were:

- Find a good location for a home port for the emergency vessels
- Find the optimal location for the emergency vessels based on the calculated criticality values
- Quantify the preparedness based on the location of the emergency vessels as set by the optimization model

Home port

Faced with the option of 5 different locations for the ports, the optimization model chose option # 3. Data on the different options is in table 6. This is to be expected, as the criticality values are relatively high in both the northern and southern ends of the region. Thus, the expectation is that the location that is near the middle will be chosen.

Optimal location for emergency vessels

Figure 17 shows the results from the optimization model. The problem was to find the optimal location for two emergency assets so that they would increase the emergency preparedness as much as possible.

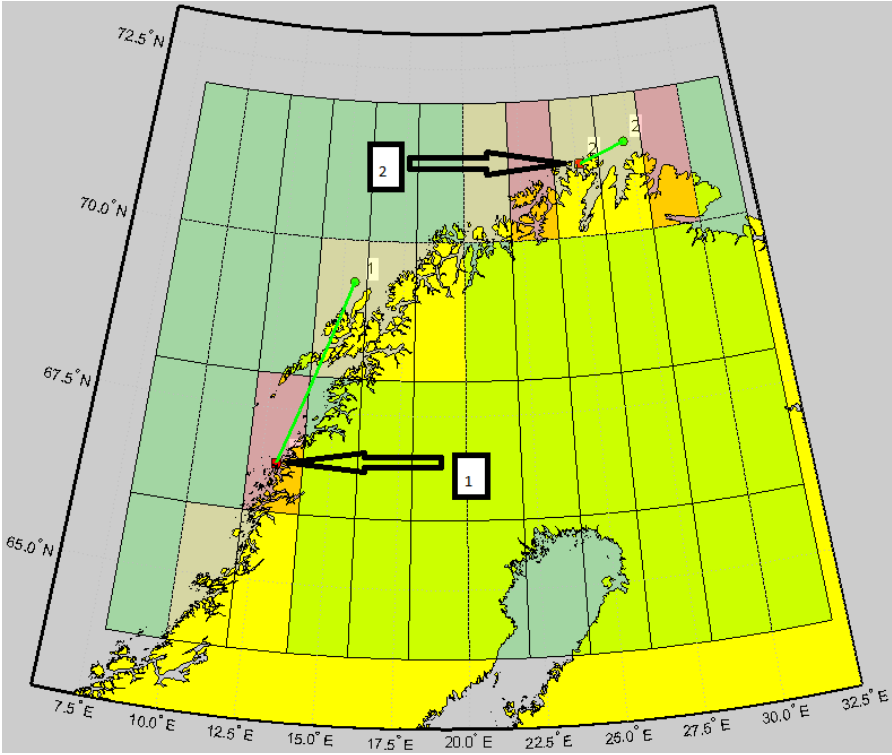


Figure 17: Showing the optimal position for emergency assets

Emergency Preparedness: Quantified

The emergency preparedness quantification measures were implemented with varying degrees of success. The second formulae returns values that are not representing reality very well. According to this measure, with values shown in figure 16b, the zone with one of the lowest criticality values, and is closest to the emergency asset, has the highest emergency preparedness value. The higher the value, the worse the preparedness is.

Luckily, one could say, the first formulation seems to correspond with the subjective values very well. Figure 16a and figure 16c correspond relatively well, with only minor differences. The formulae assesses the preparedness slightly differently further north, but still better than the second measure. It was not expected that either of these measures would provide good assessments without any calibration of the formulae.

6.2 Minimizing risk assumptions

In the model in chapter 4 it is assumed that shorter distance to a zone is equivalent to increasing the emergency preparedness in that zone. That assumption in itself is not wrong, as lowering the response time is better than increasing it. Thus, reducing the reaction time for emergency assets is important to increasing emergency preparedness. This is the reason why finding the optimal position is so interesting.

However, there are several ways to measure the distance and reaction time in the context of increasing emergency preparedness. In the model formulations in chapter 4, the sum of distances from the emergency assets to the zones is minimized by locating the emergency asset according to this criteria.

Another is to minimize the longest distance. That is, the hotspot furthest away has to be as close as possible. This might mean that the assets are not as close to the biggest hotspots, but not very far from any of the zones.

6.3 Model formulations

The first model formulation in chapter 4.1 minimizes the distance to all zones weighted by the criticality found in each zone. However, if the model tries to find the location for two or more vessels, they will be put in the same location. The model simply places the assets in the location where the sum of distances to all zones is minimum. Each zone is not tied to one asset in any way, which would be one way of avoiding clustering of assets like this.

Creating a constraint saying that there can only be one asset at each location, the model would probably place the next asset in the closest location. This does depend on the distance to the next location, but it would not do anything other than avoiding two assets at the same spot. The expectation is then that the assets would likely group together in the same way as the current formulation.

Having two assets in the same location does not necessarily imply a bad preparedness. It could be a good solution. Consider a zone with high criticality and two vessels with complementing capabilities, e.g. tug and fire fighting. The preparedness for the zone nearby would be good. Therefore, removing solutions with two or more assets in the same location seems to be the wrong approach.

In an example like this it becomes clear that the two emergency assets need to be positioned in a way that they are close to as many zones as possible.

In the second formulation it is also derived to find the optimal location for n assets, but by first investigating zone coverage of the assets. The objective function is similar to the first formulation, as it minimizes the sum of distances, but only counts the distances between the locations and the zones the asset covers. Each zone has to be covered once, and only once, and therefore the new formulation will make sure that if there are more than one asset, they will be able to find new locations. The formulation also allows for two or more assets to be at the same location.

Alternative objective function

Instead of minimizing the total distance to the zones, the objective function can be changed to other metrics.

Assuming we know how long an average vessel is in drift, i.e. we know how fast we need to react, we can create other types of objective functions, as we can also create maximization functions.

Maximizing the coverage can be done in several ways, and is dependent on how coverage is interpreted. If we define a zone as being covered if any asset is close enough to reach the zone within a certain time limit we can get creative. I define w_i as being a decision variable that is 1 if zone i is covered. $\mathcal{Z}$ is the set of all zones. I am also assuming that w_i is defined by a coupling constraint to the other variables in the problem that defines where the assets are located.

One way is to maximize the number of zones covered by all the emergency assets, or max $\sum\limits_{i \in \mathcal{Z}}$. However, this does not take into account the criticality of any of the zones, only their location. So for the zone partition method used in this thesis, this becomes somewhat useless, as it ignores information.

Another way is to maximize the number of zones and weighting them by the criticality in the zone, for example with $\sum_{i \in \mathcal{Z}} C_i w_i$, where C_i is the criticality in zone i. In this way, the emergency assets will be positioned closer to the zones with high criticality.

It is also possible to use a min max function, where I want to minimize the worst possible travel distance. Additionally, this can be done with and without weighting the criticality in the zone.

Minimizing the average distance to covered zones is a way of ensuring equity, and is principally the same as minimum envy-models where the objective is to make sure the total envy felt by all zones is minimized.

It is not necessarily clear which objective function is the best or which objective function that gives the best result. It depends on what the it is evaluated. If we want the preparedness to be as equal as possible, i.e. all zones have equal, possibly poor, coverage, maximizing the average coverage is a good candidate.

6.4 Calculating criticality

Criticality is not a perfect representation of risk in a zone. It is a simplification of the actual situation that assumes a few things that might remove important information. The point of the criticality value is to mirror the assumed risk in some way, so that the relative criticality of one zone compared to another correctly represents the need for emergency assets to prioritize it.

The criticality in a zone does not take into consideration the position of any emergency assets that are available. When assessing the criticality, the only factors that are considered are objects that increase the criticality. In the current implementation, nothing reduces criticality.

The reason for this is that the emergency assets are supposed to be moved closer to the zones that need more attention. If the optimization model that uses the criticality data attempts to move an emergency vessel, all the criticality data would change, which would probably (although untested) require very long solution times for the optimization model. At the very least the complexity would increase, and I see no trivial solution to this problem. It seems better then, to separate the two and rather use the criticality as a weight or demand or however you want to visualize this.

In addition to the area critical factors, the traffic related factors could have been included. For example in the TSS lanes near ports, where many vessels either cross or enter the lanes. Calculating the increased risk of any incidents at these locations could be done by using traffic models introduced by Kristiansen (2005).

If adding the contribution from traffic models I am expecting the criticality to increase slightly near ports and where TSS and other lanes cross. This is also expected, as the regulations for TSS state that when crossing the TSS a vessel should cross it on an angle as close to normal as possible. (Forskrift om forebygging av sammenstøt på sjøen (Sjøveisreglene), 2014)

If the criticality accounts for traffic risk as well, the optimization model will position the emergency assets closer to the areas with more crossing traffic, such as ports and lanes. However, in these areas there might be an elevated awareness and people might react faster to other vessels losing control.

In addition to this, in these areas there might be many other vessels that are able to offer tug services as well. These considerations are not covered at all in the model in this thesis, but if it were it could change things somewhat. If one is to make the assumption that areas that have many vessels also provide some emergency preparedness in themselves, the emergency assets that are there for the sole purpose of reducing risk can be positioned otherwise.

On assuming equal probability of losing manoeuvrability, it seems important to note that there has been no attempt made to find an absolute risk measure. The purpose is solely to use the levels calculated to compare between zones. And if a model like this one is to be used for decision support, it is important to also use all the available data, and not blindly trust the model as it could have a bias in some way or other. This bias could be that some vessel types or characteristics are weighted either too low or too high, giving either the impression of very high risk or criticality or simply ignoring situations that could be a problem.

Calculating time windows for hotspots

Calculating criticality for the live view of vessels is a way to see if emergency assets are positioned correctly in the present moment. However, it does not say much about the situation in 10 minutes or one hour. By just looking at the current positions of vessels, it is somewhat limited in what it can actually represent of real risk.

Estimating vessel position in a short time window is possible by simply assuming that the vessel will keep its course and speed for the duration of that time window. This is possibly true for many vessels for a short time span and might increase the value of the calculated criticality if done correctly. That is, criticality for each zone could be calculated over a timespan of, say, 10 minutes. This means that the criticality in the current moment is also based on a 10 minute forecast of the vessels positions. Of course, 10 minutes could be any length of time, but it becomes less accurate as the probability of vessels changing course in that time span increases.

This can be done by calculating the position for the vessels in n minutes and then adding both the current and the estimated future position to the current criticality value. This will increase the difference between high and low criticality, as the areas with many vessels will probably be counted twice in the same zone in many cases. The ones that are near the edge of a zone will contribute to the neighbouring zone if the new position is calculated there.

With all information available it could be possible to create hotspots with time windows. That is, by using information such as route tables for ferries and other regular traffic and historic position data for vessels, hotspots can be defined using time windows in addition to the hotspot value. This will make it possible to use patrols to greater effect, as one will cover the most critical zones.

Of course, this will depend on the actual locations of the hotspots. If they vary a lot, requiring emergency assets to move a lot to be positioned perfectly, it could become expensive. However, it is possible to use constraints on the amount of movement allowed in the model so that the actual patrol routes move between locations that are *good enough* and not necessarily the best seen from the perspective of here and now.

6.5 Zone sizes

Looking at the size of the zones after calculating the zone criticality categories, it becomes apparent that there are some weaknesses. If a zone is partially covered by landmass, the area that covers the ocean can have a relatively high density mass of vessels, but not enough vessels to actually be registered as high or even medium. This means that in some cases, one zone will be in the high criticality category and the neighbouring zone will be in the low category. The occurrence of these cases will appear depending on zone size and vessel density.

This becomes easier to see when looking at figure 18.

This model does not take into consideration any effects contributed to crowding. By that I mean the increased density when there are many vessels nearby. If many vessels are in the same area, the probability of colliding is greater, seen from a purely geometric probability question. How this scales and how this should be added to the criticality of the zone is up for discussion. Additionally, if this were to be added, the size of the zone would become an issue, as small zones wouldn't pick up on crowding.

If the criticality value of each zone is divided by the ratio of the zone that is water, the zones that have mainly landmass will also have an impact. On the other hand, zones with mostly landmass could end up as high criticality when in reality there are very few vessels, and having a high value could end up allocating resources incorrectly.

When lowering the size of the zones it becomes clearer that there are many regions that are in the low criticality category, and very few that have medium and high criticality category.

Changing the zone size from 2 degrees latitude and longitude to 0.5 degrees

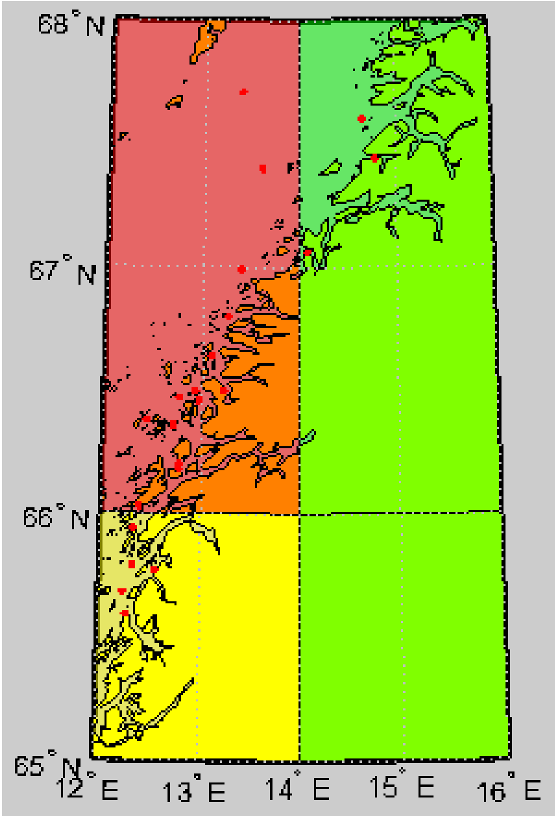
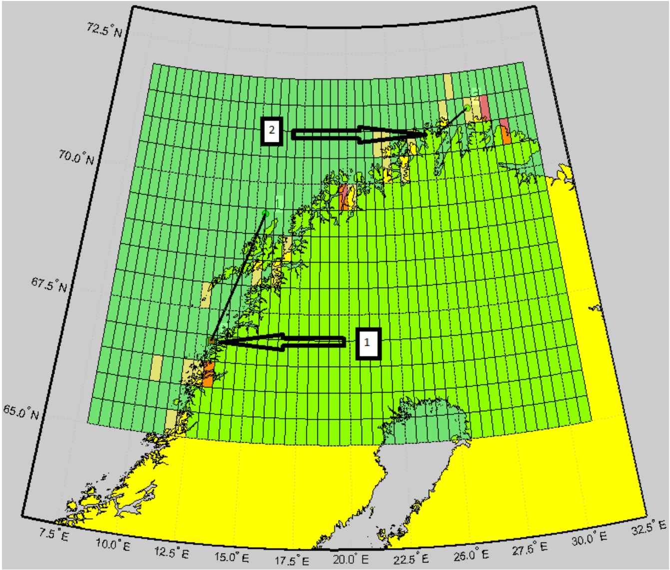


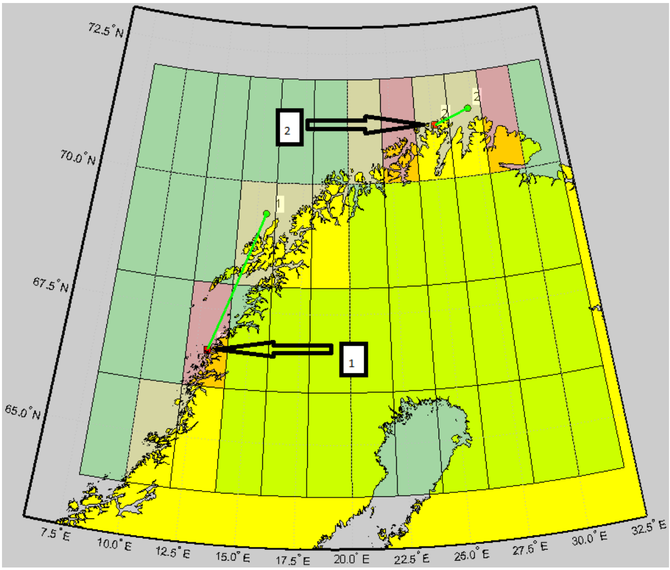
Figure 18: Map showing a small region of the map to emphasize difference in criticality between zones due to geography.

latitude and longitude, for example, does not change the solution that is returned from the optimization model much. The criticality measure scales in a linear fashion with regards to zone size, so the vessels in a zone will not have a greater impact on the criticality if they are in abundance. This means that large and small zones will give the same total demand over the same geographical area, regardless of the zone size. If the criticality took into account the density of vessels and increased the criticality based on this, the way zones are found in this thesis would have an impact.

Figure 19a and 19b show the criticality in the different zones and the position for the two emergency assets after running the optimization model. In figure 19a it can be seen that the area just north of asset 1 is green, and only a few zones closer to the shore are yellow and red. In figure 19b the zone that asset 1



(a) Zone size set to 0.5 degrees latitude and longitude



(b) Zone size set to 2.0 degrees latitude and longitude

Figure 19: Figures show zone criticality and optimized asset location for two assets with different zone size.

is in, is red, indicating that the entire zone is critical, while the first figure, 19a, shows a more nuanced view. And even if the zone partitioning at first glance looks like two different times, they are based on the same vessel data and return very similar results from the optimization model.

Alternative zone partitioning

Instead of dividing the region into zones based on a fixed size, the zones could be set by using some type of cluster analysis on the vessel data. This way the zones would be dynamically located and dynamically sized according to the vessel positions and density.

6.6 Data availability

I contacted the NCA to see if I could get access to AIS data for the Norwegian coast, but I didn't receive a reply until June 8th. This was too late for me to utilize it. Had I received it sooner, I could have used to live data to take snapshots of the vessel positions at different times to see how far into the future the estimation models would hold. Additionally, I could create statistical hotspots, which would be more suitable for location of permanent assets as bases for emergency vessels or helipads for emergency helicopters.

7 Conclusion

The objective of the thesis was to create a model that uses methods and tools to measure the threat posed to the environment by merchant traffic to allow operators at VTS to allocate resources accordingly. A method for calculating criticality was implemented and the results were used in two optimization models that both provided functional results. The results were also visualised on a map to show where the most critical zones were.

With the emergency assets positioned optimally according to the optimization model, the emergency preparedness quantification was used to analyze the results. Two methods of measuring emergency preparedness were implemented and the results of one of them is shown to be functional, whereas the other model seems to either over-report or ignore zones. Comparing them both to a subjective evaluation shows that the second formulation in the current implementation is not showing functional results.

Thus, the methods used in the thesis show promise, in that it is able to locate critical areas and utilize them in a way that gives good solutions, but also identifies many areas for future work.

8 Further work

For the calculations of the criticality values for the zones, there are a few different strategies that could be tested. In this thesis, only the current position is taken into account. Making an estimate for the vessels can improve the calculations. These predictions could become some type of forecast, which can be tested against real data.

Another extension of the criticality values is to account for crowding and other characteristics of the traffic picture. Whenever vessels approach each other, the risk of something happening is not constant. Because of this, an improved calculation could take this effect into account.

Criticality has been calculated by accumulating all the vessels in the region, where each vessel adds to the criticality. In reality, some vessels have capabilities that enable them to assist in an emergency. Because of this, the real criticality could actually be lower in some cases. This would require the criticality calculations have access to more data, such as capabilities of vessels. It would enable operators to position emergency assets differently, which overall could reduce the total risk.

For the optimization models there are several ways of measuring the value of a solution. In this thesis, distance to the zones weighted by the criticality was used. However, finding other ways to measure the value of a solution could prove to be useful. With every metric chosen, there is a discussion to what it will prioritize and what it will be biased towards. Also, is it better to have the total preparedness as equal as possible, or is it better to have the worst preparedness as low as possible. However, an operator might have access to different models to help assess the situation if a models bias is known.

Another extension to the model is to allow the operator to take control over vessels in the region. That is, include the vessel as a decision variable and find a new location for it. This could mean that a merchant vessel will be asked to sail out of an area or another vessel is asked to assist in some operation or simply assuming that a vessel can assist if something happens.

In this thesis there has been no focus on the operational costs of the emergency assets, but in reality this is a big concern. Including this in a model will mean that in some cases, it would be too expensive to move an asset to a location that could reduce the total risk. Introducing some constraint on movement or time spent sailing would require a thorough study on costs related to these activities.

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A
Criticality calculations - preprocessing

Listing 1: Matlab code for processing vessel data, criticality calculations and output to text file for use in Xpress model

```
% Matlab script to find optimal locations for n emergency assets with
% starting locations.
clear all; clc;

global timePeriods;
global periodDuration;


%% Define period, period duration and so on
timePeriods = 1;
periodDuration = 1;

% Starting coordinates for assets
% assetCoordinates = [
% 69.4 15.5;
% 71.3 27.2;
% ];
% Starting coordinates is Andenes port
assetCoordinates = [
   69.3 16.1;
   69.3 16.1;
   ];
numAssets = size(assetCoordinates,1);


%% Read the vessel traffic data for
% List of ships in the following format
% lat, lon, bearing(north=0deg, 90deg = east), speed[kn], vesseltype
% Vesseltype = { 1, 2, 3 } according to categories in thesis
load('shiplist.mat');


% Risk category weight for the hotspots. Change values here to see the
% contribution from category 1, 2 and 3 change
```

```
shipRiskCategory = [ 1.0 2.0 3.0 ];

% sPositions is then an array with the following ship positions
% timePeriod type
% Heading and speed is probably not interesting anymore

% Initialize the sPositions matrix that holds all the ships positions for
% all the timeperiods and ships have their lat and lon coordinates recorded
sPositions = zeros([timePeriods, size(shipList,1), 2]);

% Double for loop!
for t = 1:timePeriods % For all timeperiods
   for i = 1:size(shipList,1) % For all the vessels in the list
      % find the estimated position for vessel i at time t in tmp var
      %tmpPos = shipPosition(shipList(i,1:2), shipList(i,3), shipList(i,4), t);
      tmpPos = shipPosition(shipList(i,3:4), shipList(i,2), shipList(i,1), t);
      % Add this information to the sPositions matrix
      sPositions(t,i,1) = tmpPos(1);
      sPositions(t,i,2) = tmpPos(2);
   end
end

% List of spots(coordinates) that have a heightened risk of some sort.
% Distance to these locations will be checked for each vessel
% lat lon factor radius[nm]
zoneRiskSpots = [
   67.5 12.1 0.2 10; % Roest
   67.4 11.8 0.2 10; % Roestoeyan
   67.6 12.6 0.2 10; % Vaeroey
   67.9 12.9 0.1 15; % Lofoten general
   68.1 13.4 0.1 15; % Lofoten general
   68.2 13.9 0.1 15; % Lofoten general
   68.3 14.8 0.1 15; % Lofoten general
   67.5 14.7 0.2 15; % Kjerringoey
   69.3 16.1 0.2 15; % Andenes
   69.6 17.5 0.2 15; % Senja
   69.9 18.5 0.2 15; % Risoeya
   70.6 21.9 0.2 15; % Soervaer
   71.1 24.0 0.2 15; % Ingoeya
   71.1 25.8 0.2 15; % Nordkapp
   71.1 27.6 0.2 15; % Nordkinn
```

```
    70.8 29.1 0.2 15; % Berlevaag
    70.3 31.1 0.2 15; % Vardoe
    69.7 30.1 0.2 15; % Kirkenes
];

% Latitude and longitude limits, upper and lower [l,u]
latLim = [65 72];
lonLim = [8 31];

% Size of zones in degrees. This won't make them equally big in physical
% area, but makes it much easier to partition the region
zoneLat = 0.5;
zoneLon = 0.5;

% Find number of rows and columns - round up, actually giving a slightly
% larger area if the size of the area isn't dividable by the zonesize
numRows = ceil(diff(latLim) / zoneLat);
numCols = ceil(diff(lonLim) / zoneLon);
numZones = numRows*numCols;

% Number of locations is equal to zones. However, not all locations are
% reachable. More on that further down
numLocations = numZones;

% Init vars
shipsInZone = zeros(numRows*numCols,1);
hotspotValue = zeros(numRows*numCols,1);

% Var to hold 1 if zone is also a location, that means the zone is _NOT_ on
% land, i.e. one of the corners or centroid is water
zoneIsLocation = zeros(numZones,1);

% Vars for center of gravity calc
zoneLatCG = zeros(numZones,1);
zoneLonCG = zeros(numZones,1);
zoneWeightCG = zeros(numZones,1);
zoneCG = zeros(numZones,2);
% Loop over all timestamps
for t = 1:timePeriods
    % Zone is incremented in each loop, so we start at 0 to get 1 in the first
    %% zone
```

```
zone = 0;
for row = 1:numRows % Loop over all rows
   % As we start in the north west corner, we have to subtract from the
   % latitude
   % Find lower and upper latitude limits for this row of zones
   uLat = latLim(2) - ((row-1) * zoneLat);
   lLat = latLim(2) - (row * zoneLat);
   for col = 1:numCols % Loop over all columns
      % Find lower and upper column limits for this zone
      lLon = lonLim(1) + ((col-1) * zoneLon);
      uLon = lonLim(1) + (col * zoneLon);
      zone = zone + 1; % Increment zonenumber
      %str = sprintf('z= %d, LAT: %.1f - %.1f, LON: %.1f - %.1f',zone,lLat,uLat,lLon,uLon)
      %disp str;

      % Loop over all ships in the list and check if they are inside
      % this zone in this time period
      for i = 1:size(shipList,1)
         % Check to see if vessel latitude and longitude is within
         % this zone. If the vessel is larger or equal to the lower
         % limit, it is part of the zone
         if ((sPositions(t, i, 1) >= lLat) && (sPositions(t, i, 1) < uLat)) && ...
               ((sPositions(t, i, 2) >= lLon) && (sPositions(t, i, 2) < uLon));
            % Vessel is in zone so all zone calculations can go here

            % Count it
            shipsInZone(zone) = shipsInZone(zone) + 1;

            % Check if vessel is close to defined critical areas
            % and add the risk factor for that spot to the vessel
            % risk
            vesselRiskFactor = 1;
            for r = 1:size(zoneRiskSpots,1)
               % Check to see if the vessel is inside the risk
               % spot radius
               if (distTwoPoints(sPositions(t,i,1:2),zoneRiskSpots(r,1:2)) <= zoneRiskSpots(r
                  % Add the area risk factor to the vessel risk
                  % factor that will be multiplied with the base
                  % risk for the vessel
                  vesselRiskFactor = vesselRiskFactor + zoneRiskSpots(r,3);
               end
```

```
                end
                % Record its risk weight
                hotspotValue(zone) = hotspotValue(zone) + ...
                   (shipRiskCategory(shipList(i,5)) * vesselRiskFactor);

                % Record ship latitude, longitude and weight for center
                % of gravity calculation
                zoneLatCG(zone) = zoneLatCG(zone) + (sPositions(t,i,1)*shipRiskCategory(shipList(i,5)));
                zoneLonCG(zone) = zoneLonCG(zone) + (sPositions(t,i,2)*shipRiskCategory(shipList(i,5)));
                zoneWeightCG(zone) = zoneWeightCG(zone) + shipRiskCategory(shipList(i,5));
             end
          end

          % Calculate the zones center of gravity
          if (zoneLatCG(zone) == 0)
             zoneCG(zone,1) = lLat + (zoneLat/2);
             zoneCG(zone,2) = lLon + (zoneLon/2);
          else
             zoneCG(zone,1) = zoneLatCG(zone) / zoneWeightCG(zone);
             zoneCG(zone,2) = zoneLonCG(zone) / zoneWeightCG(zone);
          end

          % This is commented out because it makes things very slow. It
          % seems like checking a bunch of coordinates to see if they are
          % inside a polygon is somewhat intensive.
% % Check to see if any of the corners of the zone is water. If
% % so, mark the zone as a location
% if (landmask(uLat,lLon) == 0) || ...
% (landmask(uLat, uLon) == 0) || ...
% (landmask(lLat, lLon) == 0) || ...
% (landmask(lLat, uLon) == 0)
% % Zone is (partially) water, so it is possible for assets
% % to move here if floating.
% zoneIsLocation(zone) = 1;
% end


       end
    end
end
```

```
%% Normalize hotspotvalues
%hotspotValue = hotspotValue/max(abs(hotspotValue(:)));

% Find distance from asset starting position to possible locations
% The possible locations are all the zones. Combined with zoneIsLocation()
% we also get to exclude the zones that are on shore
distanceAssetLocations = zeros(numAssets,numLocations);
for a = 1:numAssets
   for l = 1:numLocations
      distanceAssetLocations(a,l) = distTwoPoints(assetCoordinates(a,1:2),zoneCG(l,1:2));
   end
end


%% Set category for each zone according to calculated values

% Divide the hotspotvalues into three bins so that we get three categories.
% Low, medium and high
[n, bin] = hist(hotspotValue, 3);
% Find bin ranges
binWidth = bin(2)-bin(1);
binMin = bin - binWidth/2; binMin(1) = 0;
binMax = bin + binWidth/2;

% hotspotCategory holds the category for each zone that can be used to
% color the zones in the map later
hotspotCategory = zeros(numCols*numRows,1);
hotspotCatNum = zeros(3,1);
for i = 1:numCols*numRows
   if (hotspotValue(i) < binMin(2)) % Category 1
      hotspotCategory(i) = 1;
      hotspotCatNum(1) = hotspotCatNum(1)+1;
   elseif (hotspotValue(i) < binMin(3)) % Category 2
      hotspotCategory(i) = 2;
      hotspotCatNum(2) = hotspotCatNum(2)+1;
   else % Category 3
      hotspotCategory(i) = 3;
      hotspotCatNum(3) = hotspotCatNum(3)+1;
   end
end

```

```
%% Find facility capacity

% Unconstrained capacity means that all hotspots should be possible to
% service from one facility. Thus the sum of all the demand is an OK value
% to use as "big M" but we fill out a matrix with values so that the
% printing to file will be the same even if this changes
assetCap = zeros(numAssets,1);
for i = 1:numAssets
   assetCap(i) = sum(hotspotValue);
end

%% Calculate distance from locations to zones
locationZoneDistances = zeros(numLocations, numZones);
for i = 1:numLocations
   for j = 1:numZones
      locationZoneDistances(i,j) = distTwoPoints(zoneCG(i,1:2),zoneCG(j,1:2));
   end
end

% Fixed cost for assets in locations
fixedCost = zeros(numAssets, numLocations);
for a = 1:numAssets
   for l = 1:numLocations
      fixedCost(a,l) = distTwoPoints(assetCoordinates(a,1:2), zoneCG(l,1:2));
   end
end

%% Output data for the mosel file

% Filenames and open file stream
fileName = 'Input.dat';

fID = fopen(fileName, 'w+');

fprintf(fID, '! Input file for a facility location problem\n');
fprintf(fID, '! Master thesis for Knut Stower\n');

fprintf(fID, 'nZones : %d\n', numZones);
```

```
fprintf(fID, 'nAssets : %d\n', numAssets);
fprintf(fID, 'nLocations : %d\n', numLocations);

% fprintf(fID, 'Capacity : [\n');
% for i = 1:numFacilities
% fprintf(fID, '%d\t', facilityCap(i));
% end
% fprintf(fID, '\n]\n');

fprintf(fID, 'S : [\n');
for a = 1:numAssets
   fprintf(fID, '%.0f\t', numZones);
end
fprintf(fID, '\n]\n');

fprintf(fID, 'Criticality : [\n');
for i = 1:numZones
   fprintf(fID, '%.2f\t', hotspotValue(i));
end
fprintf(fID, '\n]\n');

fprintf(fID, 'FixedCost : [\n');
for a = 1:numAssets
   for l = 1:numLocations
      fprintf(fID, '%d\t', fixedCost(a,l));
   end
   fprintf(fID, '\n');
end
fprintf(fID, ']\n');

fprintf(fID, 'Distance : [\n');
for i = 1:numLocations
   for j = 1:numZones
      fprintf(fID, '%d\t', locationZoneDistances(i,j));
   end
   fprintf(fID, '\n');
end
fprintf(fID, ']\n');

fprintf(fID, 'NoLoc : [\n');
for i = 1:numLocations
```

```
   fprintf(fID, '%d\t', zoneIsLocation(i));
end
fprintf(fID, ']\n');


%% Count the number of each vessel type in the set
vesselTypes = zeros(3,1);
for i = 1:size(shipList,1)
   if shipList(i,5) == 1
      vesselTypes(1) = vesselTypes(1) + 1;
   elseif shipList(i,5) == 2
      vesselTypes(2) = vesselTypes(2) + 1;
   elseif shipList(i,5) == 3
      vesselTypes(3) = vesselTypes(3) + 1;
   end
end


zone = 0;
for row = 1:numRows
   uLat = latLim(2) - ((row-1) * zoneLat);
   lLat = latLim(2) - (row * zoneLat);
   for col = 1:numCols
      lLon = lonLim(1) + ((col-1) * zoneLon);
      uLon = lonLim(1) + (col * zoneLon);
      zone = zone + 1;
      lol(row,col) = hotspotValue(zone);
   end
end
```

B Xpress-IVE Model implementation

Listing 2: Mosel code for Xpress IVE implementation

```
model FacilityLocation
uses "mmxprs"; !gain access to the Xpress−Optimizer solver
uses "mmive";

options explterm
options noimplicit


! Filename of input data
parameters
      DataFile = 'Input.dat';
end−parameters

! Declaring some of the data needed to initiolize data later
declarations
      nZones   :  integer;
      nAssets   : integer;
      nLocations : integer;
end−declarations

! Reads the data from the input file
initializations from DataFile
      nZones;
      nAssets;
      nLocations;
end−initializations

! Declare the sets
declarations
      Zones   : set of integer;
      Assets   : set of integer;
      Locations : set of integer;
end−declarations

! Define the sets based on input data
```

```
Zones := 1 .. nZones;
Assets := 1 .. nAssets;
Locations := 1 .. nLocations;

! Finalize the sets so they cannot be altered after this
finalize(Zones);
finalize(Assets);
finalize(Locations);


! Declare parameters for the problem
declarations
      Criticality : array(Zones) of real;
      FixedCost : array(Assets, Locations) of integer;
      Distance : array(Locations, Zones) of integer;
      S   : array(Assets) of integer;
end-declarations

! Read the parameter data from datafile
initializations from DataFile
      Criticality;
      FixedCost;
      Distance;
      S;
end-initializations

! Declare decision variables
declarations
      x : dynamic array(Assets, Locations, Zones)  of mpvar;
      y : dynamic array(Assets, Locations) of mpvar;
end-declarations

! Create decision variables after declarations and set type to binary for x
forall (a in Assets, l in Locations, z in Zones) do
      create(x(a,l,z));
      x(a,l,z) is_binary;
end-do

! Create decision variables in y
forall (a in Assets, l in Locations) do
      create(y(a,l));
```

```
      y(a,l) is_binary;
      !y(a,l) <= Criticality(l);
end-do

! Declare objective function and constraints
declarations
  ObjectiveFcn: linctr;
  AssetsOneLocation: dynamic array(Assets) of linctr;
  ZoneCoverOnce: dynamic array(Zones) of linctr;
  AssetCapacity: dynamic array(Assets,Locations) of linctr;
end-declarations

! Define the objective function
ObjectiveFcn :=
      sum(a in Assets, l in Locations, z in Zones) Distance(l,z) * Criticality(z) * x(a,l,z) +
      sum(a in Assets, l in Locations) FixedCost(a,l) * y(a,l);


! Define the constraints

! Make sure assets are assigned to a location
forall (aa in Assets) do
AssetsOneLocation(aa) :=
      sum(l in Locations) y(aa,l) = 1;
end-do

! Make sure each zone is covered once
forall (zz in Zones) do
ZoneCoverOnce(zz) :=
      sum(a in Assets, l in Locations) x(a,l,zz) = 1;
end-do

forall (aa in Assets, ll in Locations) do
AssetCapacity(aa,ll) :=
      sum(z in Zones) x(aa,ll,z) <= S(aa) * y(aa,ll);
end-do

minimize(ObjectiveFcn);

writeln("Begin running model");
```

```
writeln("Solution:");
forall (a in Assets) do
      forall (l in Locations) do
            forall (z in Zones) do
                  !i.e. the asset us in location covering zone
                  if getsol(x(a,l,z)) <> 0 then
                        writeln(a, ' is in use in ', l, ' and is covering ', z);
                  end-if
            end-do
      end-do
end-do



writeln("End running model");

end-model
```

C

Matlab code for calculating emergency preparedness

Listing 3: Matlab code for calculating emergency preparedness

```
%% Quantify preparedness

% Asset locations, lat/lon

% These locations are from the optimization model
assetLocations = [
   zoneCG(471,1) zoneCG(471,2);
   zoneCG(127,1) zoneCG(127,2);
];

% Andenes port as starting point for both assets
% assetLocations = [
% 69.3 16.1;
% 69.3 16.1;
% ];

% Result when running second model formulation with zonesize 2
% assetLocations = [
% zoneCG(27,1) zoneCG(27,2);
% zoneCG(8,1) zoneCG(8,2);
% ];

% Result when running second model formulation with zonesize 1
% assetLocations = [
% zoneCG(121,1) zoneCG(121,2);
% zoneCG(57,1) zoneCG(57,2);
% ];
%
% Asset speeds[kn] -- how fast can they reposition themselves
assetSpeeds = [
   15;
   15;
];

% Asset contribution factor -- How well is the asset able to contribute to
```

```
% the accident type. If tugging is needed and a vessel has enough bollard
% pull and tugging equipment, it is sufficient and the factor is 1.
assetContributionFactor = [
   1;
   1;
];
numAssets = size(assetLocations,1);

% Time limit -- How many hours does it take before it is too late and the
% asset cannot be assumed to be within range
timeLimit = 7;


% Formula for preparedness in zone j
% P = d * (sum (vessels in range * vessel response time)) / (number of vessels in range)

% Alternative prep function
% p = (1/c) * sum(all assets in range) (contribution factor(a,z) ) / (t(a,z) )
zone = 0;
emPrep = zeros(numZones, 1);
prep = zeros(numRows,numCols);

emPrep2 = zeros(numZones, 1);
prep2 = zeros(numRows,numCols);

noCover = zeros(numRows,numCols);

for row = 1:numRows
   uLat = latLim(2) - ((row-1) * zoneLat);
   lLat = latLim(2) - (row * zoneLat);
   numVesselRange = 0;
   sumVesselResp = 0;
   assetsInRange = 0;
   for col = 1:numCols
      lLon = lonLim(1) + ((col-1) * zoneLon); % We know the zone coords
      uLon = lonLim(1) + (col * zoneLon);
      zone = zone + 1; %We know what zone we are in

      % Zone criticality has been calculated in another script
      zc = hotspotValue;% / max(abs(hotspotValue(:)));
      %zc = zc / max(abs(zc(:)));
```

```
        la(row,col) = zc(zone);
        % zoneCG is the center of gravity of the zones. calculated in
        % another script
        % Loop through the list of assets

        if zc(zone) == 0
           tmpPrep = 0;
        else
           tmpPrep = ( 1 / zc(zone) );
        end
        tmpAss = 0;
        timeToZone = 0;
        % Count number of assets and calculate emprep2
        for a = 1:numAssets
           distZA(a) = distTwoPoints(assetLocations(a,1:2), zoneCG(zone,1:2));
           timeToZone = distZA(a) / assetSpeeds(a);

           if (timeToZone) < timeLimit
              % Asset is in range
              assetsInRange = assetsInRange + 1; % For emprep

              %emprep2-tmp var
              if timeToZone == 0 % Exception if distance(and thus timeToZone) is 0
                 tmpAss = tmpAss + assetContributionFactor(a);
              else
                 tmpAss = tmpAss + (assetContributionFactor(a) / (timeToZone));
              end
           end
        end

        emPrep2(zone) = tmpPrep * tmpAss;

        for a = 1:numAssets
           % Find distance from zone to asset
           %distZA = distTwoPoints(assetLocations(a,1:2), zoneCG(zone,1:2));
           % Dividing nautical miles by knots gives hours
           if (distZA(a) / assetSpeeds(a)) < timeLimit % Within time limit?
              sumVesselResp = sumVesselResp + (assetsInRange * (distZA(a) / assetSpeeds(a)));
           end
        end
        if zc(zone) == 0
```

```
            % No vessels. No problem.
            emPrep(zone) = 0;
        elseif assetsInRange == 0 && zc(zone) ~= 0
            % No assets in range for a zone with crit ~= 0. Potential
            % problem. Set emprep to equal criticality + some large sum
            emPrep(zone) = max(max(emPrep));
            emPrep2(zone) = max(max(emPrep2));
            disp('ajaj!');
            noCover(row,col) = 1;
        else
            emPrep(zone) = zc(zone) * (sumVesselResp) / (assetsInRange);
            disp('hei');
            %% Finn antallet til hver sone og gang det med hver enkelt greie?
            % S det blir (2*respTid)+(2*respTid) / 2 ? I stedet for
            % respTid+Resptid/2 ...
        end



        % If any of the assets are in this zone, the prep is very good,
        % i.e. == 0
        for a = 1:numAssets
            if distZA(a) == 0 %%Asset is in this zone.
                emPrep2(zone) = 0;
                emPrep(zone) = 0;
            end
        end

        prep(row,col) = emPrep(zone);
        prep2(row,col) = emPrep2(zone);
    end
end
%% Normalize both preparedness measures to easily see how much impact each zone gives for each measure
prep = prep / max(abs(prep(:)));
prep2 = prep2 / max(abs(prep2(:)));


%% METHOD 1
figure;
boundingbox = [5 60; 30 74];
mlatLim = [63 73];
```

```
mlonLim = [6 32.5];
worldmap(mlatLim,mlonLim); % Use for maps that show more detail in
%land = shaperead('./Map/GSHHS_shp/i/GSHHS_i_L1.shp','BoundingBox',boundingbox, 'UseGeoCoords',
land = shaperead('./Map/GSHHS_shp/c/GSHHS_c_L1.shp','BoundingBox',boundingbox, 'UseGeoCoords', t
h = geoshow(land);%, 'FaceColor', 'y');

title('Method 1');

%% Draw circle around emergency assets to show the range
for a = 1:numAssets
    [latc,lonc] = scircle1(assetLocations(a,1),assetLocations(a,2),(assetSpeeds(a)*timeLimit),[]
    geoshow(latc,lonc,'DisplayType','line','color','r');
    geoshow(assetLocations(a,1),assetLocations(a,2), 'DisplayType','point', ...
      'markeredgecolor', 'r', ...
      'markerfacecolor','r', ...
      'marker','s' ...
      );
end



%% Set category for each zone according to calculated values

% Divide the hotspotvalues into three bins so that we get three categories.
% Low, medium and high
[n, bin] = hist(emPrep, 3);
% Find bin ranges
binWidth = bin(2)-bin(1);
binMin = bin - binWidth/2; binMin(1) = 0;
binMax = bin + binWidth/2;

% hotspotCategory holds the category for each zone that can be used to
% color the zones in the map later
prepCategory = zeros(numCols*numRows,1);
prepCatNum = zeros(3,1);
for i = 1:numZones
   if (emPrep(i) < binMin(2)) % Category 1
      prepCategory(i) = 1;
      prepCatNum(1) = prepCatNum(1)+1;
   elseif (emPrep(i) < binMin(3)) % Category 2
      prepCategory(i) = 2;
```

```
      prepCatNum(2) = prepCatNum(2)+1;
   else % Category 3
      prepCategory(i) = 3;
      prepCatNum(3) = prepCatNum(3)+1;
   end
end

figure(1)


zone = 0;
for row = 1:numRows
   uLat = latLim(2) - ((row-1) * zoneLat);
   lLat = latLim(2) - (row * zoneLat);
   for col = 1:numCols
      lLon = lonLim(1) + ((col-1) * zoneLon);
      uLon = lonLim(1) + (col * zoneLon);
      zone = zone + 1;
      if (prepCategory(zone) == 1) zonecolor = 'g'; end
      if (prepCategory(zone) == 2) zonecolor = 'y'; end
      if (prepCategory(zone) == 3) zonecolor = 'r'; end
      if (noCover(row,col) == 1) zonecolor = 'k'; end
      p = patchm([uLat uLat lLat lLat],[lLon uLon uLon lLon],zonecolor);
      set(p,'FaceAlpha',0.8);
   end
end


%% METHOD 2
figure;
boundingbox = [5 60; 30 74];
mlatLim = [63 73];
mlonLim = [6 32.5];
worldmap(mlatLim,mlonLim); % Use for maps that show more detail in
%land = shaperead('./Map/GSHHS_shp/i/GSHHS_i_L1.shp','BoundingBox',boundingbox, 'UseGeoCoords', true);
%land = shaperead('./Map/GSHHS_shp/c/GSHHS_c_L1.shp','BoundingBox',boundingbox, 'UseGeoCoords', true);
h = geoshow(land);%, 'FaceColor', 'y');

title('Method 2');

%% Draw circle around emergency assets to show the range
```

```
for a = 1:numAssets
    [latc,lonc] = scircle1(assetLocations(a,1),assetLocations(a,2),(assetSpeeds(a)*timeLimit),[]
    geoshow(latc,lonc,'DisplayType','line','color','r');
    geoshow(assetLocations(a,1),assetLocations(a,2), 'DisplayType','point', ...
      'markeredgecolor', 'r', ...
      'markerfacecolor','r', ...
      'marker','s' ...
      );
end

% Low, medium and high
[n, bin] = hist(emPrep2, 3);
% Find bin ranges
binWidth = bin(2)-bin(1);
binMin = bin - binWidth/2; binMin(1) = 0;
binMax = bin + binWidth/2;

% hotspotCategory holds the category for each zone that can be used to
% color the zones in the map later
prepCategory = zeros(numCols*numRows,1);
prepCatNum = zeros(3,1);
for i = 1:numZones
   if (emPrep2(i) < binMin(2)) % Category 1
      prepCategory(i) = 1;
      prepCatNum(1) = prepCatNum(1)+1;
   elseif (emPrep2(i) < binMin(3)) % Category 2
      prepCategory(i) = 2;
      prepCatNum(2) = prepCatNum(2)+1;
   else % Category 3
      prepCategory(i) = 3;
      prepCatNum(3) = prepCatNum(3)+1;
   end
end


zone = 0;
for row = 1:numRows
   uLat = latLim(2) - ((row-1) * zoneLat);
   lLat = latLim(2) - (row * zoneLat);
   for col = 1:numCols
      lLon = lonLim(1) + ((col-1) * zoneLon);
```

```
        uLon = lonLim(1) + (col * zoneLon);
        zone = zone + 1;
        if (prepCategory(zone) == 1) zonecolor = 'g'; end
        if (prepCategory(zone) == 2) zonecolor = 'y'; end
        if (prepCategory(zone) == 3) zonecolor = 'r'; end
        if (noCover(row,col) == 1) zonecolor = 'k'; end

        p = patchm([uLat uLat lLat lLat],[lLon uLon uLon lLon],zonecolor);
        set(p,'FaceAlpha',0.8);

    end
end
```

D Matlab code for visualizing results

Listing 4: Matlab code for visualization of the solutions on a map

```
% Matlab script to map results

%% Mapping the results
%
figure;
% Boundinbox that limits what map data that is read
boundingbox = [5 60; 30 74];

% Lat — lon limits for map view
mlatLim = [63 73];
mlonLim = [6 32.5];

% mlatLim = [65 68];
% mlonLim = [12 16];

worldmap(mlatLim,mlonLim); % Use for maps that show more detail in

% interesting area
%worldmap('Norway'); % Use for showing the maps explaining things more in
%general

%% Read map data

% Shorelines fetched from
% http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html
% i is intermediate quality, c is crude.
%land = shaperead('./Map/GSHHS_shp/i/GSHHS_i_L1.shp','BoundingBox',boundingbox, 'UseGeoCoords',
land = shaperead('./Map/GSHHS_shp/c/GSHHS_c_L1.shp','BoundingBox',boundingbox, 'UseGeoCoords', t
%worldmap('Norway')
% Show land mass as yellow
h = geoshow(land, 'FaceColor', 'y');


%% Plot all the ship positions on the map
for i = 1:size(shipList,1)
```

```
    geoshow(shipList(i,3),shipList(i,4), 'DisplayType','point', ...
        'markeredgecolor', 'r', ...
        'markerfacecolor','r', ...
        'marker','.' ...
        );
end

%% Plots all risk areas in the list by drawing a red circle with the correct
% size
for i = 1:size(zoneRiskSpots,1)
    [latc,lonc] = scircle1(zoneRiskSpots(i,1),zoneRiskSpots(i,2),zoneRiskSpots(i,4),[],earthRadius('nm'))
    geoshow(latc,lonc,'DisplayType','line','color','r');
end

%% Plot all zone centers of gravity
for i = 1:numZones
    geoshow(zoneCG(i,1), zoneCG(i,2), 'DisplayType','point', ...
        'markeredgecolor', 'b', ...
        'markerfacecolor', 'b', ...
        'marker', '.' ...
        );
end

%% Draw all the zone grids on the map with colors corresponding to their criticality category
zone = 0;
for row = 1:numRows
    uLat = latLim(2) - ((row-1) * zoneLat);
    lLat = latLim(2) - (row * zoneLat);
    for col = 1:numCols
        lLon = lonLim(1) + ((col-1) * zoneLon);
        uLon = lonLim(1) + (col * zoneLon);
        zone = zone + 1;
        if (hotspotCategory(zone) == 1) zonecolor = 'g'; end
        if (hotspotCategory(zone) == 2) zonecolor = 'y'; end
        if (hotspotCategory(zone) == 3) zonecolor = 'r'; end

        % If the zone is a location, the grid is drawn with opacity =0.3,
        % otherwise opacity=0
% if (zoneIsLocation(zone) == 0)
% alpha = 0.0;
% else
```

```
% alpha = 0.3;
% end

      % Draw a rectangle covering the zone with the zonecategory color
      p = patchm([uLat uLat lLat lLat],[lLon uLon uLon lLon],zonecolor);

      set(p,'FaceAlpha',0.3);
   end
end


%% Draw the asset coordinates with blue dots and the facility number next to them
a = [1:numAssets]';
b = num2str(a);
c = cellstr(b);

% Asset locations -- that is the new location as returned by the model
% Make sure they correspond to the correct asset

% For lat/lon-size=2
assetLocations = [
   zoneCG(27,1) zoneCG(27,2);
   zoneCG(9,1) zoneCG(9,2);
];
% for lat/lon-size=0.5
assetLocations = [
   zoneCG(471,1) zoneCG(471,2);
   zoneCG(127,1) zoneCG(127,2);
];
for i = 1:numAssets
   latCoord = assetCoordinates(i,1);
   lonCoord = assetCoordinates(i,2);
   offset = 0.2;

   geoshow(latCoord,lonCoord, 'DisplayType','point', ...
      'markeredgecolor', 'k', ...
      'markerfacecolor','g', ...
      'marker','o' ...
      );

   textm(latCoord+offset, lonCoord+offset+0.3, c(i), 'BackgroundColor', 'white');
```

```
    % 'FontSize', 12

    % Coordinates for track
    wp = [
       latCoord lonCoord;
       assetLocations(i,1) assetLocations(i,2);
       ];
    % Find track
    [rhlatTrack,rhlonTrack] = track(wp);
    plotm(rhlatTrack,rhlonTrack,'k','linestyle','-','linewidth',2);

    geoshow(wp(2,1),wp(2,2), 'DisplayType','point', ...
       'markeredgecolor', 'k', ...
       'markerfacecolor','r', ...
       'marker','s' ...
       );

    textm(wp(2,1)+offset, wp(2,2)+offset+0.3, c(i), 'BackgroundColor', 'white');

end

%% Find facility capacity

% Unconstrained capacity means that all hotspots should be possible to
% service from one facility. Thus the sum of all the demand is an OK value
% to use as "big M" but we fill out a matrix with values so that the
% printing to file will be the same even if this changes
assetCap = zeros(numAssets,1);
for i = 1:numAssets
    assetCap(i) = sum(hotspotValue);
end

%% Calculate distance from locations to zones
locationZoneDistances = zeros(numLocations, numZones);
for i = 1:numLocations
    for j = 1:numZones
       locationZoneDistances(i,j) = distTwoPoints(zoneCG(i,1:2),zoneCG(j,1:2));
    end
end

% Fixed cost for assets in locations
```

```
fixedCost = zeros(numAssets, numLocations);
for a = 1:numAssets
   for l = 1:numLocations
      fixedCost(a,l) = distTwoPoints(assetCoordinates(a,1:2), zoneCG(l,1:2));
   end
end


[latc,lonc] = scircle1(71,25,180,[],earthRadius('nm'));
   geoshow(latc,lonc,'DisplayType','line','color','r');
```

E

List of vessels in test case

Table 7: List of vessels in scenario

Speed[kn]	Heading	Latitude	Longitude	Type
14.00	19	64.41	10.4	2
15.70	18	64.89	5.65	3
6.30	155	64.49	10.09	1
1.00	278	64.56	10.2	1
7.50	297	64.63	10.36	1
7.00	138	64.5	10.49	1
14.80	194	65.16	11.8	2
10.10	341	65.23	11.94	2
11.30	6	65.24	11.87	2
13.20	199	65.68	12.24	3
12.50	142	65.59	12.27	2
11.70	135	65.77	12.55	2
10.10	16	65.79	12.33	1
11.90	289	65.94	12.33	2
10.30	245	66.03	12.38	1
10.50	272	66.18	12.77	2
6.80	177	66.2	12.77	1
13.60	90	66.36	12.71	2
9.60	44	66.38	12.44	1
9.60	225	66.47	12.77	1
0.90	51	66.46	12.97	1
18.90	155	66.5	12.93	2
11.70	184	66.5	13.22	2
9.40	296	66.64	13.09	2
7.30	13	66.8	13.26	1
10.10	219	66.99	13.39	1

Continued on next page

Speed[kn]	Heading	Latitude	Longitude	Type
13.20	218	66.55	11.14	3
6.30	216	67.06	14.07	2
16.80	305	67.4	13.6	2
8.30	318	67.44	14.78	2
17.90	321	67.71	13.39	2
27.70	27	67.6	14.65	2
1.20	168	68.15	12.91	1
2.50	304	68.49	12.71	1
9.00	1	68.18	14.17	1
6.10	261	68.2	15.4	1
7.60	41	68.05	16.07	2
15.00	334	68.27	16.05	2
14.10	179	68.32	16.01	2
10.60	100	68.67	16.02	2
1.90	16	68.88	15.29	1
11.20	228	68.87	15.5	1
6.30	14	68.84	16.48	2
7.90	211	68.84	16.88	1
8.90	94	68.73	17.37	1
9.70	327	69.16	15.08	1
11.80	253	69.15	17.8	1
3.90	145	69.67	16.19	1
14.00	37	69.76	16.39	1
10.40	249	69.54	18.52	1
9.30	176	69.85	18.61	2
14.80	8	69.75	19.05	2
9.90	76	69.78	19.13	1
8.90	68	69.78	19.25	1
5.70	145	69.96	19.62	2
8.50	271	69.57	20.2	2
6.60	205	69.59	20.3	1

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Speed[kn]	Heading	Latitude	Longitude	Type
4.20	203	69.6	20.4	1
6.60	174	69.79	20.41	1
10.00	72	69.78	20.61	2
16.20	236	69.93	20.9	2
8.40	69	70.04	20.84	1
7.20	14	69.92	21.05	1
7.90	315	70.2	20.8	1
8.10	249	70.4	20.83	1
11.40	169	70.3	22.28	2
9.60	355	70.2	23.4	2
6.60	291	70.24	22.34	2
6.20	131	70.36	22.87	1
7.30	229	70.53	22.02	1
6.60	148	70.6	21.51	1
0.90	329	70.61	21.61	1
11.10	60	70.65	21.74	1
7.50	28	70.62	21.95	1
12.70	210	70.72	21.18	1
8.00	218	70.5	23.03	1
10.60	235	70.7	22.13	1
7.20	38	70.6	23.4	1
7.60	3	70.7	236	1
7.50	131	70.85	23.34	1
9.00	309	70.8	22.79	1
9.70	287	70.8	22.4	1
2.40	169	70.9	21.08	1
12.20	66	71.1	22.1	1
8.70	265	70.9	24.45	1
7.30	299	71	24.54	1
7.30	169	70.96	25.03	1
6.90	198	70.96	25.29	1

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Speed[kn]	Heading	Latitude	Longitude	Type
9.60	324	71.13	24.97	1
7.30	230	71.18	24.93	1
7.80	101	71.1	25.3	1
8.60	21	71.1	25.4	1
7.60	66	70.9	25.86	1
5.60	235	70.97	26.09	1
6.50	255	71.04	25.9	1
5.90	219	71.05	25.88	1
3.50	89	71.39	25.69	1
8.90	245	71.01	26.46	1
6.30	68	71.04	26.73	1
13.70	76	71.65	25.48	3
3.90	200	71	26.8	1
1.70	36	71.1	27.25	1
6.50	72	71.1	27.4	1
10.00	57	71.1	27.4	1
7.90	12	71.1	27.3	1
8.80	49	71.1	27.5	1
9.20	80	71.1	27.6	1
9.00	219	71.72	28.33	1
1.50	307	71.2	28.17	1
8.50	4	71.1	28.31	1
0.70	8	71.1	28.36	1
8.30	306	71.03	28.56	1
0.80	133	71.07	28.72	1
6.50	186	71	28.7	1
7.10	37	71	28.9	1
1.00	119	70.8	29.3	1
0.60	37	70.9	29.41	1
2.40	107	70.87	29.51	1
0.70	329	70.8	29.48	1

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Speed[kn]	Heading	Latitude	Longitude	Type
0.70	178	70.8	29.4	1
8.70	104	70.8	29.69	1
14.70	217	70.67	29.8	2
12.20	19	71.04	27.82	2