NTNU – Trondheim
Norwegian University of
Science and Technology

Planning and disruption challenges in the logistical offshore supply chain based on a simulation model

Gry Mehlgård Oleivsgard

Marine Technology
Submission date: June 2013
Supervisor: Bjørn Egil Asbjørnslett, IMT

Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS 2013

for

Stud. Techn. Gry Oleivsgard

Background

Logistical planning in the offshore supply chain can be a real challenge. Multiple disruptions and incidents may happen in every segment of the chain without the planners being able to foresee situations that may arise. Re-planning tools that considers disruptions and uncertainties are well-designed, but they are often comprehensive and hard to use in an operational setting. Due to this, Statoil wants to start a process towards the development of a simulation program that will improve the re-planning of schedules due to unforeseen events and disruptions. This will be done by designing a less extensive simulator that uses shorter time to calculate new routes and in that way is better for operational use.

Overall aim and focus

The objective is to find the relation between events and uncertainty, and demonstrate the influence of disruptions on the supply chain. This will be done by first determining the main disruption contributors, their relation and possible impact on an offshore supply chain, and secondly to demonstrate the result in a simulation model.

The thesis will include a thoroughly event analysis where the major disruptive events, their relation and dependency will be identified. Event frequencies for all uncovered events will be found. A risk- and consequence analysis will be performed where both the direct- and secondary consequences will be the main focus. A set of scenarios will be defined and analyzed with the purpose of finding the probability for the most severe incidents.

A simulation prototype will be developed with the main purpose of creating a basis for further work. The prototype will be used to identify the measures and events it will be important to focus on in the development of an operational re-planning simulator.

Scope and main activities

1. Gather and structure statistics of events in the supply chain.
2. Build general knowledge on events and consequences.
3. Understand the relation between independent and dependent events and their direct and secondary consequences
4. Establish a selection of event scenarios. Consider various measures based on these scenarios.
5. Build a simulation model that can simulate events over a one-year perspective. The model should demonstrate the relationship between different events and their consequences.
6. Based on the simulation model, suggest measures for further development of the operational re-planning simulator.

General

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

Theories and conclusions should be based on a relevant methodological foundation that

Through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

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

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

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

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

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

Supervision:
Main supervisor: Professor Bjørn Egil Asbjørnslett
Co-supervisor: Marintek v/Grethe Ose
Company contact: Gisle Nygård
Deadline: 10.06.2013

Preface

This master thesis was written the spring of 2013 and is the finalization of the Master of Science degree in Marine Systems Design at the Norwegian University of Science and Technology, NTNU. The thesis is weighted as 30 credits.

The thesis includes an event analysis over the offshore supply chain and a simulation model that simulates the daily operation in this supply chain. The program MS excel is used for the event analysis and MATLAB is used for the development of the simulator. The author has worked consistently and independently throughout the semester.

The author would like to express gratitude to her thesis supervisor Professor Bjørn Egil Asbjørnslett for guidance throughout the semester, Gisle Nygård and Endre Vik from Statoil for access to Statoil data and Marintek for steadily monitoring throughout the semester.

Trondheim, 4th June, 2013

Gry M. Oleivsgard

Gry Oleivsgard

Abstract

The offshore industry is a dynamic industry with constant demand changes. This creates many challenges, one of them being logistical supply planning. The need changes fast and this makes it important to receive the deliveries when required. If not, the consequences can be severe and costly. The supply chain may experience disruptions that may cause delays of lesser or greater extent. If possible, delay reducing measures may be taken to reduce this delay to an acceptable level. There are many existing optimization tools for this purpose, but they are very extensive and have a long lead. The purpose of this thesis is to start a process towards developing an operational rescheduling simulator that is easier, faster and more user-friendly than the existing optimization tools.

The first part of the thesis considered a study over planning-and disruption challenges in the offshore supply chain. Statistics from Statoil were analyzed and it showed that quite a few disruptions happened before vessel departure from the base. Measures for reducing delays to an acceptable level are taken here. The most used measures are extra treatment on base, extra call on route and helicopter delivery. Transit is the segment where most delays occur; this is mainly due to weather situations. The delays under installation treatment (loading operations) were negligible. It is also at the installations the most severe consequences may occur. This is a result of multiple delays and failures in safety system, functions and barriers.

Furthermore, a thorough and comprehensive event- and risk analysis was performed for the purpose of identifying the major disruption contributors in the chain and their direct and secondary consequences. The information retrieved in this analysis was combined with the Statoil case and used to define accurate event frequencies for the uncovered disruptions.

The second part of the thesis contains the construction of a simulation model that imitates the daily operation in the offshore supply chain where disruptions occur and creates delays. Measures to reduce these delays were also implemented. The risk profile from part one was used in the simulator in order to create a reliable imitation of an offshore supply chain. The model was based on a fixed route, and does therefore not include all delay reducing measures. The model gives a good demonstration of the daily flow in the supply chain, but implemented simplifications weaken the level of realism in the model. Special consideration should be taken in terms of changing the impact calculation method of the model.

To make a simulator that will cover all characteristics uncovered in part one requires careful preparations, good programming skills and time. The extent of such a model exceeds the capacity of this thesis in all requirements mentioned above. In the areas where the model is insufficient, measures for further development have been proposed. The model presented in this thesis is merely a prototype with the purpose of demonstrating the mindset of the author and create a solid basis for further simulator development.

Sammendrag

Offshoreindustrien er dynamisk og behovsendinger forekommer kontinuerlig, noe som skaper utfordringer. En av disse er knyttet til planlegging av utstyrstransporten. Behovet for utstyr kan endre seg fort, og det er viktig at leveransene kommer når de skal hvis ikke kan konsekvensene være alvorlige og veldig kostbare. Samtidig kan forsyningskjeden oppleve mange forstyrrelser som kan forårsake forsinkelser. I noen tilfeller må tiltak implementeres for å redusere disse til et akseptabelt nivå. Det finnes mange programmeringsverktøy som er til for dette formålet, men de fleste er veldig omfattende og bruker lang tid på sin re-planlegging. Formålet med denne oppgaven er å starte arbeidet mot utviklingen av en re-planleggingssimulator. En simulator som er enklere, raskere og mer brukervennlig enn de nåværende optimeringsverktøyene.

Den første delen studerer planleggings- og forstyrrelses utfordringer i forsyningskjeden. Statistikk fra Statoil har blitt analysert, og den viser at mange forstyrrelser skjer før utstyret har forlatt basen. Her er tiltak for å redusere denne forsinkelsen tatt, og de mest brukte er ekstra behandlingstid av last etter åpningstid, ekstra installasjonsbesøk på en rute og helikopterleveranser. Det er i transitt til installasjonene at de fleste forsinkelsene skjer, og de fleste er grunnet værsituasjoner. På installasjonene derimot er forsinkelsene neglisjerbare. Dette gjelder først og fremst lasteoperasjonen. Det er på installasjonene at de mest alvorlige konsekvensene inntreffer. Dette er en kombinasjon av forsinkelse og svikt i sikkerhetssystemer og – barrierer.

Deretter ble en grundig risiko- og hendelsesanalyse har blitt utført med hensikt å identifisere de største forstyrrelsene og deres primære og sekundære konsekvenser. Disse resultatene ble kombinert med Statoil dataene for å danne et grundig hendelses- og risikobilde for en offshore forsyningskjede.

Den andre delen av oppgaven bestod av å skape en simuleringsmodell som beskriver den daglige operasjonen i en forsyningskjede der forstyrrelser oppstår og skaper forsinkelser. Videre er tiltak for å redusere forsinkelser implementert. Resultatene fra del en ble brukt for å skape en så pålitelig imitasjon av forsyningskjeden som mulig. Modellen er basert på en fast rute, og inkluderer derfor ikke alle forsinkelsesreduserende tiltak. Modellen gir en god illustrasjon over den daglige flyten i forsyningskjeden, men forenklinger tatt svekker realitetsgraden til simulatoren. Videre arbeid burde spesielt rettes mot å endre konsekvensberegningsmetoden.

Det å lage en simulator som dekker alle forstyrrelsene og tiltakene beskrevet i første del av oppgaven krever nøye forberedelser, gode programmeringskunnskaper og tid. Omfanget til en slik modell overskrider kapasiteten til denne oppgaven på alle overnevnte områder. På de områder der modellen er utilstrekkelig har tiltak for videreutvikling blitt foreslått. Modellen presentert i denne oppgaven er kun en prototype med formål å demonstrere tankemåten til forfatteren og skape en grundig og god basis for videre simuleringsutvikling.

Contents

List of Figures

List of Tables

Abbreviations

AHTS – Anchor Handling Tug Supply Vessel

ATA – Actual Time of Arrival

ATD – Actual Time of Departure

D&W – Drilling & Well

ETA – Event Tree Analysis

ETA – Estimated Time of Arrival

ETD – Estimated Time of Departure

HSE – Health, Safety and Environment

IPL – Integrated planning

IPP – Incident Probability Parameter

MO – Marine Operations Statoil

NWEA guidelines – For the safe management of offshore supply and rig move operations

OPS – Operational group Transocean Spitsbergen

OR – Operational Research

PHA – Preliminary Hazard Analysis

PSV – Platform Supply Vessel

Statoil Marin – Vessel Traffic Supervisor

TSP – Travelling Salesman Problem

VRP – Vehicle Routing Problem

WOP – Waiting on Platform

WOW – Waiting on Weather

“The future is uncertain. While it in some cases will be possible to have some knowledge about what is likely to happen, no one knows for sure what the future will bring.”

Elin Espeland Halvorsen-Weare

1. Introduction

After the discovery of Ekofisk in 1969 Norway has become a major exporter of oil and gas. Today multiple actors are operating offshore installations in the North Sea, Norwegian Sea and Barents Sea. This is an industry where everything is expensive, and it is crucial for an efficient operation that they receive regular supplies when needed. The storage capacity on the installation is limited and therefore supplies need to be stored on shore before they are used in operation. Companies like Statoil operate deposits along the Norwegian coast with the purpose of supplying the installation when needed. Supply vessels are mostly used for this transportation. The delivery of these supplies is thoroughly planned and monitored.

Logistical planning of the offshore supply chain can be a real challenge. Multiple disruptions and incidents may happen in every state without the planners being able to foresee situations that may arise. Planning tools that focuses on disruptions and uncertainties are well designed, but they are often comprehensive and hard to use in an operational setting.

1.1 The supply chain

The offshore business has a high activity level and is in a continuous need for supplies at the installations. The operational needs changes fast and equipment needed in the morning might not be needed in the afternoon. [1] The demand varies depending on the different operations at the installations, and the challenges associated with planning a realistic schedule and foreseeing possible disruptions are many. The consequences may be delays, high logistical- and operational costs and may in worst case affect the production. Below a short description of the supply chain is given.

The need in the different operations has to be identified before an operation can commence. When identified, an order is placed at a supplier for the production of the needed equipment. It is the supplier's responsibility to prepare the equipment for transportation. The equipment is transported when the operational group gives the go-ahead and then transported to the base. [2]

The supply bases are important hubs in the supply chain. The equipment for the installations is delivered to the base and distributed to the installations from here. The supply vessels are mobilized here. Therefore the base needs to have a complete overview over all the cargo being transported in the chain at any time, and has to be informed on all arriving cargo and when it is needed at its destination. Statoil has seven supply bases in Norway and around 20 vessels which perform in average three trips per week. One vessel visits multiple rigs in one trip. [3]

When arriving at the installation the offloading operation commences. This is a critical operation and planning- and safety routines need to be followed. This operation usually takes from 2-4 hours, but this is depending on the cargo being loaded. The installation has limited storage capacity, and therefore it is important to always have control over the equipment currently at the installation as well as the arriving cargo.

About 75% of the cargo taken out to is to be sent back to shore. [3] This cargo also needs to be reported to the base since total visibility on all the cargo currently in the chain is a criterion for the base success.

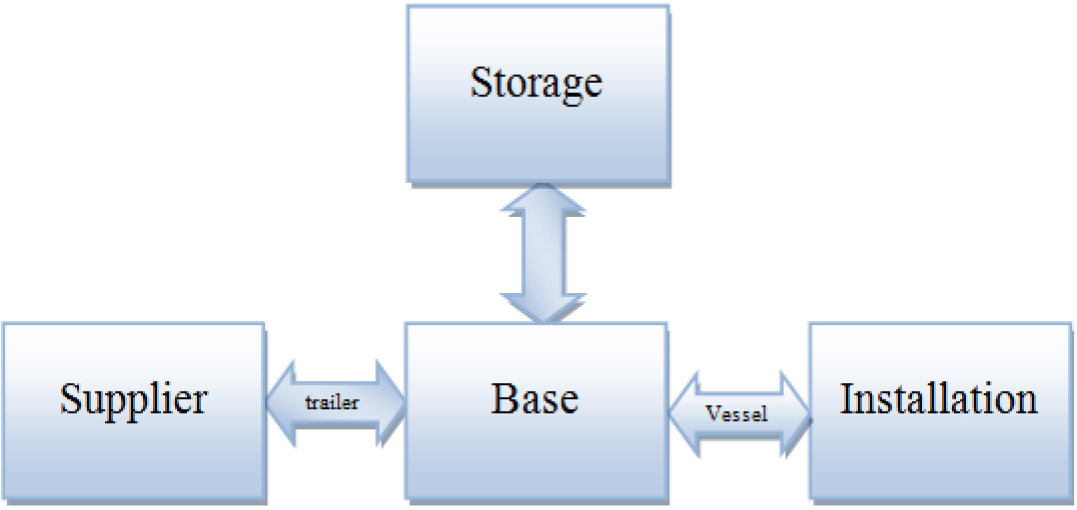


Figure 1 The supply chain

1.2 Objective and structure of the thesis

The work presented in this paper was performed on request from Statoil, The main task was to evaluate the supply chain with a focus on uncertainty and disruptions, and start the process towards making a simulation tool that will make re-planning in operational setting better and easier.

The thesis is divided in two main parts. The first part covers analyses over unforeseen events and disruptions in the chain, and the second part uses the result from part one to construct a simulation of the system with respect to disruptions.

The first chapter provides the reader with an introduction and the basic knowledge for the problem being addressed. The second chapter presents state of the literature for uncertainty planning and simulation. Chapter three contains a thorough mapping of the events that may occur in the chain. Chapter four contains an analysis of a Statoil case. It contains gathered data for an offshore supply chain, and is the basis for the event frequencies calculated. Chapter five contains event- and risk analyses performed and chapter six presents the incident data that is used in the simulator.

The second part of the thesis commences in chapter seven where probability distributions and impact calculation is explained. Chapter eight explains the structure in the simulator and how it works. The results from the simulator are presented in chapter nine. In chapter ten a final discussion is made where a sensitivity analysis of the system is performed and simulator improvement measures are given. Finally the conclusion and further work is presented. The results of the analyses have been discussed throughout the thesis, and are summarized in the latest chapters.

1.3 Special assumptions

This thesis analyses the chain from when the equipment leaves the supplier, and not from the identification of demands. The event analyses are based on data from Statoil. In the areas where this data has been inadequate, the values have been assumed based on similar values from other systems and logic.

A simulation model is developed. The focus is on event correlation understanding, and on demonstrating the relationship between events and consequences. Simplifications are made when developing this model. These are defined in section 8.3

The objective for the operational re-planning model is not to find an optimal solution, but a good solution in a short amount of time. The future model should focus on minimizing the total cost, customer satisfaction and computational time.

2. Literature study

This chapter contains a review of state of the art literature for the topics that will be presented in the thesis. The topics addressed are supply chain incidents, the influence of uncertainty in the supply chain, and the use of simulation for optimization purposes. This study has been limited to surveys, general articles and scientific papers limited by their relevance.

2.1 Events and risk

The supply chain concept and focus has developed since it was introduced by Christopher in 1992. [4] With the increased focus on the supply chain as a whole and less focus on the individual actors in the chain, there has been a natural increase of research regarding supply chain planning and possible risks and disturbances. Craighead et al. defines supply chain disturbances as *unplanned and unanticipated events that disrupt the normal flow of goods and materials within a supply chain*. As a consequence the actors within the chain are exposed to operational and financial risk. They further claim that supply chain disturbances are unavoidable and that all supply chains therefore are inherently risky. They have performed an extensive empirical research on supply chain disturbances and they have related the severity of supply chain disruptions to three supply chain design characteristics; density, complexity and node-criticality, and two supply chain mitigation capabilities; recovery and warning. These proportions define the vulnerability of a supply chain, and measures that may be carried out to reduce the occurrence of severe disruptions are suggested based on these criterions. The purpose of the proportions is to help companies to perform a systematic analysis over the severity in a supply chain, and to uncover the biggest risks and possibilities for disruptions. [5]

Kleindorfer and Saad define two broad categories of risk affecting the supply chain. The first is coordination risk; risk arising from coordination problems of supply and demand. The other is disruption risk; risk arising from disruptions in the supply chain activities e.g. weather, operational risks, accidents. They made a conceptual framework for analyzing disruption risk where the key issue addressed was the effect of alternative supply chain design options on the efficiency and robustness of the supply chain when exposed to various sources of disruption. [6] Kleindorfer and Saad also defined a two-fold approach to risk management, where the first part consists of the traditional identification, assessment, management of risk and emergency response. The second part of the risk analysis deals with disruption risk management, where the goal is to find cost-efficient risk measures that reduce the risk of disturbances. Two conditions are needed for an effective disruption analysis. The first is to identify the right approaches for the different decision environments, having in mind that in disruption risk analysis one size does not fit all. The second principle emphasizes the importance of information sharing, cooperation and coordination between the partners in a supply chain in regards to risk avoidance, reduction and preventive measures to maximize the outcome of the chain. Each industry must also base its approach on the possible disturbances in the different environments.

The offshore industry is characterized by a high degree of uncertainty, and in each of the different transportation states there is a mixture between unlikely events with fatal consequences and more likely events with less severe consequences. Some events are easy to foresee e.g. extreme weather, and some may be difficult to foresee e.g. the effect of financial crisis. A high degree of the uncertainty incidents are linked to port- or installation calls since loading and unloading are the most critical operations. [3] Bottlenecks and other capacity restrictions may also lead to a delay in the system. [7]

The maritime industry consists of multiple industry types, e.g. industrial liner shipping. The liner service is experiencing increased schedule unreliability because of a major increase in cargo volume and more complexity due to increasing capacity, reliability, time and cost requirements. [8] Notterboom has classified the disruptions that occur in the different segments of the chain into four states; terminal operations, port access, maritime passage and chance (mechanical problems, unexpected waiting etc.). The different disruptions that occur in these states will have different impact considering where they occur, and will lead to delays in the supply chain schedule. The quality of the different segments is measured in their reliability and vulnerability for possible disruption occurrences. [9]

Gkanatska has created a different categorization system. He divides the delays into two main groups; port delays and sailing delays. Some disruptions may occur in the port that may cause a delay for the vessel e.g. bottlenecks with the infrastructure, lack of service provision, breakdown of equipment while delays under sailing is often weather dependent or caused by delays on the vessel and not by other actors in the chain. [10]

Both Notterboom and Gkanaska use a structured method to describe the different events that may happen in liner shipping. This thesis will use a similar structure for its analyses where the disturbances will be divided after the segments they occur in.

2.2 Planning with uncertainty, in advance and rescheduling

There are a few papers that consider planning and logistics problems in the offshore supply chain and even fewer that consider these systems in light of uncertainty and possible disruptions that may arise in the chain.

Yu and Qi [11] have given a detailed discussion around uncertainty approaches in general and have divided these into two stages. The first stage is in-advance planning which consists of contingency planning, stochastic planning and robust optimization. The second stage is real time re-planning where a good example is disruption management. Many disruptions are rare and cannot be predicted in advance. Dealing with disruptions is a complicated decision process where quick algorithms that can find a good solution in a short amount of time when disruptions occur are wanted. [12] According to Mu et.al there is a clear trade- off between computing time and the quality of a solution, and algorithms developed should have a clear balance between these two factors.

In her doctor thesis Weare explains ways of simulating different systems for considering uncertainty in these systems. [7] Deterministic, stochastic and robust solutions are explained. Deterministic models describe the system flow well, but it does not directly consider uncertainty. Stochastic modeling considers uncertainty in systems, and is assumed to be a more realistic model. A drawback with this method is the need for accurate probability distribution. A more recent developed approach for describing uncertainty is robust optimization where the goal is to construct a solution that is feasible for all realizations of the uncertainty in a given system set. This method is also constructed based on probability distributions. With this method it may be easier to implement specific system restrictions, but it may produce inflexible and expensive results. [7] All these planning methods have their advantages and drawbacks. Optimization under uncertainty is difficult, and it is not easy to say what method should be preferred over another.

Weare has written papers on optimal planning of the offshore supply chain. One of the articles gives a good description on how voyage-based solution methods can be used to provide decision support in the supply vessel planning process, considering major uncertainty elements as weather impact on sailing and loading operations. This is a new solution where simulation is combined with optimization to create more robust fleet- and schedule solutions for the supply planning. [13]

Weare has also written an article that considers vessel scheduling with uncertainty for a LNG fleet. A simulation-optimization framework that imitates real life situations by incorporating a recourse action consisting of a re-route optimization procedure is developed with the purpose of analyzing different routing and scheduling strategies. [14]

Christiansen et al. has written an article based on a robust model that punishes solutions that are defined as risky. This article considers ship scheduling problem concerned with the pickup and delivery of bulk cargoes within given time windows. Ship schedules are found a priori. They are generated taking uncertainty and multiple time windows into account. The computational results show that robustness of the schedules can be increased at the sacrifice of increased transportation costs. [15]

Fagerholt et al. has written an article where uncertainty is considered by punishing the risky solutions. This is in situations where small deviations from the original plan will have severe consequences. The article considers the effect of night- closed installations for the supplement of offshore installations e.g. port arrivals close to the weekend are defined as risky since this may lead to the vessel lying in port over the weekend. To avoid this, the solution is punished in the objective function. [16]

Fagerholt has also proposed a decision support methodology for planning in tramp- and industrial shipping where the focus is on fleet size and mix. They proposed a method that combines simulation and optimization, where a Monte Carlo simulation framework is built around an optimization-based decision support system for short-term routing and scheduling. The method is tested on a real shipping case, and has provided the shipping companies with valuable decision support. [17]

List et al. has created a model for robust optimization for fleet planning under uncertainty based on a two-stage stochastic model. The model focuses on robust optimization using risk analyses to assess the impact of uncertainty. The model determine the optimal choices for varying levels of risk acceptance and support explicit decisions in regards of expected costs against different risks. [18]

Bidhandi et al. has proposed an integrated model for solving supply chain network design problems under uncertainty. They have made a stochastic model that consists of making strategic decisions of the design of the chain where the customer demand, the operational costs, and the capacity of the facilities may be highly uncertain. The goal is to satisfy customer demands while minimizing the sum of strategic, tactical- and operational costs. [19]

Mu et al. has written a review on a disrupted vehicle problem. They have suggested two tabu- search algorithms for disruptions that involve vehicle break downs. These algorithms take advantage of the original plan and a new routing plan is found within a limited time. [12]

Even though little research has been done on disruption management in the maritime industry, other transportation segments have done a lot of research considering in this area. This is especially true for the airline industry. This is because flight disruptions often include huge losses and because a major challenge is to not let disruptions affect the passenger loyalty. [12] This is difficult since there only are a few factors the airline can control to gain competitive advantage. One of the areas where the airlines can be responsive is by detecting problems early and preventing these to affect the schedule. [20]

The airline industry is one of the most successful examples of applying operation and research methods for planning and scheduling of resources. In this industry optimization-based decision support tools have proven to be cost efficient for rescheduling of crew, aircrafts and short term rescheduling of the current schedule. [21] Clausen et al. has written a review over disruption management in the airline industry where they present many different disruption management strategies. There are many current ways to solve these recovery problems, but Clausen et al. also state that disruption management probably will achieve more and more interest in the years to come, especially linked to transportation and logistical systems e.g. Offshore supply chains.

A disruption management model for aircraft recovery was designed by Rosenberg et al. This model is set up as a set packing problem, and the objective is to reschedule legs and reroutes aircrafts by minimizing the costs. The objective function involves rerouting and cancellation costs.

Another transportation segment which has conducted disruption research is the railway passenger industry. Disruption management in the railway industry is less studied than in the airline industry since the cost of disruptions are considerably less in the railway industry. [22] One of the most recent articles was written by Jespersen- Groth et al. and describes the different actors in a supply chain and their roles in the supply chain totality. They divide the industry into three different main areas; timetable, rolling stock and crew rescheduling. Each of these main groups is given different focuses in regards to disruption management planning. [23]

When a disruption that causes a delay occurs the schedule needs to be recovered. Rezanova & Ryan have defined a set partitioning problem in the railway industry to solve this problem. The LP relaxation of the set partitioning problem is solved with a dynamic column generation approach with the limited subsequence strategy and expanding disruption neighborhood for solving the set partitioning problem is suggested. [22]

Xu et al. has used disruption management to model and optimize a dynamic supply chain system. They assumed that the demand is a nonlinear decreasing function, and based their case on a deterministic demand.

2.3 Simulation

In the article *integrating optimization and simulation* Yu-Chi Ho states that there is no question that simulation is the only generally applicable modeling tool for truly complex systems, natural or human made. [24] Simulation in operational research involves developing a design or operation procedure for a stochastic system. The system uses probability distributions to randomly generate events that can occur. The main purpose is to imitate the performance of the real system in a realistic way. [25]

Terzi et al. has computed an article review with the goal of ascertaining the main objectives of simulation. Their concluding remarks was as the supply chains grows more and more complicated, simulation will play an important role in supply chain management because of its ability to provide what-if analyses leading to better planning decisions, to permit the comparison of various solutions without interruption the real system and to permit time compression for the development of time policies. [26] A draw back with the use of simulation may be the need for a long computational time to find the optimal solution. Therefore a heuristic might be used instead of an optimization program. [24]

The integration of optimization and simulation has become common and most discrete-event simulation includes some type of optimization routine. The field of optimization simulation concerns the use of simulation to design and optimize systems. Some examples of research areas that use simulation and optimization are presented below.

Cheng and Duran consider a worldwide crude oil supply chain. They have designed a decision support system that improves the decisions for a combined inventory and transportation system. The system is a combination between discrete- event simulation and stochastic optimization. [27]

Shyshou et al. has made a simulation study for a fleet sizing problem. The problem is from anchor handling operations where weather conditions and future spot prices raise uncertain situations. The operations are unevenly spread out through the year, and the specialized vessels are hired on long-term charter. The solution is a simulation- based decision tool that provides cost optimality. [28]

In the airline industry the use of simulation models is a common used method to solve disruption management planning problems. This industry is well known for their use of simulation to verify their optimization models e.g. Rosenberg et al. and Clausen et al.

Another example is SimAir, a simulation model developed by Rosenberger et al. This is a modular airline simulation that simulates the daily operation of a domestic airline with the purpose of evaluating the air schedules and recovery policies. It does not explicitly cover the sources of delay. Instead an event generator uses an aggregate distribution for additional flight and ground time.

The use of simulation modeling for solving disruption management problems in the offshore is not as recognized as in the air industry yet. Some of the articles described above like the reviews written by Weare, Christiansen and Fagerholt are examples of just this. Fagerholt et al. has also written a review that combines simulation and optimization for strategic planning in shipping. [17]

3. Potential incidents causing delays

In this chapter an incident analysis over the different supply chain segments will be performed. The different incidents that can arise in the supply chain and their consequences will be discussed. There will also be a focus on the correlation between different incidents.

Throughout the whole supply chain there are many incidents that may arise and result in delays. Weather, traffic accidents, human errors, mechanical problems and priority deliveries are among the top reasons for the presence of uncertainty risk. Disruptions may occur anywhere in the chain, and the impact is dependent on where in the chain they occur. In this thesis the chain is divided into cargo operating segments where the disruption may occur. These cargo operating segments are defined below, and their flow described in figure 2:

- Production
- Transportation on land
- At base
- Transit to installation
- At installation
- Return-transit to base

Figure 2 Cargo-operating segments in the supply chain

As mentioned, there are many possible situations that may arise from an incident. The consequence can range from negligible to extremely severe. This analysis has defined a set of different impacts that may arise from the different incidents. They are:

- Cargo damage
- Delayed delivery
- Non-delivery of cargo
- Misdirected cargo
- Ahead of schedule
- HSE damage
- Cargo sent with separate ship/helicopter
- Re-planning of sailing route

- Cargo sent with next departure
- Reduced production at installation
- Production stop
- Economic loss
- Operational stop
- Loss of well control
- Priority delivery

Cargo damage is disruptions that cause damage on the cargo being delivered. This may lead to a need for repair or reorder of equipment. *Delayed deliveries* are when the cargo is delivered to a segment later than scheduled. In most situations this will not have any severe consequences, since the delayed time may be reduced in the next segments in the chain. If there is an extreme delay when the cargo has reached the installation, then it may develop into severe consequences like r*educed production at installation, production stop, operational stop, loss of well control* and *great economic loss*. These impacts, defined in this thesis as secondary consequences, and are explained in section 3.5.1

Non- delivery is situations where disruption lead to equipment not being delivered, e.g. if a fire occurs on a vessel and the cargo burns. *Misdirected cargo* is delay caused by the cargo being sent wrongly, e.g. to a storage or another installation.

A different consequence can be *vessel being ahead of schedule* e.g. if the vessel is fully loaded and ready before estimated time of departure. This will rarely lead to any negative consequences for the chain. An exception being when rented equipment is sent early to the base and causes extra rental costs.

Measures may be taken to deal with the delays that have occurred in the earliest segments. *HSE damage* is incidents that may have consequences for the health and safety of the personnel involved, or for the environment. These are among the most severe consequences.

When the cargo has reached the base it may be sent to the installation as *priority delivery*. In this analysis this is defined as a rescheduling of sailing plan or sending the cargo with a separate ship or helicopter. Priority delivery may also be solutions like extra treatment time at the base, but in this analysis this is included in delayed delivery.

3.1 Production

Most of the needed supplies are sent from the supplier and delivered to a base for further transportation. This analysis only considers transportation disruptions; therefore no specific incidents are presented for the production segment.

3.2 Transit to base

Deliveries of supplies by trailers are the most commonly used transport mean on shore.

The transit to base is the least controlled part of the supply chain. The planner on the installation follows up the transport, but this is done in direct contact with the supplier and not through any computerized tool. This makes tracing of the cargo difficult, and causes uncertainty regarding when the equipment will be delivered and whether it will be delivered to the base in time to reach its intended ship. [1].

Most of the delays that may occur in this segment are either in relation to queue, closed tunnels or other changes in the highway conditions. The most severe incidents would be accidents that may damage the cargo or lead to fatalities. The table below presents the most common reasons for delays during land transport and their impact on the schedule.

Transit to base		
	Incident	**Consequence**
1	Queue	Delayed delivery
2	Closed roads	Delayed delivery
3	Closed tunnels	Delayed delivery
4	Collision	Delayed delivery
5	Collision	Cargo damage
6	Collision	HSE damage
7	Damaged under transport	Cargo damage
8	Destroyed under transport	Non- delivery
9	Engine problems	Delayed delivery
10	Break down of vital trailer parts	Delayed delivery
11	Extreme weather	Delayed delivery
12	Driving wrong	Delayed delivery
13	Slippery roads	Delayed delivery

Table 1 Incidents in transit to base

3.3 At base

Most of the base incidents occur in conjunction with arrival of cargo or departure from the base. The loading operations are critical operations where the chances of disruptions increase compared to the remaining base treatment. Some base incidents are direct consequences of disruptions in the previous segments. If the cargo is poorly marked, poorly packed or poorly treated at the supplier, the consequences will manifest themselves during base handling.

For the arrival, the main rule is that deliveries have to be at the base before 12.00 am on the sailing day. If they do not make this time limit they have to report to the base. This is because it is an advantage to early be able to evaluate if any measures has to be implemented to reduce the delay. All delay reducing measures are mainly taken at the base. These decisions depend on the criticality of the delayed delivery compared with the rest of the cargo. The supply vessel can either leave without the delayed cargo or wait for it to arrive. Alternative transportation with a different vessel or a helicopter may also be arranged.

Other incidents may occur at the arrival on the base. The arriving trailers may collide in the base area, the cargo can be poorly treated or misdirected by the base personnel and if equipment is delayed from the supplier then the base personnel may need to stay after opening hours to treat the late arriving cargo.

The supply vessel incidents may also cause disruptions at the base. The vessel may arrive late at the base and delay the next departure, the crew personnel may be delayed, the vessel may collide in harbor or experience technical problems that make it impossible for it to leave the base harbor, bad weather conditions may not allow the vessel to departure from base etc.

All of these events above are incidents that may result in delays of major and minor scale. They are all presented with their direct impact in table 2.

Base treatment incidents		
	Incident	**Consequence**
1	Poor marking of cargo	Misdirected cargo
2	Poor treatment of cargo	Cargo damage
3	Poor treatment of cargo	Non delivery
4	Early arrival at base	Ahead of schedule
5	Collision in base area	Delayed delivery
6	Collision in base area	Non delivery
7	Extra treatment of cargo at base after opening hours	Delay
8	Early departure from base	Ahead of schedule
9	Delayed departure from base	Delay
10	Vessel waiting on late cargo	Delay
11	Collision in harbor	Delayed delivery
12	Collision in harbor	Non-delivery
13	Improper loading of ship	Delay
14	Late arrival of vessel till base	Delay
15	Late arrival of crew	Delay
16	Waiting on weather base	Delay
17	Break down on vital parts of the ship	Delay
18	Congestion	Delay
19	Change of sailing plan: Priority deliveries	Economical costs
20	Labor strike at base	Delayed delivery
21	Labor strike at base	Non delivery
22	Delayed cargo from supplier	Delayed delivery
23	Delayed cargo from supplier	Re-planning of sailing plan
24	Delayed cargo from supplier	Cargo is sent with next vessel
25	Delayed cargo from supplier	Cargo is delivered with separate ship
26	Delayed cargo from supplier	Cargo is delivered with helicopter

Table 2 Base treatment incidents

3.4 Transit to installation

Many events may occur during transit to the installation. This is the entity with the most delays, and if a delay occurs in this entity there are no external solutions that can reduce a delay.

Transit to installation		
	Incident	**Consequence**
1	Change of sailing plan: priority deliveries	Delayed (on their installations)
2	Extra call for supply ship	Delayed (on their installations)
3	Machinery problems	Delayed delivery
4	Machinery down	Delayed delivery
5	Break down of vital parts of the ship	Delayed
6	Fire onboard	Delayed, cargo damage
7	Fire onboard	Cargo damage
8	Man over board	Delayed
9	Sickness onboard	Delayed
10	Waiting on weather installation	Delayed
11	Waiting on weather base	Delayed
12	Waiting on platform	Delayed
13	Extreme weather	Delayed
14	Collision (with other vessels)	Delayed
15	Collision (with other vessels)	Non delivery
16	Grounding	Delayed
17	Grounding	Non delivery
18	Ships nearby in distress	Delayed
19	Early departure from base	Ahead of schedule
20	Early departure from other installations	Ahead of schedule
21	Delayed departure from base	Delayed
22	Delayed departure from other installations	Delayed
23	Too low tide at base	Delay
24	Late arrival of vessel	Delay
25	Early arrival of vessel	Ahead of schedule
26	Waiting on weather installation	Delay
27	Collision in harbor	Delayed
28	Collision in harbor	Non delivery
29	Labor strike at base	Delayed unloading
30	Labor strike at base	Non delivery
31	Late offloading	Delay
32	Late unloading	Delay

Table 3 Incidents in transit to installation

Weather is the main reason for delays during transit mode. The weather can be too bad to leave the base port, or too bad to lay deck alongside the installations. This may lead to the supply ship waiting on weather close by the installation or alterations in the sailing plan in regards to changing the order of installation visits. [3]

The vessel might also experience disruption during the transit. Machinery problems, fire onboard, disease in the crew and other similar situations that affect the vessels ability to keep the schedule or continue the trip. Collisions with other ships or installations and grounding are also potential risks for the vessel.

The vessel may also arrive or depart late from the installations on a trip, and this may lead to delays for the installations waiting on equipment. It is normal to include some slack in the transit schedule to make sure that this does not happen. The slack included depends on the season. [29]

3.5 At installation

It is in this segment of the chain the consequence of delays or other events turn visible, and the most severe operational consequences may arise.

There is a lot of uncertainty factors related to having the vessel laying alongside the installations. First of all, the ship has to be allowed to enter the 500 m safety zone of the vessel. If the weather does not allow offloading a delay may occur at the installation while waiting for the operation to commence. There is also a risk for the operation being aborted during loading because of the weather. The operation will then be temporarily stopped and restarted when the weather allows it. Night closed installations may also create unnecessary disruptions since these installations are sensitive for changes in the schedule.

The lifting operation is the most critical activity in the supply chain, and good planning reduces the time and risk of this operation [3]. Technical problems with the crane equipment may arise, and if this is not fixed in a reasonable amount of time then the consequences may be severe. The installation treatment disruptions can be found in table 4.

At installation		
	Incident	**Consequence**
1	Waiting on platform	Delayed delivery
2	Extreme weather	Delayed delivery
3	Extreme weather	Non- delivery from this vessel
4	Abort of loading due to bad weather	Delayed delivery
5	Crane equipment down	Delayed delivery
6	Crane equipment down	Non-delivery
7	Break-down of equipment	Reduced production at installation
8	Break-down of vital equipment	Priority delivery
9	Break-down of vital equipment	production stop
10	Night-closed installations	Delayed delivery
11	Delay to night closed installations	Re-planning of sailing plan
12	Poor placement of already delivered equipment	Delayed delivery
13	Full deck	Delayed delivery
14	Full deck	Non-delivery
15	Wrong delivery because of bad marking	Delayed delivery
16	Collision with installation	Delayed delivery
17	Collision with installation	Possible production stop at installation
18	Collision with installation	Reduced production at installation
19	Labor strike	Delayed delivery
20	Labor strike	Non-delivery of cargo
21	Extra lay time at installations for supply ship	Delayed delivery

Table 4 Installation treatment incidents

3.5.1 Secondary consequences

As mentioned previously it is on the installation that the most severe consequences for the supply chain may occur. When major delays affect the operation or for any reason not delivered to the installation then probability for these consequences to occur increases. This is defined as secondary consequences since they can never be the direct consequence of one disturbance in the chain. The secondary consequences are presented in table 5.

If equipment does not arrive on time or if it is not repaired in time, there is a risk of operational stop, production stop and loss of well control may arise. This will lead to severe economic consequences for the operator. The risk of leakage may also be present.

HSE damage includes damages that may affect the safety of the personnel and the environment. Potential harm on human lives is a constant risk throughout the chain and not only in the last entity. Risk of human lives and environmental damage are the most severe consequences in the chain since this will affect other people and not only the operator.

Severe secondary consequences	
Incident	**Consequence**
HSE damage	Extreme economical expenses, Environmental damage
Stop/loss of production	Extreme economical expenses
Risk of Stop/loss of production	Extreme economical expenses
Stop in well operation	Extreme economical expenses
Risk of stop in well operation	Extreme economical expenses
Loss of well control	Extreme economical expenses
Environmental accidents	Extreme economical expenses, Environmental damage

Table 5 Severe secondary consequences

3.6 Return transit

The incidents that occur on the return transit to the base are mainly the same as in transit to and in between the installations. The difference in is the lack of certain risks related to operational delays.

Return transit		
	Incident	**Consequence**
1	Urgent return due to storage shortage at installation	Ahead of schedule
2	Early departure from installation	Ahead of schedule
3	Delayed departure from installations	Delayed
4	Waiting on weather base	Delayed
5	Machinery problems	Delayed delivery
6	Machinery down	Delayed delivery
7	Break down of vital parts of the ship	Delayed
8	Fire onboard	Delayed
9	Fire onboard	Cargo damage
10	Man over board	Delayed
11	Sickness onboard	Delayed
12	Extreme weather	Delayed
13	Collision (with other vessels)	Delayed
14	Grounding	Delayed
15	Ships nearby in distress	Delayed

Table 6 Return transit

3.7 Handling measures for dealing with delays

To be able to prevent or reduce the possible delays, handling measures needs to be defined. As mentioned, most of these measures are decided and implemented at the base. In this chapter, the measures Statoil use on a daily basis is presented.

The corrective measures performed are dependent on the criticality of the equipment, the size of the equipment and the length of the delay. Every measures means an additional cost, and as long as the cost of the preventive measure is less that the possible economical cost of the delay, the operator will do what he can to reduce the delay as much as possible. The offshore supply chain is an industrial supply chain, where the operator is involved in all aspects of the chain and the goal is to minimize the total cost of the chain [30]. Therefore the operator must consider the total cost of an alternative delay for all of the involved installation and not only an installation with a need.

3.7.1 Priority delivery

Priority delivery is when a delivery needs to get to the installation in the fastest possible way, with the goal of reducing the probability of down time at the installation as much as possible. It is a solution for situations where incidents cause delays that may have a consequence for the production at the different installations, which in turn will have a great economical consequence. [3]

Priority delivery is not an economical viable solution for the operator since they have a much higher transportation cost than preordered deliveries. It is a solution which is mainly used as a last resort in situations caused by delays in the chain or by unforeseen incidents occurring on the platform. An exception is when equipment has such high rental costs that is economical viable to hold the transportation until the equipment is needed, and then transport it as a priority delivery. This is called a tactical priority delivery. This is often an economically good move for the given installation, but is not desirable for the chain since it may cause delay for other installation leading to greater expenses for the chain in total.

Logistically priority is a bad phenomenon. First of all, a major part of the priority cargo is equipment that does not reach the base on the intended time or is reported late. This cargo makes it difficult for the base to predict what is going out with the ship. Secondly, if a shipment is priority accepted, but the ship is fully loaded, another cargo unit must be loaded off in order to accommodate the priority equipment. This also makes the departure planning difficult. Thirdly, re-planning of a sailing schedule can make the vessel tour very sub-optimal by making the ship go back and forth in between installations that are distant from each other instead of taking a direct route.

The priority system is in some cases essential for the operations at one installation, but a change in the cargo- and sailing plan will also affect the other installations on a trip. The consequences of the change for other installations may have an equal impact as for the rig with the critical need. [1]

It is often more than one installation that has applied for priority. In these cases the base often let the installations decide in between them who have the greater need.

3.7.2 Vessel delays

Priority deliveries cannot be used on delays arising in vessel transit. Other preventive measures therefore need to be implemented for these situations.

As described in section 3.4, weather is the main reason for delays with vessel transportation. There are no preventive measures for this delay since we cannot control the weather. This, combined with vessel transport being the last transportation segment in the chain, is the main reason for why vessel transportation causes the highest number of delays in the chain.

One way to reduce transit delay is to increase the speed of the vessel. This leads to a higher transportation cost since a ship uses more fuel per distance when it is sailing with a higher speed. [31] Furthermore, a possible consequence may be a production stop, and that is extremely more costly than higher fuel expenses [32].

3.7.3 Other delay reducing measures

Some of the installations are closed at night. They do not produce and they cannot receive deliveries outside the normal opening hours. To increase the productivity then there should be a possibility of extending the opening hours on these installations.

4. Statoil case analysis

A study of delays in Statoil's offshore supply chain is performed. The analysis is based on data retrieved from Statoil for a one-year period. These data contains information on the estimated- and actual sailing routes, the actual schedule and route for all of the Statoil supply ships and priority deliveries. This analysis examines this data in regards of the proportion of delays, reasons for delays and actions performed to reduce or prevent delays.

4.1 Delays

The data retrieved provided delay information for vessel transportation only. It gave information for three segments: Departure from base, arrival at installations and departure from installations.

The delay information was extracted by finding the difference between the estimated time of departure (ETD) and actual time of departure (ATD). A delay is defined as a 15 minute interval from the estimated time.

The table below summarizes the Statoil data and gives the amount of delayed departures or arrivals. An equal number of arrival and departures are found when adding base- and installation departure since arrival on installation also includes the arrival at the base after the deliveries are completed. Table 7 is used to reveal the distributions of delays in the different segments.

40% of the departures are delayed from the base, most of them caused by delays that has occurred in the earlier segments. There are also an equal number of early departures. This might be caused by alterations in the sailing plan. It can be clearly seen that the vessel transit is a segment where many disruption occurs causing a delay in the schedule. Still, when evaluating this, one also has to consider the early departures which also experience a smaller increase in their distribution.

Delays in different segments						
	Departure from base		**Arrival installation**		**Departure installation**	
	Quantity	Distribution	Quantity	Distribution	Quantity	Distribution
Not delayed	965	0,41	1741	0,13	1092	0,10
Early departure	460	0,19	3743	0,28	3741	0,34
Delayed departure	948	0,40	7897	0,59	6149	0,56
Total trips	**2373**	**1**	**13381**	**1**	**10982**	**1**

Table 7 Statoil delay distribution

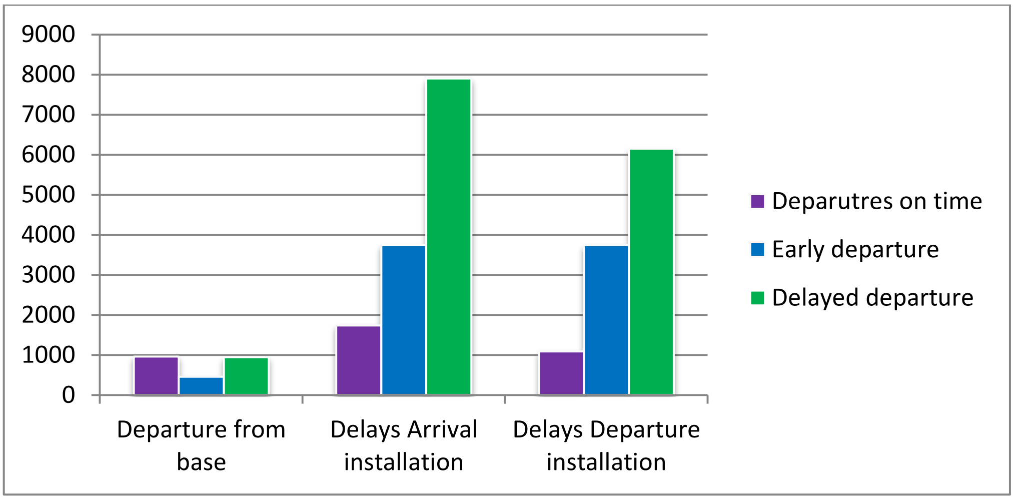


Figure 3 Delay distribution vessel transit

The delay distributions are also shown in figure 3 to give a clear demonstration of the distribution between early, delayed and on time departures and arrivals. From this figure we can see that the delays increase considerably during transit, especially when considering that the amount of on time departures is almost the same for all three situations. The amount of early departures has increased compared to the base value, but is constant during transit.

The next figures show the distributions from the different segments in a seasonal perspective. Figure 4 shows departures from base. The y-axis represents the number of departures and the x axis the different seasons.

Unexpectedly the seasonal differences are very small. This may be because Statoil constantly adjust their estimated schedule, and the seasonal adjustments include more slack in the late seasons. This makes the seasonal difference not appearing in this study. [2]

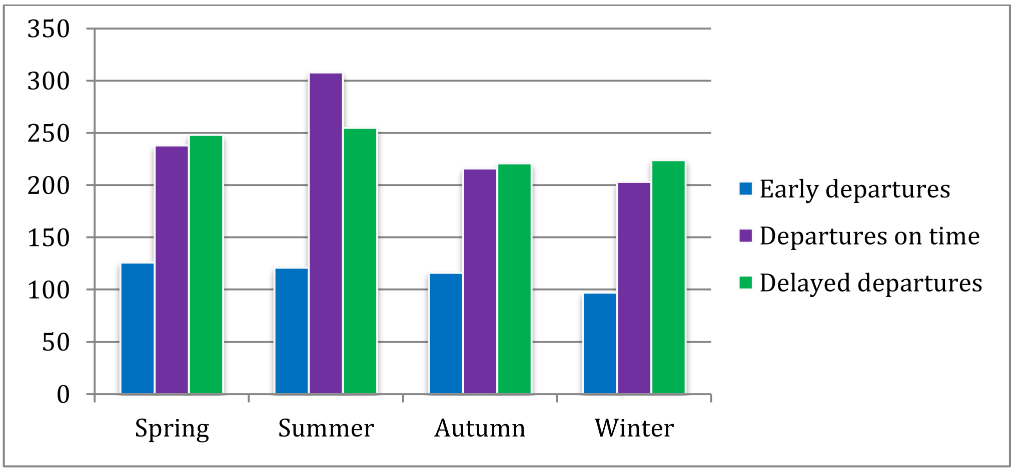


Figure 4 Departures from base

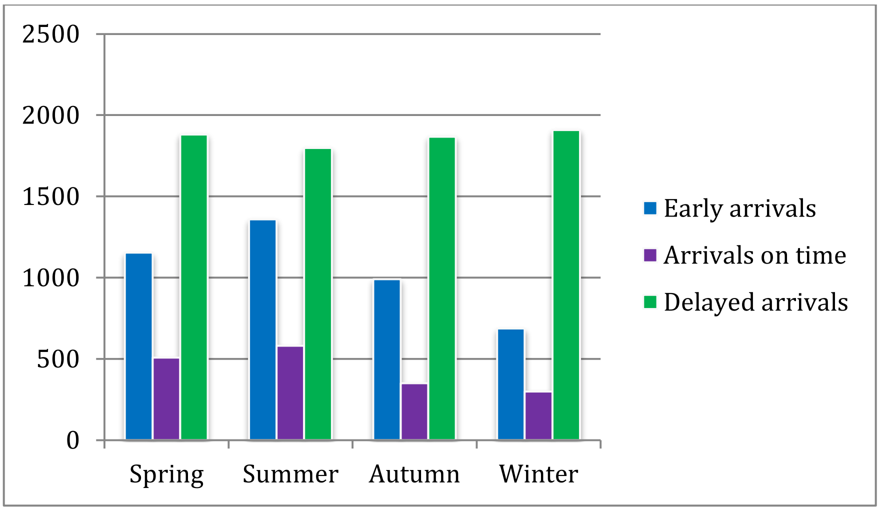


Figure 5 Arrivals at installations

Figure 5 shows vessel arrival at the installations. From the figure we can see that the increase in delays is evenly distributed for the different seasons. It is also easily seen that the number of delays are very similar for each of the seasons. This is surprising since the weather is much worse in the late seasons, but this can also be explained with slack, as in the section above.

Figure 6 demonstrates vessel departure from the installations. The shapes of the distribution columns are very similar to figure 5. This indicates that the treatment duration at the installations often lasts as long as estimated and does not add more delay to the schedule. It also indicates that the amount of disruptions is higher in transit than on the installations.

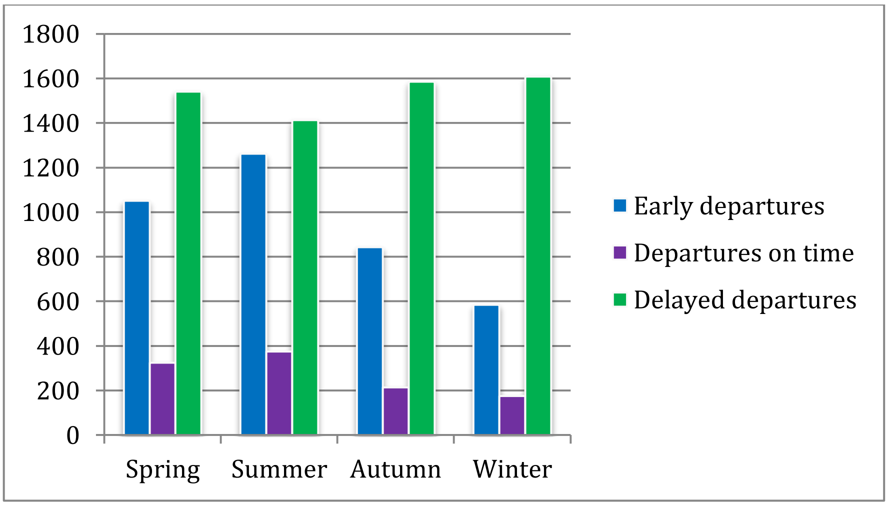


Figure 6 Departures from installation

4.1.1 Case analysis

A case analysis is done for the Statoil supply ship, Far Seeker. It is based on the actual schedule of the ship. In figure 7, distribution over the time used in different transit states is displayed.

When studying figure 7 it can be seen that a lot of time is used in transit and in the base harbor. This may be since time is used for bunkering. It can also be seen that a much time is used on waiting on weather (WOW) on the base or by the installation, or for the installation to be ready to receive the vessel (WOP). Since no other disruptions are given, it is assumed that WOP and WOW are the biggest contributors for disruptions in vessel transit.

It is assumed that the segment distribution for the Far Seeker is representative for all the Statoil supply ships.

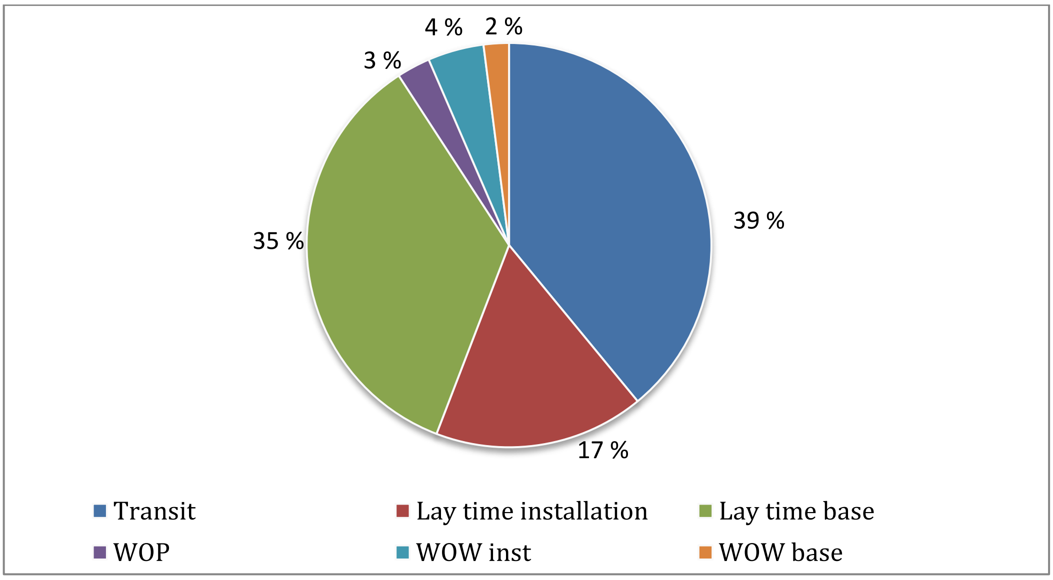


Figure 7 Distribution of states, Far Seeker

4.1.2 Remarks Statoil delay

From the comparison of the three segments in section 4.1, it is clear that there are some delays on the vessels when leaving the base, but that most of the delays occur in the transit to the installations. The fact that these delays are mainly caused by weather situations e.g. waiting on weather to enter the 500 m safety zone around the platform is confirmed by the case analysis, which demonstrates that quite a lot of time is used for waiting on weather.

Priority

Last year Statoil performed 2373 trips out to its installations. In the same year they received 7265 applications for priority. This gives an average on three priority application per vessel departure. Priority deliveries are defined in section 3.7.1 as *when a delivery needs to get to the installation in the fastest possible way, with the goal of reducing the probability of down time at the installation as much as possible.*

4.1.1 Statoil definitions

In this section Statoil's definition related to priority deliveries are presented. This information was used in the next section for analyzing of the Statoil priority data.

When applying for priority the planners have to state a reason for their application. It is the base or Statoil Marin that performs the evaluation. [1]. The different sets of reasons are presented below.

1. Urgent delivery due to late requisition
2. Urgent delivery due to operational changes
3. Urgent delivery due to high renting costs
4. Urgent delivery due to supplier
5. Cargo arriving late at the base
6. Alteration of sailing plan
7. Urgent return of equipment to base due to need on other installation/ high renting costs
8. Urgent return due to storage shortage at the installation
9. Urgent transfer to another installation

Urgent delivery due to late requisition is when the planners have ordered or reported the equipment very late and wants their equipment delivered with the next possible departure. *Urgent delivery due to operational changes* is when a change in the operational need has required the installation to retrieve new equipment or the need for equipment has been expedited.

Urgent delivery due to high renting costs is used when the rental costs are so high that it is more economical viable for the operator to combine the rental of this equipment with a priority delivery rather than paying rent for the time used for transportation and storage as well as the operation. This also applies *for urgent return of equipment due to high rental costs. Urgent delivery due to the supplier* is when the supplier is delayed with the equipment. In these situations it is the suppliers that pay for the delivery.

When critical *cargo arrives late at base* the vessel must wait for this cargo or alternative transportation has to be organized, e.g. helicopter transportation. *Alteration of sailing plan* may happen if an installation wants to change the sequence of the installation visits or add an extra leg on the route.
Priority solutions may be used if there is a *storage shortage on an installation*. This equipment is often found on the base. It can also be borrowed from a near-by installation. Then it is an *urgent delivery from a near-by installation*.

When the planners apply for priority they also have to state the potential consequence that may occur if their application is declined. The consequences defined from Statoil are the same as presented in chapter 3.5.1

Statoil has defined eleven different solutions for these situations. These solutions are as follows:

1. Extra treatment of cargo at base after opening hours
2. Delayed departure from base for supply ship
3. Earlier departure from base for supply ship
4. Rerouting of sailing plan
5. Extra call for supply ship on sailing plan
6. Extra lay-time at installation for supply ship
7. Supplies with vessel from a different supply base
8. Sharing of extra vessel with other installations
9. Use of extra supply vessel
10. Supplies delivered by helicopter
11. Supplies delivered with extra helicopter

Extra treatment after opening hours and *delayed departure for supply ship* are two closely related solutions that does not lead to major economic consequences and are simple solutions that does not require much organizing. A vessel might be sent *earlier from the base* if an installation has an urgent need. This will reduce the potential of severe consequences, and as long as all of the planned cargo is loaded on, then this is an easy solution on the same line as measure one and two.

In some cases a *rerouting of the sailing plan* is necessary. This may be in cases where e.g. one installation has a more urgent need than the earlier legs on the route, or an installation that was not on the original route suddenly has a need.

Extra lay-time at installations might also be needed. This is dependent on the cargo being delivered. *Supplies delivered from other installations or other supply bases* are used when an installation has an urgent need and need to borrow equipment from other installations.

In some situations extra measures has to be made to get the equipment delivered in time. The cargo might be *sent with helicopter*, or an *extra vessel* might be rented if it cannot be sent with helicopter. If multiple installations have extra needs they may *share an extra vessel* as well.

4.1.2 Analysis of priority deliveries

An analysis over the priority deliveries at Statoil during a one year period is performed. It is based on the reasons, consequences and solutions presented above.

	Priority reasons	Number	Percentage
1	Urgent delivery due to late requisition	1318	18,1
2	Urgent delivery due to operational changes	2633	36,2
3	Urgent delivery due to high renting costs	51	0,7
4	Urgent delivery due to supplier	951	13,1
5	Cargo arriving late to the base	1409	19,4
6	Alteration of sailing plan	600	8,3
7	Urgent return of equipment to base	37	0,5
8	Urgent return due to storage shortage at the installation	188	2,6
9	Urgent transfer to another installation	72	1,0
	Unmarked	6	0,1
	Total	**7265**	**100,0**

Table 8 Reasons for priority

A distribution over the given reasons for applying for priority is presented in table 8.

The distribution of reasons shows that the most common reason for priority deliveries are due to *urgent changes in the operations*. *Late requisition* and *late arrival of cargo to the base* are also major reasons for priority applications, while high renting costs and urgent equipment return are the least applied reasons.

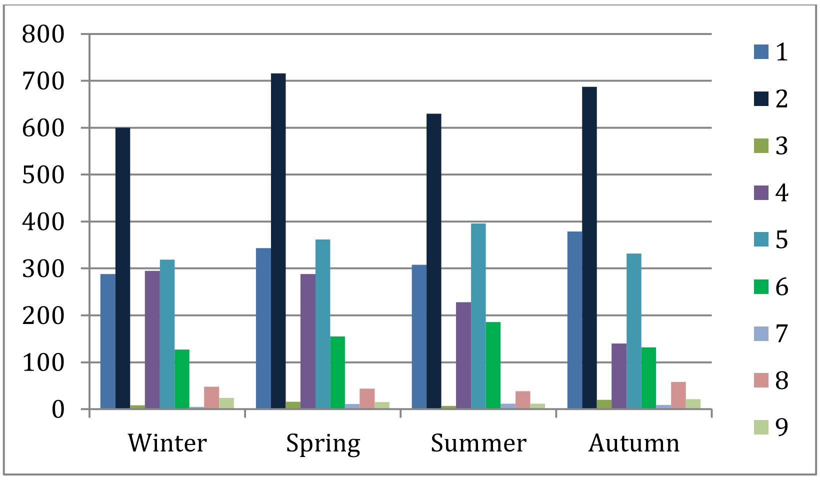


Figure 8 Seasonal reasons for priority

Figure 8 shows a seasonal distribution over the data presented in table 8. This was done to see if there were any seasonal trends of reasons. Just as with the delay distributions these variations are not well demonstrated, and one can only assume that this is due to implemented seasonal variations. To be able to make any solid remarks regarding seasonal priority distributions, data for multiple years should be analyzed.

Consequences

Well operation involves the construction of a well, and was the most given consequence for priority applications. This is reasonable since there are more operational changes in the making of a well compared to the production from a well.

Great economical expenses were also a commonly given reason for priority. This may be related to expenses that arise for different delays in general. In some cases it is difficult to separate between situations that risk the operation or production, and situations that have great economical expenses, since these situations are almost always related to each other.

Loss of well control is a rarely used reason. This is due to the high safety criterions at the installations. Had this consequence distribution been higher then measures had to be taken to increase the safety for human lives and the environment. Similarly HSE damage also has a low frequency. This can be explained with the same arguments.

The consequences presented in table 9 corresponds with the secondary consequences presented in section 3.5.1

Consequence	Number	Percentage
HSE damage	327	4,5
Stop/loss of production	520	7,2
Risk of Stop/loss of production	999	13,8
Stop in well operation	1227	16,9
Risk of stop in well operation	2630	36,2
Loss of well control	27	0,4
Great economical expense for the company	1530	21,1
Undefined	5	0,1
Total	**7265**	**100,0**

Table 9 Consequences if declining priority applications

Solutions

In table 10 it is demonstrated that the most common solution for priority applications was *extra treatment of cargo at the base*. *Alteration of the sailing plan* in terms of an extra leg on a supply delivery was also a much used. A slightly less used solution was alteration of the sailing plan in terms of changing the sequence of the installations.

For cargo that needs to be delivered with other modes of transportation, *helicopter* is preferred since it is less expensive to rent a helicopter than an extra ship, and is also a faster mean of transport. Still, since some cargo is too large to be delivered with helicopter, the *rental of an extra vessel* is sometimes necessary. Rental of a ship may be economical viable if there are multiple rigs needing extra delivery, but this solution is rarely used. *Supplies delivered from another base* happen very rarely, and is mainly a solution when operational needs cannot be covered from the intended base.

Section 4.1 shows that early and delayed departures from the base are quite common. This analysis shows that these situations are rarely connected with priority deliveries.

Solutions	Number	Percentage
Not possible to solve application for priority	63	0,9
Extra treatment of cargo at base after opening hours	3860	53,1
Earlier departure from base for supply ship	43	0,6
Delayed departure from base for supply ship	165	2,3
Rerouting of sailing plan	359	4,9
Extra call for supply ship on sailing plan	871	12,0
Extra lay-time at installation for supply ship	227	3,1
Supplies with vessel from a different supply base	14	0,2
Sharing of extra vessel with other installations	36	0,5
Use of extra supply vessel	74	1,0
Supplies delivered by helicopter	818	11,3
Supplies delivered with extra helicopter	187	2,6
Undefined	548	7,5
Total	**7265**	**100,0**

Table 10 Solutions for priority applications

5. Analysis of event frequencies and consequences

In addition to the Statoil case analysis an extensive event- and risk analysis have been performed. These analyses have resulted in a thoroughly mapping of different disruptions that may occur in the chain and the correlation between these incidents. A Preliminary Hazard Analysis (PHA) was performed for a thorough mapping of the possible events that may result in an unwanted incident or a hazard. An event tree analysis (ETA) was performed to examine the relationship between different events an find the probability for the most severe incident occurrences. Dependency & incident diagrams and Restriction matrices were made to show the correlation between events and how different events may affect each other. Risk matrices were made establish the severity for all identified disruptions.

The results of these analyses are used to determine event frequencies and –restrictions in the simulation model.

5.1 Preliminary hazard analysis

Most of the systems that are analyzed are often very complex, and the hazards facing the system are not always very obvious. A PHA analysis is an analysis identifies different hazards and consequences in a system. It is a good evaluation method for identification of the different incidents that may occur. It also identifies potential accidents that have an increased probability when another incident has happen. This may be referred to as dependent incidents.

A PHA analysis is a general and non-specific analysis that makes it easier to identify potential hazards and formulate appropriate measures for dealing with these hazards. It is a good support tool to have in the development of event trees and risk matrices. The result of the analysis can be found in appendix A.

5.1.1 Probability of different events

The probability of events occurring will vary. Below the accident probability classification that is used in the PHA analysis is presented.

Accident probability classifications	
Extremely Remote	Likely to occur once per 10-100 years
Remote	Likely to occur once per 1-10 year
Occasional	Likely to occur 1-10 times every year
Probable	Likely to occur 1-10 times every month
Frequent	Likely to occur 1- 10 times every week

Table 11 Accident probability classification

5.2 Scenarios

To perform detailed event analysis on all possible disruptions that may occur in the offshore supply chain is not possible in one master thesis. Therefore five scenarios have been chosen in the execution of such analysis.

1. Cargo delayed from the supplier
2. Cargo arriving late at base
3. Bad marking of cargo
4. Extreme weather during vessel transportation
5. Changes in operational need at installation

5.2.1 Scenario 1 – Cargo delayed from the supplier

Small production delays or other events may cause the equipment from the supplier being sent from the supplier later than agreed. This may lead to the cargo arriving at the base after the given time limit. If the criticality for this equipment is high, priority measures may be implemented to make sure that the equipment reaches its destination in time. Some incident has a high probability of occurrence in transit to the installation, which will increase the delay.

5.2.2 Scenario 2 – Cargo arriving late at base

It is not uncommon for cargo to arrive at the base after the time limits. The treatment of this cargo is dependent on the installations need for the equipment. If there is no urgency the equipment is put on storage for the next departure. If there is a pressing need the ship is either detained for the loading of the late arrival cargo, or it is sent with a separate vessel or helicopter.

5.2.3 Scenario 3 – Bad marking of cargo

When the cargo is sent from the supplier it is their responsibility to mark the cargo. This marking is sometimes done very poorly. [1] This creates an uncertainty regarding the contents, and valuable time is spent on either identifying the contents or on retrieving incorrect delivered cargo. If this is not discovered, it may result into the cargo being misplaced or sent to the wrong destination. Depending on the criticality of the equipment, this may lead to consequences of varying severity.

5.2.4 Scenario 4 – Extreme weather during vessel transportation

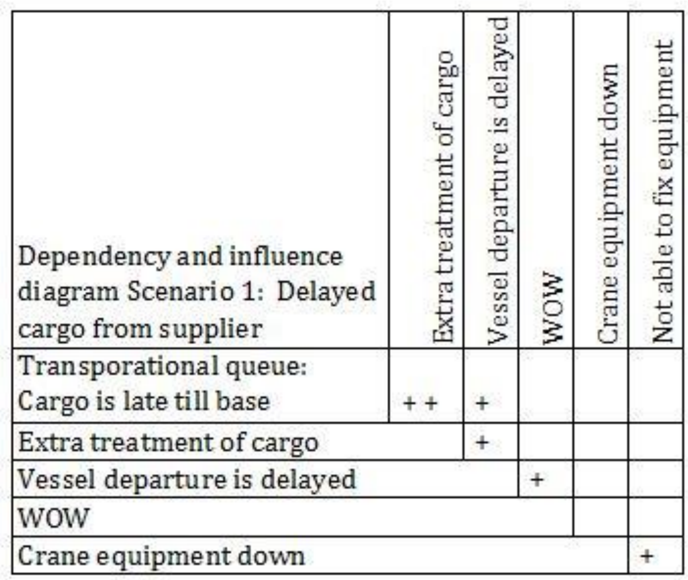
The most uncertain factor in vessel transit is the weather. This is also the only factor an operator cannot change regardless of the initiative they take, and it is the greatest reason for delays. Before departure precautions with respect to possible weather situations need to be taken. If anything happens, the possibility of repair must be present. If not it might affect the production on the installations.

5.2.5 Scenario 5 - Changes in the operational need at installation

The operational plans are pretty accurate up till two-three days ahead of the operation. After that they are not held in the way they should. [2] The oil industry is a dynamic business, and this makes planning unpredictable. When disruptions occurs the demand changes fast, and equipment that is order in the morning can be cancelled in the afternoon. [29] This creates logistical challenges in regards to following up the new need in an effective manner.

5.3 Dependency and influence diagram

Dependency and incident diagrams are a tool that describes the dependency between disruptions in terms of increasing probabilities. It is closely related to the ETA. They are used to estimate the probabilities for the event trees. The influence diagram also demonstrate the relationship between incidents that affect each other e.g. that the probability of a queue increases with the closing of a tunnel. It can therefore be used to illustrate event relations in the system. Figure 9 shows the matrix for the first scenario, the rest of the matrices may be found in appendix B.



Dependency and influence diagram Scenario 1: Delayed cargo from supplier	Extra treatment of cargo	Vessel departure is delayed	WOW	Crane equipment down	Not able to fix equipment
Transporational queue: Cargo is late till base	+ +	+			
Extra treatment of cargo		+			
Vessel departure is delayed			+		
WOW					
Crane equipment down					+

Figure 9 Dependency and influence matrix 1

5.4 Event tree analysis

An Event Tree Analysis (ETA) is a quantitative method used to analyze possible consequences of an incident or an accident. It is a logical diagram that describes the relationship between an initiating event and the following possible outcomes [33]. It is constructed using forwarding logic.

Each level in the chain of events consists of two different outcomes, yes or no. These outcomes are mutually exclusive which means that it is impossible for both of them to occur at the same time. This makes an ETA analysis a binary technique.

An initiating event may develop into severe and less severe outcomes. The probability of each event is based on the previous event. This makes the ETA analysis a good tool towards revealing the dependence between the different events.

5.4.1 The method

First an initiating event is defined. The initiating event is the first in a sequence of events that will lead to a hazardous situation or accident. Secondly, a possible sequence of events including safety system, functions and barriers are defined. The probabilities for the outcomes of each event (yes or no) are estimated and an initial event tree is then established. In this analysis the probabilities for the different outcomes were not dependent on the previous events and situations. This is called independent events. The dependency of event can be evaluated related to time, their chronology in a series of events and involvement of previous events.

5.4.2 Calculation of probabilities

The probabilities used in this analysis were based on the Statoil case, dependency and incident diagrams, and on common sense. They were later re-evaluated based on the event frequencies described in chapter 6 and appendix G. The probabilities were used to calculate the consequence probabilities for the event chains. It was found by multiplying the events leading down to the different consequences. The probability for the initiating top event was also included in this calculation.

An example of the ETA is demonstrated in figure 10. The rest of the ETA trees are to be found in appendix C

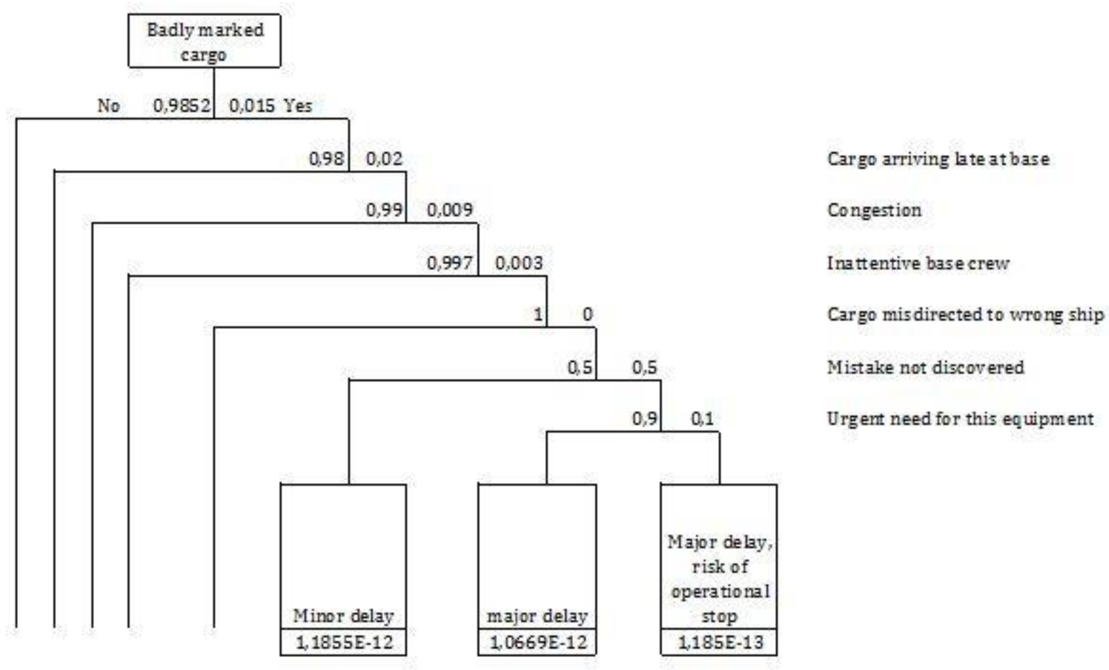
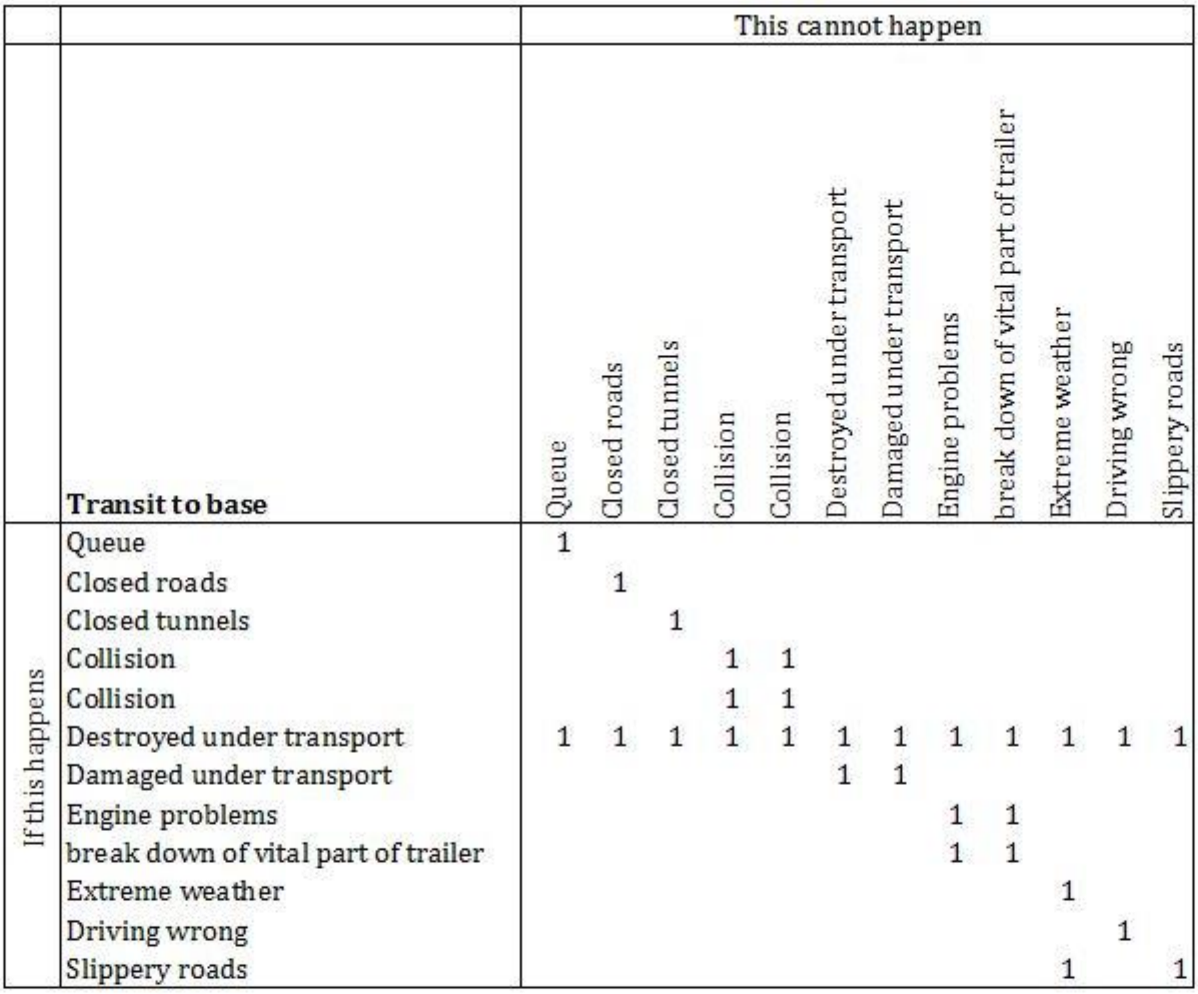


Figure 10 ETA scenario 1

5.5 Restrictive event matrix

These matrices are based on the event analysis in chapter 3. The matrices demonstrate the different events in a segment and shows which incidents that cannot occur at the same time, and which incidents that prevent others from happening, e.g. if a cargo is slightly damage under a collision it cannot be totally destroyed at the same time. The matrix for the transit to base is presented in figure 11, the matrices for the other segments are found in appendix D.



		This cannot happen											
	Transit to base	Queue	Closed roads	Closed tunnels	Collision	Collision	Destroyed under transport	Damaged under transport	Engine problems	break down of vital part of trailer	Extreme weather	Driving wrong	Slippery roads
If this happens	Queue	1											
	Closed roads		1										
	Closed tunnels			1									
	Collision				1	1							
	Collision				1	1							
	Destroyed under transport	1	1	1	1	1	1	1	1	1	1	1	1
	Damaged under transport						1	1					
	Engine problems								1	1			
	break down of vital part of trailer								1	1			
	Extreme weather										1		
	Driving wrong											1	
	Slippery roads										1		1

Figure 11 Restriction matrix base

5.6 Risk matrices

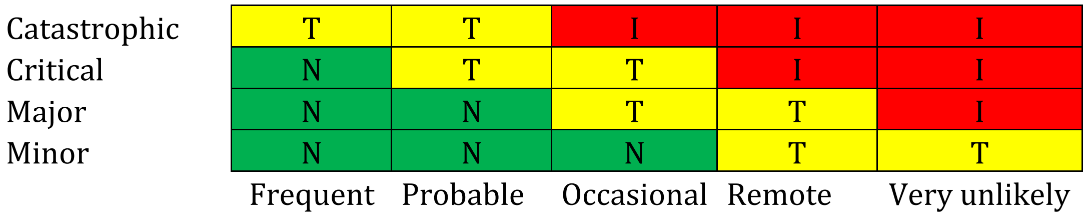
The risk matrix is a tool for categorizing hazards and describing the severity of an incident. It has been made for the different event analyses presented in chapter 4 and for the PHA. The matrices were made evaluate the potential disruptions and incidents in terms of consequence and probability of occurrence. Tables developed by DNV were used in order to define the frequency and consequence level. These can be found in Attachment E.

The matrix was divided into severity and likelihood. High severity and likelihood means a great risk, and is indicated with red. The yellow zone indicates medium risk, also referred to as ALARP (As low as reasonably possible). This is an important zone where it is decided if risk levels can be reduced to a reasonable level without using an unreasonable amount of resources. The green areas indicate an acceptable risk level. An example of the matrix is demonstrated in figure 12, where N, T and I mean negligible, tolerant and intolerable.

The matrices were developed by dividing the risks into three categories, human-, environmental and material factors. The consequences for most of the incidents are only to be seen in the material matrix. However, there are still some situations that are critical for the safety of humans and the environment. Therefore are the three matrices included for all states.

From the matrices presented in appendix F it can be seen that most situations are acceptable for the system. This is because it is an already existing system that is analyzed, and not a new designed system. The purpose with this analysis was to demonstrate where the greatest risks in the chain are in terms of severity.

The analysis suggested that it is in the transit and the installation handling that the risk of the most severe consequences is found. This result was consistent with information retrieved through interviews with Arne Angelshaug, base handler and Geir Korneliussen, operational planner. Both of them are Statoil employees.



Catastrophic	T	T	I	I	I
Critical	N	T	T	I	I
Major	N	N	T	T	I
Minor	N	N	N	T	T
	Frequent	Probable	Occasional	Remote	Very unlikely

Figure 12 Risk matrix

5.7 Result event analysis

A short presentation of the event- and risk analysis results will be presented in this section.

The event analysis has identified all the main disruption contributors in the system. It showed that there were quite a few disruptions that happened before the vessel departure from the base. Measures to reduce these delays are taken at the base. In 53% of the times, extra treatment on base is the implemented delay reducing measure. An extra call for a supply ship or the use of helicopter for delivery is the second and third largest solutions, respectively with 12% and 11%. Most of the delays occurred during transit. Except for speed regulations for the vessel, there are no priority solutions to be implemented here. All of the needs for the chain arise at the installation, and 36% of the time it is due to operational changes. It is at the installations where the most severe consequences turn visible. This is a result of multiple delays and failures in safety system, functions and barriers.

In the risk analysis the PHA has uncovered relation between the events presented in the event analysis, and how the presence of certain events has led to the occurrence of other disruptions. The ETA has demonstrated how event chains may lead to severe consequences. These consequences will not occur without the presence of certain disruptions and the fail of multiple safety barriers. The probabilities of these consequences occurring are presented in table 12. The restrictive matrices have demonstrated that certain disruptions cannot occur with the presence of others disruptions. Ultimately, risk matrices have been made for the event analysis and for the PHA to demonstrate the severity of the possible disruptions uncovered. Together with the Statoil case these analyses gives a good and comprehensive demonstration of the disruptions in the supply chain, and a good basis for the development of the simulator.

Top event	Possible outcomes at installation	Probabilities
Cargo is delayed from supplier	Minor delay	5,63E-06
	Major delay	1,13E-09
	Risk of operational stop	2,25E-14
Cargo arriving late to base	Cargo sent to storage for next departure	0,0072
	Cargo sent with separate ship	7,84E-04
	Cargo with separate vessel, high logistical costs	1,58E-05
	Minor delay, high logistical cost	1,59E-07
	Delay, High logistical costs	2,00E-01
	HSE risk, risk of operational stop	8,00E-10
Badly marked cargo	Minor delay	1,18E-12
	Major delay	1,06E-12
	Major delay, risk of operational stop	1,18E-13
Extreme weather at sea	Risk of operational delay	6,99E-09
	Risk of operational failure	2,40E-09
	Reorder of cargo from supplier, temporary operational shut down	5,99E-10
Change in operational needs	Economical loss, delay	9,70E-14
	Economical production loss , risk of delay	1,08E-14
	High logistical costs, economical production loss , risk of delay	2,16E-17

Table 12 Probabilities from the event tree analysis

The values from the event analysis and the results from the risk analysis will be used later in this thesis for determination of the event frequencies to be used in the simulation.

6. Event frequency and probabilities

In chapter 3 all potential incidents were described. The next step was to find realistic event frequencies for these incidents. This chapter explains how this is done.

6.1 Event frequencies

The frequencies involving vessel transit and priority deliveries were calculated based on the Statoil case data.

Some of the priority solution values were altered slightly to gain a more realistic result. This alteration was done after consulting with Arve Angelshaug at supply base Kristiansund. He claimed that the frequency rate for *vessel delay at base* was the main solution for priority applications, but due to the constant adjustment of the schedules this is rather logged as *extra treatment at the base*. This value was then slightly increased. At the same time, the frequency for *extra treatment time at base after opening hours* was slightly reduced. This was in the Statoil case presented as the most chosen solution. Given the claim from Angelshaug and the close relation between these two solutions, a minor alteration in between these values would give more realistic frequencies.

Except for the priority events, the Statoil case did not include information on the occurrence of any specific disruption or incident. These values are therefore assumed based on conversations with base- and operational planning personnel, events in other supply chains, common sense and iteration based on the risk analyses in chapter 5. It is conducted in this matter due to lack of relevant data. The simulator made is only a prototype, and a more thorough event analysis should be done before implementing them in a developed model.

For incidents related to vessel transportation, the frequency is based on assumed incidents within a one year period. One year is assumed to include 2500 vessel trips. This number is similar to the number of trips conducted in the data given from Statoil. For incidents related to trailer transportation the frequency is based on an arrival rate at the base for 2-3 cargo units. This is approximately 1000 deliveries/year. This assumption was sat based on a consolation with Arve Angelshaug.

The simulator is directly based on these event frequencies, and the relative probability of their occurrence. A summary of the values are presented in the appendix G.

6.2 Incident probability parameter

The event analysis results were also used to assume an incident probability parameter (IPP) for each segment. The IPP represents the probability of any disruptions occurring. It is used as a determination mean for the occurrence of disruptions in each of the segments. A bionomical distribution is used to decide if a disruption occurs or not. The bionomical distribution is explained closer in section 7.4.4.

The IPP values were sat based on the highest event frequencies in a segments e.g. the probability of a vessel departing the base after schedule is 0,4. Based on this the base handling parameter is sat to 0,4. To set it higher will give too many incident occurrences. To set it lower will make the distribution of occurring incidents too low.

Another assessment criterion for the determination of this value was consultation with base personnel and the results from the Statoil case analysis regarding the number of delays in the different segments. The concluding values are seen as realistic, but an iteration process towards more accurate values should be conducted by further development of the project.

The incident values for the different segments are presented in the table below, and the usage for the parameter is explained in section 7.6.3.

State	Disruption	Secondary disruption
Transport to base	0,3	0,3
Base handling	0,4	0,4
Transit to installations	0,55	0,5
Installation handling	0,3	0,3
Return transit to base	0,55	0,5

Table 13 Incident probability parameter

7. Probability of incidents

The consequence of an occurring event varies depending on where it occurs and on the previous events that has occurred. The consequence of e.g. extreme weather will have a less serious impact if it happens during transportation to base and not at vessel arrival at the installation. The disruptions and impacts in the simulation model developed were determined by random variables.

Different distributions should be used for different incidents based on their possible impact. A probability density function considering the impact of an event should be developed for each incident that may occur in the supply chain. A description of the different distributions that should be used is presented in this chapter.

For the simulation in this thesis, event occurrence was based on a statistical distribution, random numbers and the incident probability rates. The occurrence of an event was decided based on the incident probability of a given rate, and not on the impact of the different incident. This is a simplification that was chosen in this model, since the objective of the simulator was to demonstrate disruptions in the supply chain.

Further development of the model should primarily include an alteration of the disruption occurrence method.

7.1 Deterministic vs. stochastic modeling

The input variables in a model can either be randomly distributed or known in advance. In a deterministic model all the variables are known in advance while in a stochastic model one or more input variables are randomly distributed [34]. The simulation model in this master thesis is stochastic.

7.2 Discrete vs. continuous simulation

In a discrete event simulation changes in the state of the system occur instantaneously at random points in time as a result of the occurrence of discrete events. [35] Everything that occurs between these events is seen as irrelevant and does not influence the system in any way. When an event occurs it may trigger new events, activities and processes. The systems state will change, e.g. when cargo arrives at the base. [36]

In a continuous simulation the system state changes continuous with time. This simulation type is used when the system behavior throughout the whole system is interesting. Continuous models are often described with differential equations. [36]

This thesis is a discrete simulation, where the system only changes on given times and everything that happens in between is irrelevant. It is based on continuous probability distribution.

7.3 Model assumptions

Incidents will have different impact depending on where in the schedule they occur. Because of the different consequences that may occur, different stochastic distributions are needed. Distributions that describe the different impacts are proposed in the next section.

Prior to finding the probability distributions, some incident assumptions were made:

- Most of the incidents are independent
  $P(A|B) = P(A)$
  $Where\ A\ and\ B\ are\ incidents.$
  This was a simplification made in the model. The exception is incidents that are preventing other from happening, which is considered in the simulation Dependent incidents were demonstrated in the event analyses such as the dependency matrices, and dependence of incidents should be considered in a further development of the model..

- The model does not have a memory
  $P(A; t) = P(A; t + t_b)$
  $where\ A\ is\ an\ incident, t\ is\ time\ and\ t_b\ is\ the\ time\ neded\ for\ recover\ if\ incident\ A\ occurs$

After a disruption occurs, there are multiple possible outcomes from the effect of an incident. A Monte- Carlo simulation was used to calculate impact of the different consequences.

7.4 Stochastic distributions

The different impacts from the incidents are divided into different behaviors.

- Delayed
- Behind or ahead of schedule
- Bionomical incidents

7.4.1 Delayed

The consequence of the majority of hazards happening in the chain will be a delay. The duration of the delay will vary with the severity of the occurring incident. The typical behavior is that most of the delays are short, but some of them last for a longer time e.g. a queue during transportation to base. Since incidents with probability density in respect of the impact may be a bit complicated, an exponential distribution is considered a good distribution for these events.

The exponential distribution is given as a density distribution for the continuous variable x. Here x is the delayed time and β is the mean value of the distribution. [37]

$$f(x;\beta) = \begin{cases} \frac{1}{\beta} e^{-\frac{x}{\beta}}, & x>0 \\ 0, & elsewhere \end{cases} \tag{1}$$

$$Where\ \beta > 0$$

A figure of the exponential distribution density function with $\beta = 0{,}5$ is presented below.

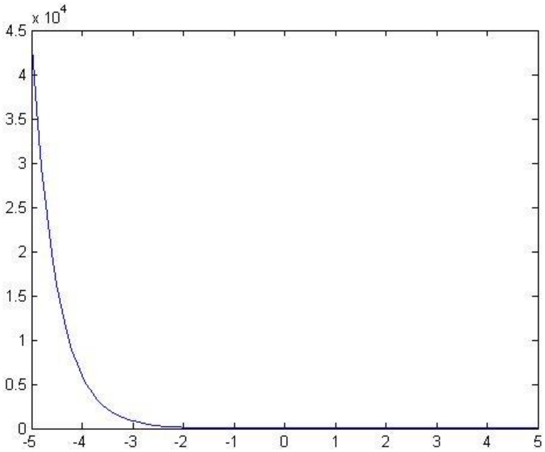


Figure 13 Exponential distribution with b=0,5

7.4.2 Behind or ahead of schedule

When a disruption occurs it is does not necessarily mean that the system will experience a delay and thus be behind the intended schedule. The exponential distribution gives a realistic probability function for the incidents where a delay in the schedule is the consequence, but it does not give a realistic distribution for incidents that may lead to either a delay or being ahead of the schedule, e.g. an operational need makes a ship depart from the base earlier than scheduled or depart later than scheduled when waiting on arriving cargo. For these incidents, a distribution with lower values on both sides of the maximum point is needed. This means a distribution that covers both the positive and negative impact on the schedule. A Weibull distribution can be used for these situations. This is a continuous distribution. [37]

The Weibull density distribution is given as [37]:

$$f(x;\alpha,\gamma) = \begin{cases} \alpha\gamma x^{\gamma-1} e^{-\alpha x^{\gamma}}, & {\scriptstyle x>0} \\ 0, & {\scriptstyle elsewhere} \end{cases} \tag{2}$$

$$Where\ \alpha > 0\,, \gamma > 0$$

The curves for a Weibull distribution change considerably in shape for different values of the parameters α and β. A figure of the Weibull distribution density function with $\alpha = 2\ and\ \gamma = 3$ is presented below.

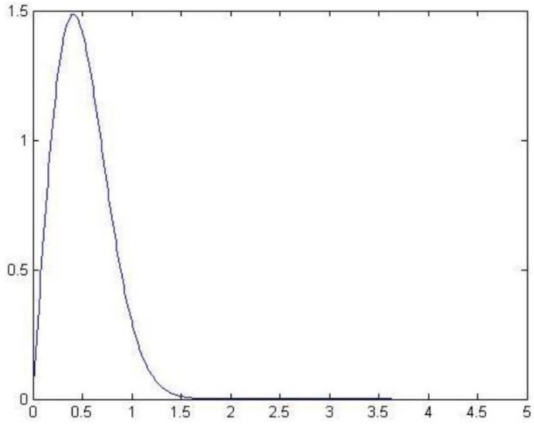


Figure 14 Weibull distribution with a=2 and b= 3

Both the exponential- and the weibull distribution may have occurring major delays due to the tail effect. This effect can be excluded by defining an upper impact limit.

7.4.3 Monte- Carlo applied on continuous distributions

Given a probability density function, one may find the cumulative distribution function and the following method may be used.

This may be demonstrated with the exponential distribution where x is the time unit. The probability distribution is given in section 7.4.1. The cumulative distribution is presented here:

$$F(x;\beta) = \begin{cases} 1 - e^{-\frac{x}{\beta}}, & x > 0 \\ 0, & elsewhere \end{cases} \tag{3}$$

The algorithm used is as follows:

1. Calculate a random variable r between 0 and 1, e.g. r =0,8946
2. Calculate x with the cumulative function F(x)
3. The delay is found to be x=0,5912

This method should run many times, and after that be valid through the strong law of numbers. It should be used to find the impact on continuous probability functions.

7.4.4 Bionomial incidents

Some incidents only have one possible outcome dependent on when and where in the system they occur, e.g. total machinery break down. These incidents are of bionomial distributions.

This distribution is as follows:

P(i) is the probability of incident *i* occurring. (4)

7.5 Probability function used

The triangular distribution will be used in this thesis since it is a good alternative for simple probability distributions when only is a limited amount of sample data is available. It is often used in simulations. Due to the linearity of the function it may create too many incidents with a high impact on the schedule.

The triangular distribution is a continuous probability distribution with a lower limit x_L, upper limit x_U and peak value x_p where $x_L<x_P<x_U$. The variables around x_P are more likely to occur [38]. The triangular distribution is given as [39]:

$$f(x|x_L,x_P,x_U) = \begin{cases} 0 & for\ x < x_L \\ \frac{2(x-x_L)}{(x_U-x_L)(x_P-x_L)} & for\ x_L \leq x \leq x_P \\ \frac{2(x_U-x)}{(x_U-x_L)(x_U-x_P)} & for\ x_P < x \leq x_U \\ 0 & for\ x_P < x \end{cases} \tag{5}$$

Where x represents the impact on the schedule

This distribution will be used in a Monte-Carlo simulation to calculate delays in the different states.

7.6 Impact

The impact of events should be calculated based on probability cumulative distributions.

The cumulative distribution function F(x) of a continuous variable X with probability density function f(x) is given as [37]:

$$F(x) = P(X \leq x) = \int_{-\infty}^{\infty} f(x)dx \qquad for - \infty < x < \infty \tag{6}$$

Where x is a continuous random variable

7.6.1 Monte- Carlo simulation

A Monte- Carlo simulation is a method for exploring the sensitivity of a complex system by varying parameters within statistical constraints. [40] It is a numerical method that relies on repeated random sampling to obtain a numerical result. It is a good method for modeling complex situations with significant uncertainty in inputs. A Monte- Carlo simulation assesses the impact of a risk, allowing for better decision making under uncertainty. [38]

During a Monte- Carlo simulation, values are sampled at random from the input probability distribution. A simulation is done many times, and the output is a probability distribution of possible outcomes. The result is the impact of the given disruption. [38]

In this thesis the Monte- Carlo simulation will be used on continuous distributions.

7.6.2 Monte- Carlo applied on bionomial distributions

Monte- Carlo may be used on bionomial distributions as well. This may be useful when disruptions prevent the cargo from being delivered.

The algorithm is as follows:

Give a bionomial probability P(i) for incident *i*

1. Generate a random number r between 0 and 1.
2. If r≤P(i) then incident *i* has occurred.

This method should be run many times, and after that be valid through the strong law of numbers.

7.6.3 Monte- Carlo applied in the simulator

In this thesis the impact of an event is based on the segment it occurs in, and not on the occurring incident. This simplification was chosen based on conversations with professor Asbjørnslett. By subsequent evaluation of the model the author has realized that this is not a good solution for calculating the impact since the impact is not related to the incidents in any way. Still this evaluation method has not been altered. This is due to limited amount of time and the fact that the model is a prototype with the objective of describing disruptions in a supply chain. There are multiple changes required in the further development of the model, and the needed alterations are explained rather than implemented.

Due to the simplification explained above, the algorithm for impact calculation is done in a different way than for the other distributions explained in the earlier sections. The impact calculation is based on a triangular distribution, the IPP and a cumulative probability value over the event frequencies. These values can be found in appendix G. The type of incident that occurs is decided by a random number, r.

The triangular distribution is defined for each segment, and the algorithm is as follows:

1. Generate a random number r between 0 and 1.
2. If r≤IPP then an incident *i* has occurred.
3. For incident *i,* an impact value is randomly retrieved from the triangular distribution of the given state. The retrieval of an impact value is done many times, and will therefore be valid through the strong law of numbers.
4. The type of incident that occurs was identified through the cumulative probability distribution.

8. Simulation

Simulation can be defined as “experimenting with a system model”. [36] Simulation is a very popular OR technique because it is such a flexible, powerful and intuitive tool. It can imitate the conditions for a system and it can imitate years of operation in a very short time and foresee likely outcomes of different operations. This makes it possible to test multiple design possibilities and situations before implementation. Because of its flexibility it can be applied to numerous different situations and areas, and it is a good tool in situations where analytical techniques are inadequate. [35]

8.1 Problem description and plan

The purpose of this simulation model was to demonstrate how a supply chain with a given schedule behaved on a daily basis. It investigated how cargo flows through the chain following a given route where the transportation was exposed to disruptions. The model showed the effect of the incident by comparing the new true time with the scheduled time.

This model is a simple model with the objective of demonstrating the effect of disruptions on the supply chain schedule, and establishes a solid basis for further simulation development.

The programming script MATLAB was chosen for the simulation modeling.

MS Excel was used for the processing of result and consequence calculation.

8.2 Main objectives

The main objectives with this simulator were the following:

- Simulate the occurrence of incidents in the supply chain, and calculate the impact on the schedule for each event.
- Simulate how the most influencing incidents are solved e.g. the usage of priority transportation from the base.
- Demonstrate the effect of disruptions on the vessel schedule.
- Demonstrate the main contributors for disruptions in the supply chain.
- Estimate the impact of incidents occurring in a segment given that another incident has occurred
- Demonstrate how the occurrence of certain incidents may prevent other incidents from occurring.

Certain objectives were not included in this model. This is mainly due to limitations of the model caused by the simplifications implemented, and also due to limitations in programming features. These objectives should nevertheless be implemented in a later edition of the program.

Objectives for the final model (not included in this simulation):

- Demonstrate the direct impact of specific disruptions on the schedule.
- Demonstrate the relation between events.
    - Demonstrate the relation between dependent events and how the occurrence of certain events may increase the probability of other events taking place.
    - Demonstrate the effect of chain events, and how certain top events are dependent on the occurrence of event chains to occur.
    - Demonstrate the dependence between the different segments in terms of specific disruptions that has occurred earlier in the system.
- The simulator should evaluate delayed cargo and make priority decisions based on the criticality of the equipment.

8.3 Assumptions

Simulation time: 1 year
The incidents and impacts will be random stochastic variables.

The segments used in the simulator are as follows:

- Transportation to base
- Base handling
- Vessel transit to installations
- Offshore installation handling
- Return transit to base

The simulator will be event based. The simulation will advance from one discrete event to the next, and the time in between will be disregarded.

8.3.1 Other assumptions

- The availability of ships was assumed unlimited.
- Cargo and vessels were assumed homogenous.
- The disruptions were assumed independent.
- The states are assumed independent. (The occurrence of specific disruption in a state will not affect the calculations in the next state)
- The simulation is based on a fixed route, this is explained in section 8.5
- Due to the event- based simulation, all incoming cargo for the base is evaluated one time.

8.4 Conceptual design

The framework of the model is presented in the flow chart illustrated in figure 15. The flow chart gives a comprehensible demonstration over the logic used in the simulation that was performed, and made it easier to write the code.

First preparation of the simulator was conducted and the time variables were sat to zero. Then the simulator commenced. The model simulated the supply chain activity for a time, T. As long as the total time used in the simulator was less than T, the model ran.

For each state the possible occurrence of a disruption and its impact was decided, and the total duration of the segment was calculated. The impact calculation was done based on the Monte- Carlo principle explained in section 7.6.3.

Decisions for priority deliveries were evaluated in the base handling segment.
If a disruption could lead to the cargo not reaching its intended vessel departure, a further transportation decision had to be made. The cargo was either transferred to the next departure or transported as priority delivery on an extra vessel or helicopter.

The duration of the simulation run and the different segment delays were summarized when the cargo reached the installation. If the total simulation duration was less than T, a new simulation run began. If not, the simulation stopped and the results were summarized.

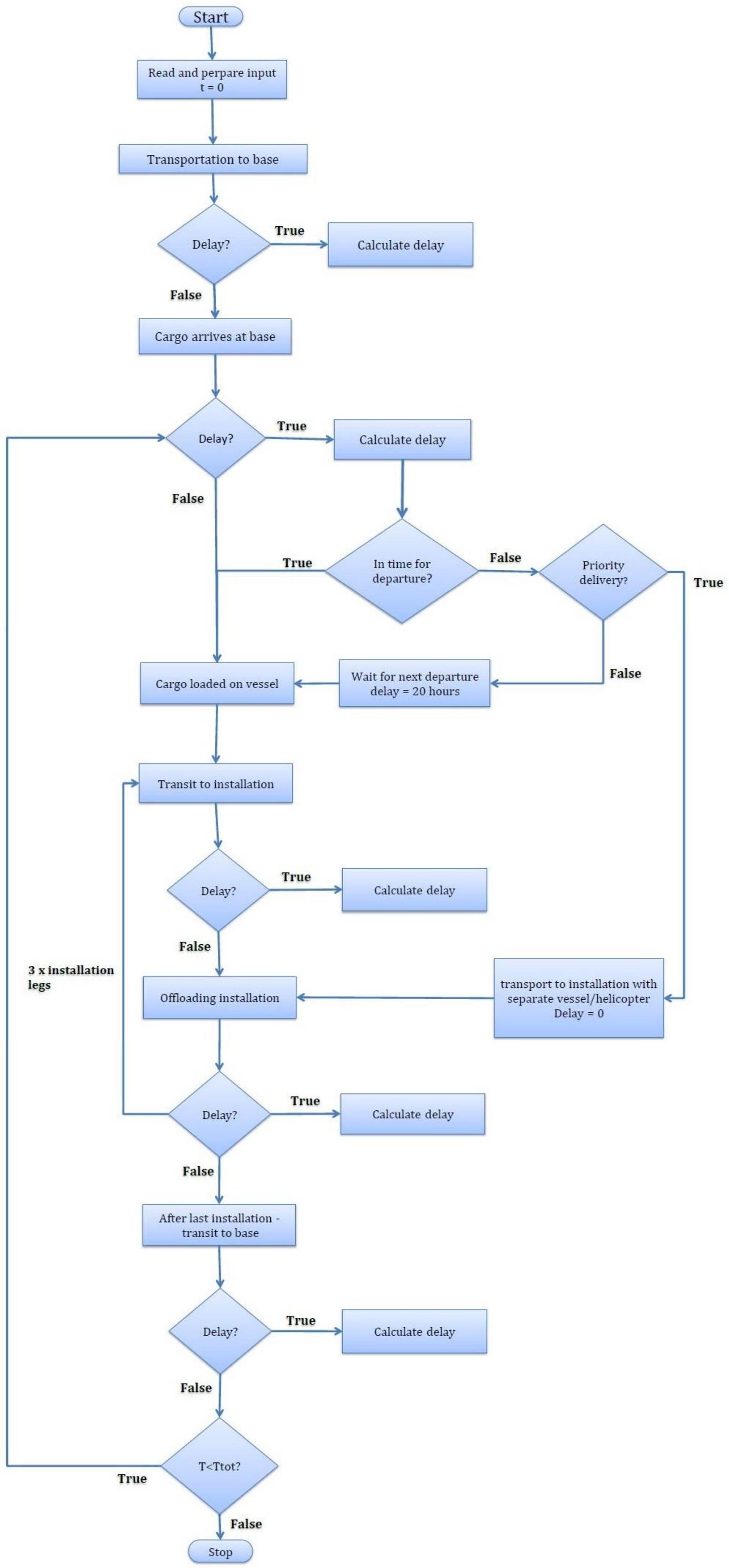


Figure 15 Flow chart

8.5 Schedule

The simulation was based on a fixed route. This route was designed as a perfect route where cargo was delivered before 12.00 on departure day, and the vessel left the base at 16.00 every third day. In real life the Statoil routes are re-estimated every day. In these situations this means that e.g. when a re-estimated vessel departs at 20.00, the delay is zero. This was not considered in this model, and all deviation from the perfect schedule was considered as a delay.

The route was calculated to use 58 hours from the supplier to the vessel returning to base from delivery at the installations. The route is presented in section 8.5.2.

8.5.1 Supplier transit

The delivery time from supplier was estimated based on transportation time from Stavanger to Kristiansund since most of the equipment Statoil uses is produced there. [41]. [1] The normal transport time on this distance was calculated to be 14 hours. [42]

The triangular distribution for transportation is presented in table 14.

8.5.2 Vessel route and schedule

The simulator is based on a fixed route where the vessel departs from Vestbase, Kristiansund and out to installations on Haltenbanken. The route is chosen based on the installations that Vestbase supplies [43]

The route that was chosen for the simulator run is:

1. Departure Vestbase
2. Njord
3. Heidrun
4. Kristin
5. Return Vestbase

Even though these installations were defined, the triangular distribution for the transit in between the installations was assumed equal. A simplification made since the model follows a fixed route that cannot be altered.

The triangular distributions for the transit times from the base and in between the installation and the handling time at the installation are all found by using average values from the data given by Statoil. These values are presented in the table below.

Entity	Low	Peak	High
Delivery from supplier	10	14	20
Transit installation	8	12	16
Inter-installation transit	0,5	2	10
Return transit	8	12	16
Treatment time base	0,5	4	24

Table 14 Triangular distributions

The treatment time for the base were assumed based on consultation with Arve Angelshaug. [44] If a cargo with a high criticality is delivered late till the base, then the personnel will push the cargo through the system fast. If the cargo has a low criticality and there is insufficient capacity at the vessel, the cargo will be temporarily stored for the next departure and thus have an extended turnaround time. The maximal delay time was sat to be 24 hours. This is assuming that the cargo is delivered later than 16.00 to the base, and that the next departure is at 16.00 the next day.

The peak value is based on the standard treatment interval on a base from 12.00-16.00.

8.6 Delaying incidents

In the simulation a delay was defined as any deviation from the given schedule.

The occurrence of disruption in the different states was based on random numbers. If the random numbers was below the IPP defined for a segment this signified the occurrence of a disruption. Event intervals were defined for all possible disruptions. The type of incident that occurred was indicated by the value of the random number. If a random number was in a given interval, this indicated the occurrence of this incident.

8.6.1 Duration delay

The duration of a delay was calculated based on a triangular distribution and a Monte-Carlo simulation as explained in section 7.6.3.

8.6.2 Multiple delaying events

In each state two incidents may occur. These are independent of each other.

Disruptions may have happened in every segment of the chain. When added, these events form a chain of events in the chain. These events are independent of each other.

8.6.3 Priority

Restrictions are implemented to represent the situations where priority delivery is needed.

8.6.4 Restrictive events

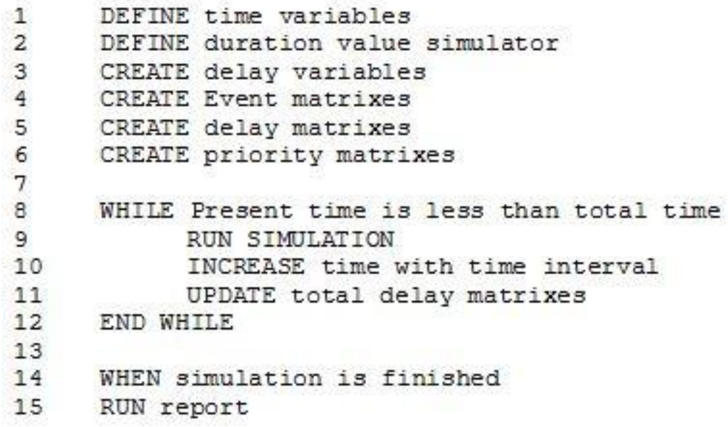
Restrictions are implemented to represent the situations where certain incidents prevent the occurrence of other events.

8.7 Script

The simulation was conducted through one main script and several subscripts. In this chapter, these scripts are explained. Due to the incomprehensible structure of the code, pseudo codes for the different scripts are presented. The codes in their entirety can be found in appendix H.

8.7.1 Main

This script ran the simulation. It created all the variables and matrices that were to be completed through the simulations, and initiated each simulation run. At the end of a run it compared the total time used with the total simulation duration and decided if another run should be initiated.



```
1     DEFINE time variables
2     DEFINE duration value simulator
3     CREATE delay variables
4     CREATE Event matrixes
5     CREATE delay matrixes
6     CREATE priority matrixes
7
8     WHILE Present time is less than total time
9           RUN SIMULATION
10          INCREASE time with time interval
11          UPDATE total delay matrixes
12    END WHILE
13
14    WHEN simulation is finished
15    RUN report
```

Figure 16 Pseudo code for main script

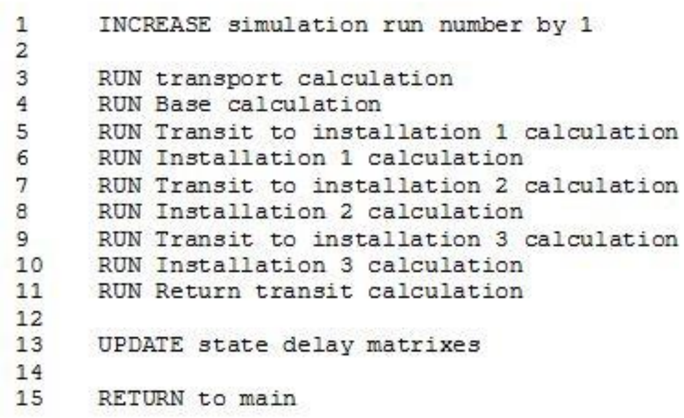
In line 1 and 2 all the time duration variables were defined and sat to zero. In line three the total duration of the simulation was defined. This was sat to be one year, or 8760 hours. Lines 4-6 created matrices that displayed the different occurring incidents, their impact and possible priority- or storage deliveries. These were created as zero matrices.

In line 8 the script compared the current simulation time to the duration constant defined in line 2. If the total time in the simulator was less than this value, the main program initiated the subscript *simulation.* When this was done and simulation had returned to the main program, then the total delay matrices were updated with the values calculated in the forgoing run.

If the current time was higher than the duration constant, the main script ran *results* and terminated the simulation.

8.7.2 Simulation

This script ran all of the calculation scripts. Combined with the calculation scripts, this script followed the logical structure demonstrated in figure 17.



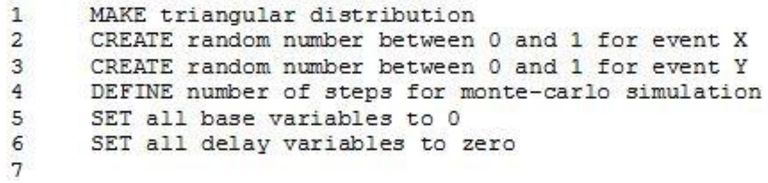
```
INCREASE simulation run number by 1

RUN transport calculation
RUN Base calculation
RUN Transit to installation 1 calculation
RUN Installation 1 calculation
RUN Transit to installation 2 calculation
RUN Installation 2 calculation
RUN Transit to installation 3 calculation
RUN Installation 3 calculation
RUN Return transit calculation

UPDATE state delay matrixes

RETURN to main
```

Figure 17 Pseudo code for simulation script

In the first line the counter that counts the number of simulations was updated. Then the script systematically ran through the different calculation script, which each represented a different cargo handling segment. When the run was completed the delay matrices for the current simulation was updated before returning to the main script.

8.7.3 Triangular calculations

The simulation consists of nine triangular subscripts, one for each segment in the chain.



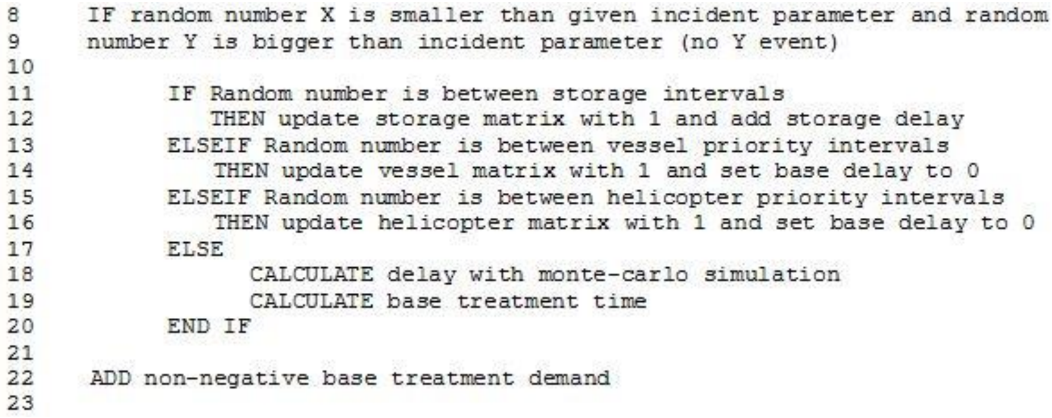
```
1     MAKE triangular distribution
2     CREATE random number between 0 and 1 for event X
3     CREATE random number between 0 and 1 for event Y
4     DEFINE number of steps for monte-carlo simulation
5     SET all base variables to 0
6     SET all delay variables to zero
7
```

Figure 18 Pseudo code for base calculation 1

The duration and delay of each segment was calculated in these subscripts. Separate calculation script for each of the transit and installation treatments segments was made to make the overall code simple and comprehensible.

The pseudo code presented is for base treatment since this code also includes the priority calculation code that is not found in the other scripts. Apart from these restrictions, all scripts are similar in their structure, but their triangular values and incident intervals vary. See table 14 and appendix G for the different values.

The triangular distribution was defined in line 1. All impact calculations were based on these calculations. In the line 2 and 3 the model generated random numbers between 0 and 1. These numbers were later compared with the IPP for determining if any incident had occurred. For the second incident, Y, to be valid, then incident X needed to have occurred. Line 4 defined the number of runs for the Monte- Carlo simulation. In line 5 and 6, all segment variables were sat to zero.



```
8     IF random number X is smaller than given incident parameter and random
9     number Y is bigger than incident parameter (no Y event)
10
11          IF Random number is between storage intervals
12             THEN update storage matrix with 1 and add storage delay
13          ELSEIF Random number is between vessel priority intervals
14             THEN update vessel matrix with 1 and set base delay to 0
15          ELSEIF Random number is between helicopter priority intervals
16             THEN update helicopter matrix with 1 and set base delay to 0
17          ELSE
18                CALCULATE delay with monte-carlo simulation
19                CALCULATE base treatment time
20          END IF
21
22    ADD non-negative base treatment demand
23
```

Figure 19 Pseudo code for base calculation 2

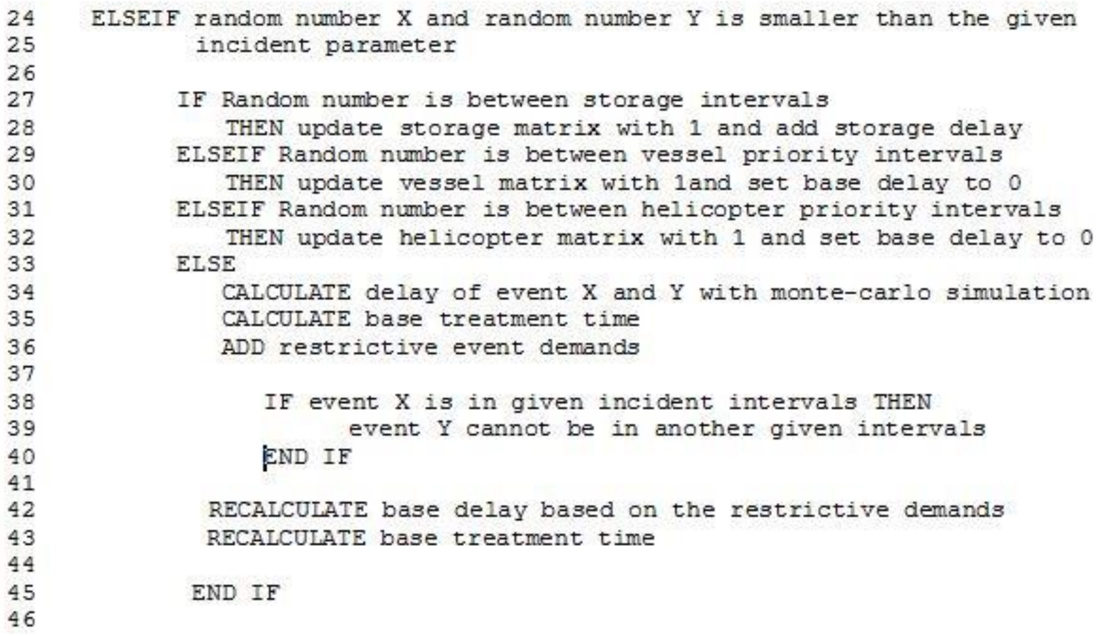
The code presented in figure 19 is the first part of an extensive if-loop where it is decided if one or multiple disruptions occur. In line 8 and 9, the random numbers were evaluated. If the random X value was smaller than the IPP, and the random Y variable was bigger than the IPP, then this first part of the loop presented in figure 18 was initiated. This indicates that one disruption had occurred in the given segment.

The random number was first compared with the priority restrictions to see if any extra treatment of the cargo was needed. The storage restriction applies for situations where the cargo arrives late to the base, but is sent to storage due to low criticality. The storage delay was sat to 20 hours. (Assuming that the cargo that was supposed to arrive at 12.00 arrived after 16.00, and then sent with another vessel on the next day.) If the random number was in this interval, the storage restriction was effected and its matrix updated.

If the storage restriction was not initiated, then the simulation compared the random number with the priority restrictions. They are defined in line 13-16. If the cargo was priority, the delay was sat to zero and the priority matrix was updated.

If none of the restrictions above were valid, a Monte – Carlo simulation was performed to calculate the disruption delay. 10.00 delay values were extracted from the triangular distribution and their average value was calculated. This value represented the delay duration for the occurring disruption.

Ultimately, an if-loop restriction ensured that the base treatment time calculated was positive a positive value.



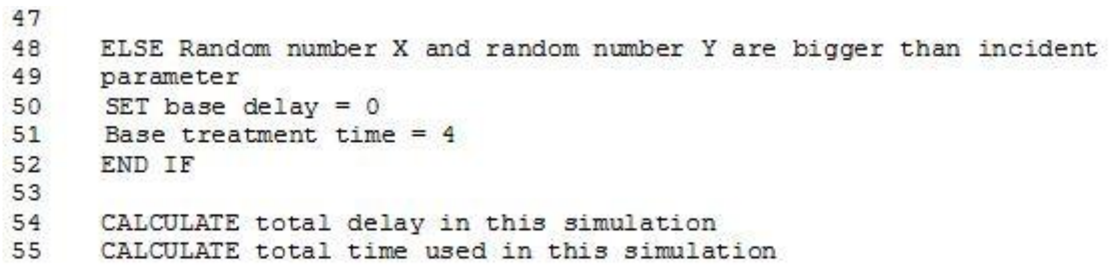
```
24  ELSEIF random number X and random number Y is smaller than the given
25         incident parameter
26
27        IF Random number is between storage intervals
28           THEN update storage matrix with 1 and add storage delay
29        ELSEIF Random number is between vessel priority intervals
30           THEN update vessel matrix with 1and set base delay to 0
31        ELSEIF Random number is between helicopter priority intervals
32           THEN update helicopter matrix with 1 and set base delay to 0
33        ELSE
34           CALCULATE delay of event X and Y with monte-carlo simulation
35           CALCULATE base treatment time
36           ADD restrictive event demands
37
38              IF event X is in given incident intervals THEN
39                    event Y cannot be in another given intervals
40              END IF
41
42          RECALCULATE base delay based on the restrictive demands
43          RECALCULATE base treatment time
44
45         END IF
46
```

Figure 20 Pseudo code for base calculation 3

The next part of the code is presented in figure 20. It considered situations where two disruptions had occurred in the same segment. It is the second part of the if-loop showed in figure 18, and consists of many of the same restrictions.

A similar if-loop was used to control if any cargo were to be sent to the storage or be delivered as priority. If these restrictions were not valid, a Monte- Carlo simulation was performed as explained in the last section. The main difference in this part of the code is that it includes two disruptions, and not only one. This means that if a storage or priority event occurred, a Monte-Carlo simulation was conducted for the second disruption. A simplification in the model was that only one storage or priority delivery could occur in each run.

After these restrictions were run and the impact calculation was completed, restrictive event constraints were run. This was to assure that restrictive events did not occur at the same time. The restrictive events are presented in section 5.6 and appendix D. After these restrictions were controlled, a re-calculation of the different delays was performed.



```
47
48    ELSE Random number X and random number Y are bigger than incident
49    parameter
50     SET base delay = 0
51     Base treatment time = 4
52    END IF
53
54    CALCULATE total delay in this simulation
55    CALCULATE total time used in this simulation
```

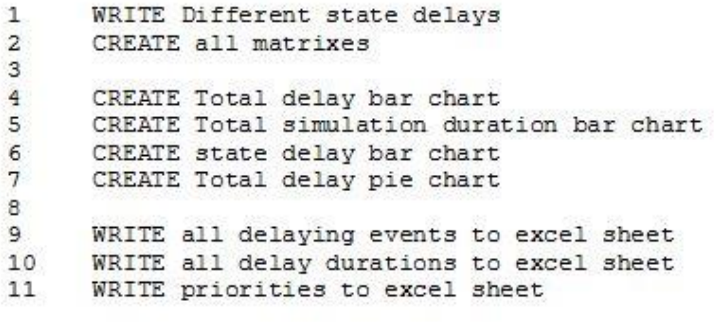
Figure 21 Pseudo code for base calculation 4

Figure 21 is the last part of the if-loop, and calculates the segment duration when no disruptive event occurred. The delay was automatically sat to zero, and the treatment time was sat to the triangular peak time, which is the estimated duration time for the segments. For the base treatment this was defined as four hours.

In line 52, the main if-loop is ended. Then the delay and time used in the simulation was summarized for all segments. When the script was completed, the simulation returned to the script *simulation* and continued to the next segment for its delay calculation.

8.7.4 Output

The report script is presented in figure 22. It is initiated after the simulation is complete.



```
WRITE Different state delays
CREATE all matrixes

CREATE Total delay bar chart
CREATE Total simulation duration bar chart
CREATE state delay bar chart
CREATE Total delay pie chart

WRITE all delaying events to excel sheet
WRITE all delay durations to excel sheet
WRITE priorities to excel sheet
```

Figure 22 Pseudo code report script

This script summarized the simulation in matrices. The matrices stated the different events that had occurred in the different segments, and the duration of these disruptions. Matrices that demonstrated priority deliveries were also made. This information was also sent to an excel spread sheet for further consequence analysis.

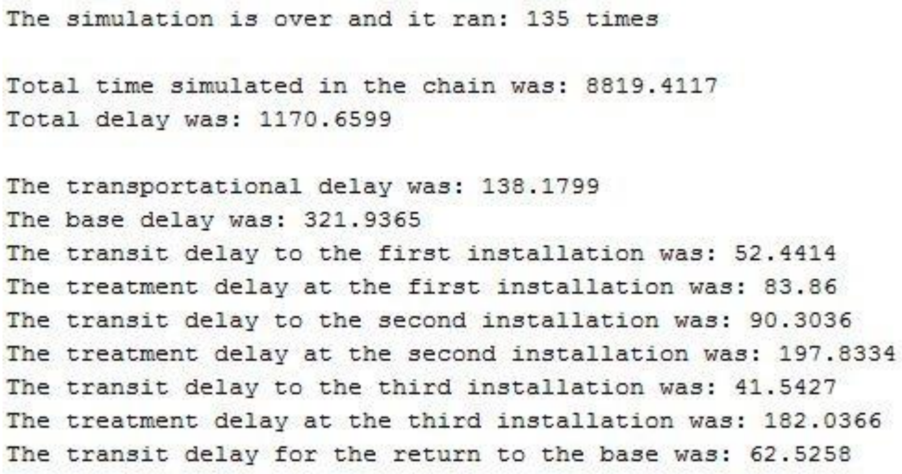
Graphs over the duration of each simulation run, the delays in each segment and the total delays in the chain were created. A pie chart over the total delay distribution for the different segments was created. They are presented in the next chapter.

When the simulation was completed a short summary of the simulation was written out in the command window. It stated the total time and the delays in the simulation. This is demonstrated in figure 23.

9. Results

In this chapter the results from the simulation model are presented. First, the result for one simulation is presented. Secondly, the combined and analyzed result from 10 simulation runs is presented.

9.1 The results from one run



```
The simulation is over and it ran: 135 times

Total time simulated in the chain was: 8819.4117
Total delay was: 1170.6599

The transportational delay was: 138.1799
The base delay was: 321.9365
The transit delay to the first installation was: 52.4414
The treatment delay at the first installation was: 83.86
The transit delay to the second installation was: 90.3036
The treatment delay at the second installation was: 197.8334
The transit delay to the third installation was: 41.5427
The treatment delay at the third installation was: 182.0366
The transit delay for the return to the base was: 62.5258
```

Figure 23 Simulation output

When one simulation is completed the simulator writes out a short summary. This is shown in figure 23. The delay times are given in hours, and are the key values from a simulation. This graph shows that the average delay of one simulation is almost 9 hours, which is a too high result. It can also be seen that it is the transit modes that has the highest occurrence of delays, which is consistent with the Statoil case.

The simulation result is also illustrated with graphs. Figure 24 shows the duration of the different runs. The average duration of one run is around 65 hours. This seems like a slightly high result since the duration of a perfect run is around 58 hours.

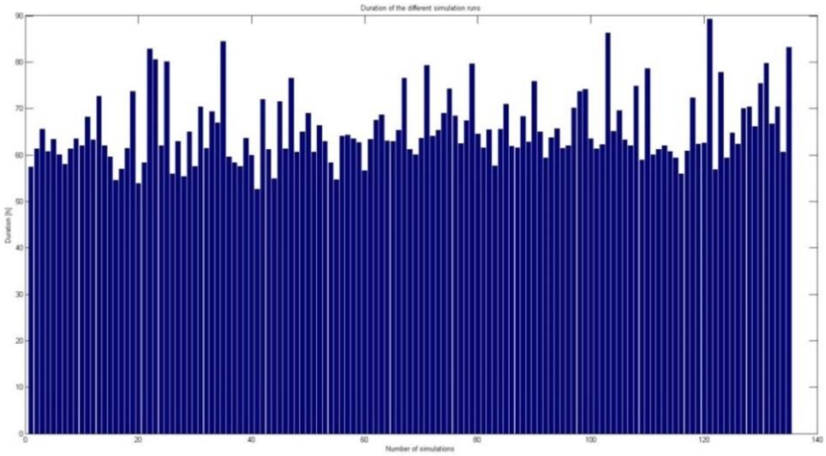


Figure 24 Duration simulations

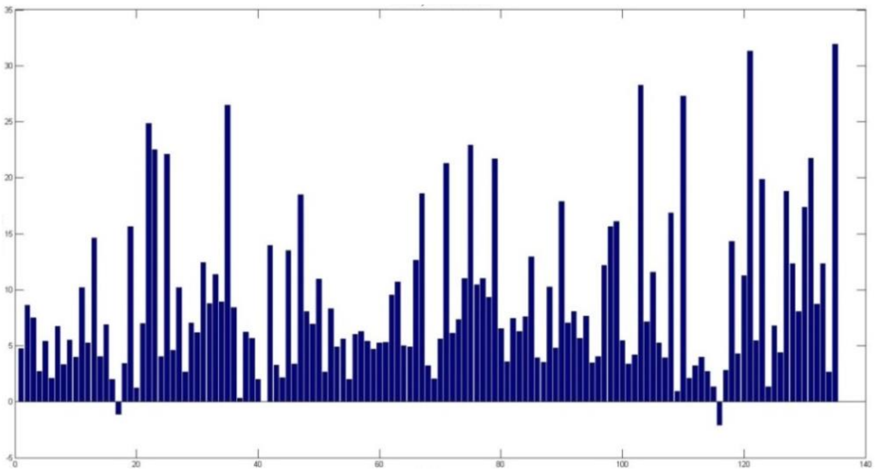


Figure 25 Simulation delays

Figure 25 writes out the different delays in each run. It demonstrates the different delay durations, and the deviation from the planned schedule. From the figure we can see that only one run is completely on schedule, and that the average delay is a bit higher than expected. The number of major delays is also very high.

In one simulation run, a majority of the segments have occurring incidents. The delays presented in figure 25 are the summarization of all the delays in a run. Even though most of the delays are small, it indicates a very high number of occurring incidents. From this observation we can conclude that the IPPs should be reduced to a lower value.

9.2 Excel template

When completing one simulation, the gathered information was sent to excel for further analysis. The information was sorted and compared with the purpose of identifying the types of disruptions that had occurred in the simulation and the consequence for each disruption.

The excel template was specially designed for analysis of the simulation results. First, all the results from a simulation was gathered in an excel template. This template linked the random numbers from the simulation to the event frequencies defined, and revealed the types of incidents that had occurred in the simulation and their durations. It also gave the number of storage- and priority treatments, as well as their occurring time. The result was a complete event distribution from a simulation run.

When the durations of the different delays was compared it showed that disruptions occurring in the same states had the same delay duration, e.g. all disruptions that occurred in the base was either under two or around 15 hours. This is due to the impact of an event being connected to the segments and not the specific events. These results are an indication for the need of changing the method for impact calculation in the simulation model.

9.3 The results from 10 runs

To be able to perform a sensitivity analysis a certain quantity of information was needed. The simulation was performed 10 times, and the data was collected and analyzed in the excel template. A precise and complete event distribution was illustrated.

Figure 26 shows the occurring events at the base over a 10 year period. The numbers on the x-axis coincides with the events presented in table 2. The y-axis represents the number of times an event has occurred during a ten year period. The distributions for the segment distributions are given in appendix I.

Figure 26 shows that the most occurring events at the base were number 9; *extra treatment of cargo at the base after opening hours*. The second largest was number 8; *delayed departure from base*. These disruptions are mainly caused by earlier disruptions and delays in the chain, and this coincides with the frequencies found in section 4.2.2 and in appendix G.

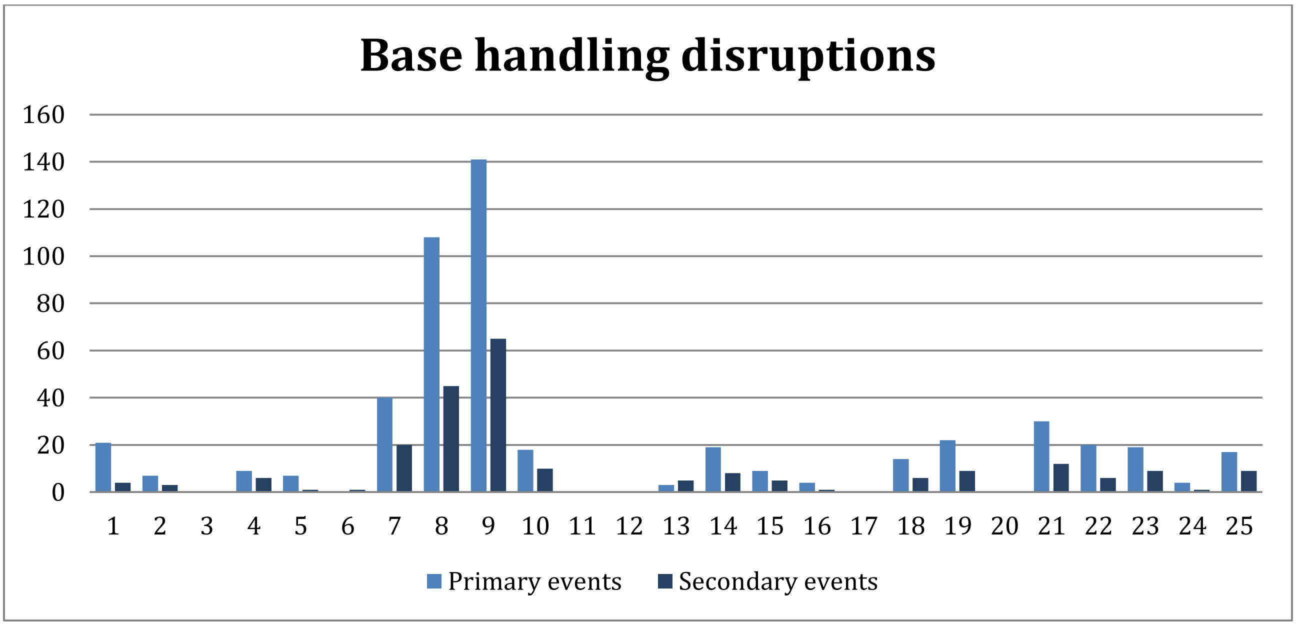


Figure 26 Base handling disruptions for a 10 year period

For the transportation to base the most occurring event was clearly *extreme weather.* This implies that alteration of base frequencies are needed since the impact of this event does not affect the transportation in such a great extent in the reality. The other values seemed realistic.

For the transit to the installation the most occurring event was *the vessel arriving late for offloading*. This is a disruption caused by earlier delays in the chain. *Changes in the original sailing plan* were also a contributor for delays in this segment, this may also be a disruption caused by decisions made earlier in the chain, but can also be caused by other installations where a change in the sailing plan has been used as a delay reducing measure. Besides this, weather, *waiting on weather at the base or the platform* or *waiting for the platform* to be ready, are the biggest contributors for delays in this segment. This coincides with the Statoil case in section 4.1.1. When it comes to event definitions for this segment, some of the incidents defined are very similar, and an alteration of them should be conducted.

Weather and *abortion due to weather* is an often occurring disruption in installation handling as well. The offloading process is included in this entity. *Night closed installations* and *poor placement of equipment on deck* is also a contributor for delays on the platforms. *Extra lay time for supply vessels* is also a noticeable incident that delays the installation operation slightly.

For the return transit back to base the two most common contributors for delay is *weather situations* or *delayed departure from the last installation* due to delays earlier in the chain.

The simulator does not consider the occurrence of secondary events, as defined in section 3.5.1. This is because they are not directly related to transportation of supplies. Probabilities for the occurrence of these events may still be found from the ETAs and are given in table 12.

When analyzing the event distribution in the different segments it is clear that many of the values given from the simulator can be seen as realistic. Alteration is needed for some of the frequencies and the IPP. The event frequency values need to be confirmed, and the IPPs need to be reduced since the simulation gives a higher disruption frequency and delay duration than what is seen as realistic. A reassessment of the different occurring event should also be conducted.

9.4 Sensitivity analysis

This section contains a sensitivity analysis where the simulator results will be compared to the Statoil case presented in chapter four. The analysis is done to find the reliability in the simulation results.

The simulation provides information on which event that occurs in every segment, and their impact on the schedule. The results from ten runs are summarized to provide a good information basis for the comparison.

The Statoil case is only based on a one year period, but contains more information than the simulation since it includes vessel- and sailing information. Information on vessel (planned schedules and real sailing times) and over the priority treatment conducted the same year is provided from the Statoil case.

9.4.1 Delay

The Statoil case results are based on the number of delayed departures in the vessel transit. The duration of each delay was given, but the specific incident type was not specified.

Segment distribution	Departure from base		Arrival at installation		Departure from installation	
	Total disruptions	Distribution	Total disruptions	Distribution	Total disruptions	Distribution
Early departures	460	0,19	4189	0,31	3741	0,34
Departures on schedule	965	0,41	1737	0,13	1092	0,10
Delayed departures	948	0,40	7455	0,56	6149	0,56
Total	2373	1,00	13381	1,00	10982	1

Table 15 Delay distribution Statoil

The simulation results are based on specific events that have occurred in three situations, base treatment, arrival at installation and departure from installation. The data is divided into three categories: Early departure, departures on schedule and delayed departure. The duration of the delays are given. All these incidents were independent of each other, and they were calculated based on a fixed route. The simulation results are presented in table 15.

Delay distribution Simulator		
	Total disruptions	Distribution
Transport	377	0,28
Base	512	0,38
Transit 1	723	0,54
Installation 1	427	0,32
Transit 2	738	0,55
Installation 2	404	0,30
Transit 3	747	0,55
Installation 3	366	0,27
Return base	688	0,51

Table 16 Delay distribution Simulator

The distributions given in table 16 are based of the share of segment runs with occurring disruptions.

A rough comparison has been made between the tables presented above. An approximation has been made concerning the segments in the tables. The simulation result is created from the average between the similar segments, and this average is compared with the Statoil case segments. This is demonstrated in table 17.

This comparison shows that, except for the installation departures, the proportion of delaying events in the simulator is quite similar to the Statoil case. A major difference is that the disruptions in the simulator are independent of each other. Because of this the disruption for each segment is calculated separately, and the dependency between events is not considered in a realistic manner. Each segment has a fresh start, and the delays from earlier segments are merely added to the total delay.

For the Statoil data, all disruptions are dependent on each other, and the delays in a segment could have been caused by disruptions in earlier stages. An already existing delay will be considered both when arriving and departing the installation, and not only in one segment as for the simulator. Still, the distributions are quite similar. This comparison shows that the number of disruptions in the simulation is realistic when not considering the dependence between different events.

Delayed departures	Statoil	Simulator
Base/departure from base	0,40	0,38
Transit/Arrival at installation	0,56	0,54
Installation/Departure from installation	0,56	0,30

Table 17 Comparison delays

Figure 27 compares the amount of delays in the two situations. The simulator does not consider early departures in the same way as the Statoil case. This is because early departures not give a negative impact on the schedule, and is therefore neglected in the simulation. For the simulator, early- and on scheduled departures can be considered as one. When this is done, it can be seem that the distribution of delays is quite similar, but the Statoil case has a higher degree of delays than the simulation distribution.

This means that when assuming the events in the simulator to be independent, then the quantity of disruptions is a bit lower than in the real life.

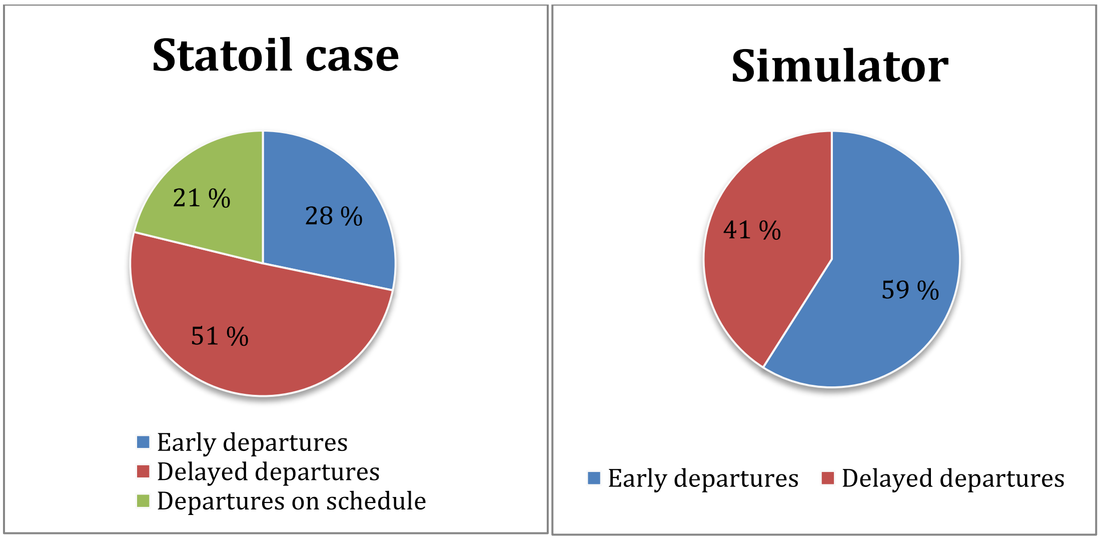


Figure 27 Delay distribution Statoil case and simulator

9.4.2 Duration of delays

In this section a classification of the delay durations are presented for the Statoil case and simulation result. These tables are then compared to see if the impact of the duration is realistic.

The table below shows the distribution for the Statoil case study. *On schedule* is defined as a 15 minute interval from the estimated times.

Statoil	**Delay base departures**		**Delay installation arrivals**		**Delay installation departures**	
	Incidents	Distribution	Incidents	Distribution	Incidents	Distribution
Departures on schedule	965	0,407	1737	0,13	1092	0,099
Early departures	460	0,194	4189	0,313	3741	0,341
Delay under 1 hour	565	0,238	1420	0,106	960	0,088
Delay under 2 hours	242	0,102	1186	0,089	930	0,085
Delay under 3 hours	62	0,026	822	0,061	832	0,076
Delay under 5 hours	35	0,015	1011	0,077	847	0,077
Delay under 10 hours	10	0,004	1137	0,085	945	0,086
Delay under 15 hours	10	0,004	588	0,044	494	0,045
Delay under 24 hours	12	0,005	599	0,044	521	0,047
Delay over 24 hours	12	0,005	692	0,052	620	0,057
Total amount of departures	2373	1	13381	1	10982	1

Table 18 Delay distribution Statoil

Table 18 present the Statoil distribution for the delay durations. Table 19 presents the delay durations calculated in the simulator. When comparing these tables it is easily seen that the durations of the delays in the two tables are far from similar. This indicates a weakness in the delay calculation. This weakness is due to the probability distribution being based on the segments, and not on the specific events. Since there is no differing between events, their delay will be almost the same value each time an incident occurs in a segment.

The solution to this is to calculate the delays according to the occurring events and not the entities they occur in. A proposed solution will be presented more detailed in chapter 10.

Simulator	Delay base departures		Delay transit installations		Delay installations	
	Incidents	Distribution	Incidents	Distribution	Incidents	Distribution
Departures on schedule	831	0,62	2476	0,47	2832	0,703
Early departures	0	0	94	0,02	1	0,0002
Delay under 1 hour	0	0	703	0,13	4	0,001
Delay under 2 hours	164	0,12	1967	0,37	28	0,007
Delay under 3 hours	142	0,11	24	0,005	932	0,231
Delay under 5 hours	0	0	0	0	25	0,006
Delay under 10 hours	194	0,14	13	0,002	145	0,036
Delay under 15 hours	2	0,001	1	0	48	0,012
Delay under 20 hours	8	0,006	1	0	12	0,003
Delay under 24 hours	1	0,001	0	0	2	0,0005
Delay over 24 hours	1	0,001	0	0	0	0
Total amount of departures	1343	1	5279	1	4029	1

Table 19 Delay distribution Simulator

9.4.3 Priority and occurring events

A comparison over the priority events was also performed. The information in table 20 is gathered from the Statoil case, whilst the information in table 21 is gathered from the simulation and adjusted in excel for comparison with the Statoil case.

This comparison gives an indication on the reliability of the event frequencies used in the simulator. For an optimal reliability control, information on all occurring incidents was needed, but this information was not obtainable.

Priority events Statoil case	Number of times	Distribution
Extra treatment of cargo at base after opening hours	3860	0,53
Earlier departure from base for supply ship	43	0,006
Delayed departure from base for supply ship	165	0,023
Rerouting of sailing plan	359	0,049
Supplies delivered by helicopter	818	0,113
Supplies delivered with extra helicopter	187	0,026
Extra call for supply ship on sailing plan	871	0,12
Extra lay-time at installation for supply ship	227	0,031
Supplies with vessel from a different supply base	14	0,002
Sharing of extra vessel with other installations	36	0,005
Use of extra supply vessel	74	0,010
Not possible to solve priority application	63	0,009
Total priority applications	7265	

Table 20 Priority events Statoil case

Priority events simulator	Number of times	Distribution
Extra treatment of cargo at base after opening hours	141	0,425
Early departure from base	40	0,120
Delayed departure from base	108	0,325
Rerouting of sailing plan	22	0,066
Use of extra vessel	4	0,012
Use of extra helicopter	17	0,051
Extra call for supply ship on sailing plan	Not considered	
Extra lay-time at installation for supply ship	Not considered	
Supplies with vessel from a different supply base	Not considered	
Sharing of extra vessel with other installations	Not considered	
Supplies delivered with extra helicopter	Not considered	
Total priority events	332	

Table 21 Priority events Simulator

The events that occurred in the simulator where scaled for comparison with the Statoil case. The number of priority occurrences has been summarized and a distribution has been made based on this.

All of the Statoil priority situations where not included in the simulator. This was due to the structure of the model. The model is based on a given schedule, and all priority solutions based on changes in the schedule are not considered.

A pie chart comparison was used to compare these two distributions. At first sight these distributions looked very different, but when adjustments were considered and the charts are compared, it was shown that the simulation distribution was not as divergent as first assumed.

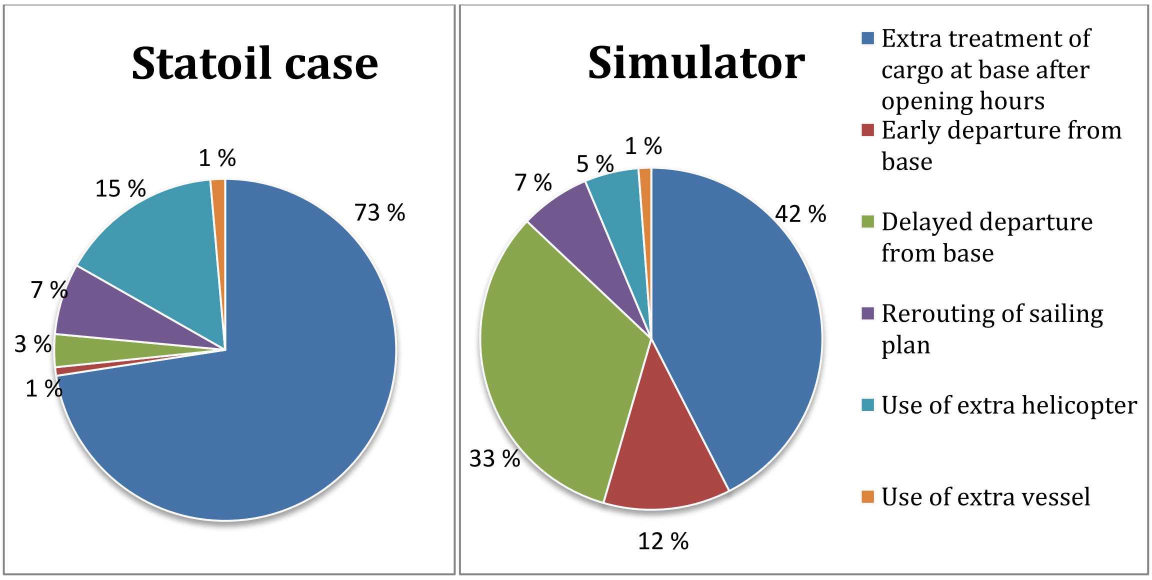


Figure 28 Comparison of priority solutions

Delayed vessel departure from base is a bit higher in the simulator than in the Statoil case. This corresponds with the alterations of priority frequencies explained in section 6.1, where this solution and *extra treatment on base after opening hours* is adjusted between each other. The distribution in between these solutions is acceptable.

The *delayed departure* value for the Statoil case does not match the value presented figure 26. This is because figure 28 only includes delays used as a priority solution, and not all delayed departures.

Early departures as a priority solution is not fully included in the simulator since early departures do not have a negative impact on the schedule. It is only included as an event in the incident tables. This deviation is therefore implemented, and the result is as expected.

The *Rerouting of sailing plan* distribution are quite similar, and the result is realistic. This is just considered as an event, and not implemented as a priority solution. This should be altered in a future simulation model.

The simulator has considered extra vessel and helicopter departures, and one sees that helicopter transportation occurs more frequently in the simulator than in real life. This is an adjustment that should be conducted. The vessel transportation frequency looks realistic.

This part of the sensitivity analysis is mainly a confirmation of the event frequencies. It reveals which frequency values are realistic, and which that needs to be altered. This should be performed for all incidents in the chain when this information is available.

10. Comments and further work on the simulator

The simulator gives a good description of the offshore supply chain, but there are certain aspects that should be revised if this project were to be continued. In this section, suggestions for improvement of the simulator are presented.

10.1 Input

The data on the occurring events (frequencies, probabilities) should be imported from MS excel into MATLAB. Then MATLAB would be able to analyze the occurring events directly and there would be no need for evaluation of the events in excel.

The event restrictions should be more general and be linked to the excel input via MATLAB. This would make the simulator more general and it would be easier to adjust it to other systems.

10.2 Simplifications

The model is simplified by assuming homogenous cargo. Different types of cargo should be considered since there is a difference in their treatment time at the base, and loading time at installations. Certain equipment also has a different transit time out to the installation.

The simulator should generate different types of routes. The author proposes to make the system into a VRP model where all feasible routes first will be generated, and then solved as a TSP to make sure that the best possible route is found. The simulator should pick randomly between the different routes. The coordinates for all relevant installations should be provided for MATLAB in an input file.

The model is simplified by assuming a homogenous fleet. This means that there is no emphasis on a ships age, size, operational equipment etc. There is also a difference in types of ships that can carry the different types of cargo e.g. bulk. A future model should consider the cargo relative to its size and weight, and to the available space on the vessels. It should also be restrictions for cargo that needs to be transported with special vessel.

The simulator should be divided into two parts. A part that considers cargo arriving at base, and another part that considers the transit to the installations on the different routes. This is because there are multiple cargo units arriving at the base, and therefore the probability of more disruptions increase, and also to make it possible for the simulator to consider the cargo units based on the loading terms suggested above. The second part will be similar to the model given in this thesis.

10.3 Distributions of incident

The current model calculates delay with a triangular distribution for each segment. This is a simplified way of calculating delay. The next move should be to calculate the impact of an occurring event on probability distributions directly related to the disruptions, as explained in chapter 7. This will give a more realistic calculation of impact since it will depend on the disruption and its probability distribution, and not just the entity the disruption occurs in. Distributions for the different incidents are proposed and explained in chapter 7.

Attention should also be given to bionomial incidents. The impact of a bionomial disruption can be a non-delivery of the needed equipment, and the consequences for the operation and production may be severe.

When calculating impact, the cargo should be considered in terms of criticality and the possible delay it already has gained in the earlier segments. This will be an important factor when deciding if a priority solution is needed. Alterations for dependency between incidents are suggested later in this chapter as well.

10.4 Events

The simulator should consider dependent events. When certain disruptions occur this may increase the probability of other incidents occurring, e.g. late crew till base increases the probability for the ship being delayed from base. Many disruptions in one state increases the probability for further delay in other states. This dependency between events and across segments is not considered in this simulator, and should be a priority if further work with this simulator is to be conducted.

Additional types of priority transportation should be included e.g. change of sailing route and consideration of additional legs. This is an alteration that should be done when the simulator generates its own routes. In this model the transit time in between the installations is sat to be equal, and therefore a shuffle in the route legs will not have any effect on the different simulations. And additional route legs were not considered since the simulator operated on a fixed route. With the generation of different routes in the simulator, more priority constraints need to be added to the model.

For priority deliveries it should be specified which installation the cargo is intended for. This is a necessary alteration to make the alterations of sailing plan solution valid.

There are too many events occurring in each run. The incident parameters should be reevaluated. With the implementation of probability distributions for each event there might not be any use for these parameters since the occurrence of an event will be dependent on their distribution. Event distributions should still be linked to each segment as done in this thesis. This is due to the fact that the same incident may have different consequences when occurring in different segments, e.g. weather.

The model is restricted by the events that may occur in a state. Only two disruptions may occur in one event. It is not likely that more events will happen in one segment, but this restriction limits the model nevertheless. An alteration that randomly chooses the number of disruptions in a state may be considered added. This should be different for the two simulation parts.

Restrictions concerning the restrictive events and priority solution conditions should be added. For some incidents, the restrictive restrictions should be implemented. Restrictions that make sure that equal incidents do not happen multiple times in the same segment should be implemented as well, e.g. bad weather cannot affect the transportation to the base two times in one delivery.

A code that registers and evaluates chain events should be registered in the simulator. This may be applied with the evaluation of dependent events. The most catastrophic incidents needs that several safety regulations fail to happen. These dependent chains should be programmed into the model with the other event restrictions.

Situations like dry-docking, bunkering and other irregular off-hire situations for the vessels are neglected.

10.5 Other implementations

Another factor that should be included in a future model is seasonal differences. The Statoil data presented in chapter 4 present seasonal distributions for vessel delays and incidents that may be implemented in a future model.

11. Conclusion

The first part of the thesis consists of a thorough event- and consequence analysis. The system is analyzed, and the result gives a clear impression on the different events that may occur in the chain and the relationship between them. This analysis showed that it is in the transit most of the disruptions occur. It also showed that many disruptions occur during transport to and under treatment in the base, but for these segments delay reducing measures can be implemented. Secondly risk- and consequence analyses are performed to make a clear representation of the supply chain.

The second part of the thesis consists of a simulation model that demonstrates the daily activity in an offshore supply chain. It is directly based event frequencies defined in part one.

A sensitivity analysis has been performed. It showed that certain parts of the results from the simulator prove to be accurate and reliable. This applies for the distribution of delay when assuming independent events in the simulator and the share of priority solutions. The duration of the different delays was not reliable, and gave excessive durations.

The model gives a good illustration on the system flow, but alterations are needed for it to be as realistic as possible. The main alteration is to change the impact calculation to be based on the different events and not on the segment where it occurs. This will make the delay durations realistic. A focus on a more complete modeling of dependent incident should also be an important objective. The implementation of these measures, combined with the event analysis, should make the process towards developing a re-planning tool much easier.

The author also will acknowledge that if she were to continue this work, she would have used a completely different structure for the simulation model. She would have made a model that to a greater extent demonstrated the relationship between event and impact.

The goal of this thesis was to achieve a good understanding of the events and consequences in the system, and the author feels that this is accomplished. Some of the proposed developments probably could have been implemented in the simulation, but the task was to make a model that demonstrates the relationship between events and consequences and based on this suggest measures for further development. The model is not optimal, but a good basis where the further work is clearly identified.

11.1 Further work

Even though this thesis is a good basis for further work there is still much that needs to be altered before it can perform its intended tasks. The main alterations are:

Part 1: Event and risk analysis

- The analysis performed is limited by access to data and imagination. A more extensive event analysis should be made and it should solely be based on real data and experience by competent people with a greater understanding of the chain.

- A confirmation of the all estimated event frequencies should be made.
  Attention should also be directed towards verification of the incident parameter. This is for preventing that too many events occur in the different entities.

- An ETA analysis should be performed for all of the possible dependent events. In this thesis five scenarios are analyzed, but there are more possible combinations of possible event chain that should be analyzed closer for a total incident comprehension.

Part 2: Simulation

Further development of the simulator should be done with the goal of making a planning tool for Statoil.

- The simulator needs to be more general. In the current model, the specific restrictions for certain events are written into the code. The simulator should retrieve the event frequencies from excel. This will make it easier to adjust the model to another system.

- A more advanced data program than MATLAB should be used to retrieve greater control of the system.

- A new calculation method for impact should be made based on probability distributions for the different events. The probability distributions should be decided based on the possible consequence of a disruption.

12. Bibliography

1. Oleivsgard, G., *The drilling supply chain from a logistical perspective*, 2012: NTNU - project thesis.
2. G.Korneliussen, *Interview*, 11.12 2012.
3. Statoil. *Logistikkportalen*. 2013.
4. Christopher, M., *Logistics and supply chain management.* Financial times, London, 1992.
5. Craighead, et al., *the severity of supply chain disruptions: Design characteristics and mitigaition capabilities.* Decision Science instutute, 2007: p. 131-156.
6. Kleindorfer and Saad, *Managing disruption risks in the supply chain.* production and operations management, 2005. **14**(1): p. 53-68.
7. Halvorsen-Weare, E., *Maritime fleet planning and optimization under uncertainty.* Thesis for the degree of philosophiae doctor, NTNU, 2012.
8. T.E Notteboom and J.P Rodrigue, *Conteinerisation: Box logistics and Global supply chains: THe integration of ports and liner shipping networks.* maritime economics and logistics, 2008(10): p. 152- 174.
9. Notteboom, T.E., *The time factor in liner shipping services.* maritime economics and logistics, 2006(8): p. 19-39.
10. Gkanaska, E., *Operation Planning and the Concept of Robustness in Maritime Transportation*, 2005, Erasmus University Rotterdam.
11. G. Yu and X.Qi, *Disruption managment: Framework, models and applications.* World scientific publishing, 2004.
12. Q. Mu, et al., *Disruption management og the vehicle routing problem with vehicle breakdown.* Journal of operation research society, 2011(62): p. 742 - 749.
13. E. Espeland Halvorsen-Weare and K.Fagerholt, *Robust supply vessel planning.* Network optimization, Springer, 2011. **6701**: p. 559-573.
14. E. Halvorsen-Weare, K. Fagerholt, and M.Rönnqvist, *Vessel routing and scheduling under unvcertainty in the liquefied natural gas business.* Computers and industrial engineering, 2011.
15. M. Christiansen and K. Fagerholt, *Robust ship scheduling with multiple time windows.* Naval research logistics, 2002. **49**(6).
16. Kjetil Fagerholt and Håkon Lindstad, *Optimal policies for maintaining a supply service in the norwegian sea.* omega, 1999(28 (2000)): p. 269 - 275.

17. K.Fagerholt, et al., *A decision support methodology for strategic planning in maritime transportation.* Omega, 2010. **38**: p. 465-474.
18. G. List, et al., *Robust optimization for fleet planning uinder uncertainty.* Transportation research part E, 2003(39): p. 209- 227.
19. H. Bidhandi and R.Yusuff, *Integrated supply chain planning under uncrtainty using an improved stochastic approach.* applied mathematical modelling, 2011(35): p. 2618 - 2630.
20. TIBCO, *Airline disruption management*, 2007.
21. J. Clausen, et al., *Disruption management in the airline industry - concepts, models and methods.* Computers and operations research, 2010(37): p. 809-821.
22. N.J Rezanova and D.M Ryan, *The train driver recovery problem - a set partitioning based model and solution method.* Computers and operational research, 2010(37): p. 845 - 856.
23. J. Jespersen-Groth, et al., *Disruption management in passenger railway transportation.* Robust online Large-scale optimization, 2009. **5868**: p. 399-421.
24. Fu, et al., *Integration optimization and simulation: Research and practice*, 2001.
25. A.W Law and W.D Kelton, *simulation, modelling and analysis*, ed. 2. 1991.
26. S. Terzi and S. Cavalieri, *Simulation in the supply chain context: A survey.* Computers in industry, 2004(53): p. 3-16.
27. J. Cheng and M.A Duran, *Logistic for world wide crude oil transportation using discrete-event simulation and optimal control.* Computers and chemical engineering 2004(28): p. 7.
28. A. Shyshou, I. Gribkovskaia, and J. Barceló, *A simulation study over the fleet sizing problem arising in offshore anchor handling operations* Transportation science, 2010(39): p. 340-348.
29. group:, T.S.O., et al., *interview*, 30.08 2012, Interviewer: G. Ngård, G.Ose, G. Oleivsgard.
30. Fagerholt, K., *Maritime transportation: ship routing and scheduling*, 2012. p. 22- 36.
31. Stopford, M., *Maritime economics*, ed. t. edition. 2008.
32. J.Rønholt, O.H Pedersen, and T.Grieg, *Simulation and rescheduling of operation for a roro fleet*, in *Institute of marine Technology*2012, NTNU.
33. Kristiansen, S., *Maritime transportation safety management and risk analysis*. 2005.

34. Carson, J.S., *Introduction to modeling and simulation*, in *Proceedings of the 2005 winter simulation conference*2005.
35. F.S hillier and G.J. Lieberman, *Introduction to operation research*, ed. 9. 2010: McGraw- Hill
36. T. Kråkenes, H. Ljøgodt, and S. Malerud, *simuleringsmetoder innen operasjonsanalyse, en overssiktsstudie*, F. Rapport, Editor 2007.
37. Warpole, et al., *Probability and statistics for engineers and scientists*. 8 ed. 2007: Pearson education.
38. Palisade. *Monte- Carlo simulation*. 16.04 2013; Available from: http://www.palisade.com/risk/monte_carlo_simulation.asp.
39. Wikipedia. *Triangular distribution*. 16.04 2013; Triangular distribution]. Available from: http://en.wikipedia.org/wiki/Triangular_distribution.
40. Mathworks. *Monte- Carlo simulation*. 27.05 2013; Available from: http://www.mathworks.se/discovery/monte-carlo-simulation.html.
41. Oleivsgard, I.G., *Interview: B.Gullberg*, 21.11 2011: Sandsli Bergen.
42. Google. *Transportation from Stavanger to Vestbase* 15.04.2013]. Available from: https://maps.google.no/maps?hl=no&tab=wl.

43. Statoil. *Vestbase*. 15.04 2013; Installations from Vestbase]. Available from: http://www.vestbase.com/om-vestbase/vestbase-as.
44. Angelshaug, A., *Base coordinator*, 04.05 2013.

Appendix A – Preliminary hazard analysis

Hazardous elemen	Trigging event 1	Hazardous conditions	Trigging event 2	Potential incident/disturbance	Probability	Effect
Cargo	Bad packing of cargo	Bad ways/poor driving	Cargo destroyed under transport	Cargo needs repair	Extremely remote	operational loss
Cargo	Bad packing of cargo	Bad ways/poor driving	Cargo destroyed under transport	Cargo needs replacement	Extremely remote	high operational loss
Cargo	Bad sea fastening of cargo	Cargo may loosen	Extreme weather	Destroyed or lost cargo, human damage	Extremely remote	Reparation or reporduction
Cargo	Badly marked cargo	Poor overview of load	Inattentive personell	Cargo is delivered wrongly	remote	Delay, production stop
Cargo	Badly marked cargo	Inattentive base personnel	Congestion of ships in base area	Cargo delivered to wrong ship	Extremely remote	Major delay
Base handling	Badly marked cargo from supplier	Inattentive base personnel	Congestion of cargo in base are	Cargo is sent wrongly to storage	Remote	Delay
Base handling	Badly packed cargo	Easy to break	Bad handling of base crew	Destroyed cargo	Remote	Reparation or reproduction
Cargo handling	Badly packed cargo	Easy to break	Bad handling of base crew	Destroyed cargo	Remote	Reparation or reproduction
Base	Broken equipment delivered to base	Problems at work shop	Not able to repair equipment	Reorder from supplier	Extremely remote	Risk of operational stop, delay
Base	Broken equipment delivered to base	Congestion	Long waiting time on repair of equipment	Risk of operational delay	Remote	High costs for operator
Base handling	Delayed delivery from supplier	Possibility for more delay	Delay persists	Priority delivery	Occational	Delayed departure of ship
Base handling	Delayed delivery from supplier	Possibility for more delay	Delay persists	Priority delivery	Remote	Change of sailing plan
Base handling	Delayed delivery from supplier	Possibility for more delay	Delay persists	Priority delivery	Extremely remote	Rental of helicopter
Installation	Extreme weather	loading is temoprarily suspended	Night closed installation	Change of sailing plan	Occational	High logistical costs, delay
Installation	Broken equipment	Need for new equipment	Not able to repair equipment	Reorder from supplier	Extremely remote	Risk of operational stop, delay
Installation	Broken equipment	Not able to repair equipment	Broken equipment sent to base	Not able to repair	Extremely remote	Risk of operational stop, delay
Installation	Broken equipment	Need for new equipment	Storage at installation is empty	Delivery from base storage	Remote	Delay, logistcal costs
Installation	Broken equipment	Need for new equipment	Storage at installation is empty	Reorder from supplier	Extremely remote	Risk of operational stop, delay
Installation	Change in operational need	Need of new equipment	Base does not have this equipment	Reorder from supplier	Extremely remote	Risk of operational stop
Installation	Change in operational need	Need of new equipment	Base does not have this equipment	Borrow from near by installation	Remote	Risk of operational stop
Installation	Change in operational need	Need of new equipment	Near-by installation don't have equipment	Reorder from supplier	Extremely remote	Risk of operational stop
Installation	Broken equipment	Need for new equipment	Inattentive installation crew	Loss of well control	Extremely remote	Risk of operational stop
Supplier	Handling of cargo is delayed	Futher transport may lead to greater delay	Trailer is delayed due to incident	Cargo misses indended vessel	Occational	Operational delay, logsitical costs
Supplier	Bad marking of cargo	Possibility of wrong sending cargo	Personell is inattentive	cargo is sent to storage/wrong ship	Extremely remote	Delay, operational failure
Trailer	Queue	Trailer is delayed	Trailer drives faster to make up for lost time	Collision, destroyed cargo, fatalities	Probable	Delay, logistical costs
Trailer	Queue	Queue is not dissolving	Queue persists	Delayed delivery to base	Occational	high operational loss, priority delivery
Trailer	Closed roads/tunnels	Trailer driving in unknown enviroment	obstacles prevents futher transport	Delaed delivery to base	Remote	high operational loss, priority delivery
Trailer	Queue	Queue is not dissolving	Problems with removal of reasons for queue	Delayed delivery to base	Probable	Additional cost for operator
Trailer	Closed roads/tunnels	Trailer driving in unknown enviroment	obstacles prevents futher transport	Delaed delivery to base	Remote	Additional cost for operator
Trailer	Closed roads/tunnels	Long detours	Delayed delivery of cargo till base	Delayed departure of ship	Occational	small cost for operator
Trailer	Closed roads/tunnels	Long detours	Cargo delivered too late to base	Change of sailing plan	Remote	Additional cost for operator
Trailer	Closed roads/tunnels	Long detours	Cargo delivered too late to base	Rental of helicopter	Extremely remote	Great additional cost for operator
Trailer	Extreme weather	Trailer continues with reduced speed	Bad sighting	Delayed delivery of cargo to base	Occational	Great additional cost for operator
Trailer	Extreme weather	Trailer continues with reduced speed	Bad sighting	Collision, destroyed cargo, fatalities	Extremely remote	Fatalities, severe damage of cargo
Trailer	Dark roads	Trailer continues with reduced speed	Bad sighting	Delayed delivery of cargo to base	Occational	Great additional cost for operator
Trailer	Dark roads	Trailer continues with reduced speed	Bad sighting	Collision, destroyed cargo, fatalities	Remote	high operational loss, priority delivery
Trailer	Engine problems	Trailer continues with reduced speed	Break down of vital parts	Delayed delivery to base	Remote	Fatalities, severe damage of cargo
Trailer	Break down of vital parts	Need for new trailer	New trailer is late	Delayed delivery to base	Occational	operational loss

39	Trailer	Break down of vital parts	Need for new trailer	New trailer is extremely late	Delayed delivery to base	Remote	high operational loss, priority delivery
40	Trailer	poor loading of cargo	Possibility for breaking parts of cargo	Bad roads and poor driving	Distroyed cargo	Extremely remote	High operational costs
41	Trailer	Slippery roads	Trailer drives with reduced speed	Dark roads	Delayed delivery of cargo to base	Remote	High logistical costs
42	Vessel	Busy due to season	Little available equipment	Late arrival of vessel	Delayed cargo	Probable	High logistical costs
43	Vessel	Cargo is delayed to base	Cargo is behind schedule	Base handling is delayed	Delayed cargo	Probable	High logistical costs
44	Vessel	Cargo is delayed to base	Cargo is behind schedule	Prioruty cargo: vessel waits for cargo	Delay	Occational	Operational loss for all installations
45	Vessel	Cargo is delayed to base	Cargo is behind schedule	Extreme weather	Delay	Probable	Operational loss
46	Vessel	Bad weather	WoW	Cargo equipment is broken	Delay, no delivery of cargo	Remote	High operational and logistical costs
47	Vessel	Extreme weather	Wow	Loss of vessel control	Grounding	Remote	High costs, HMS damger
48	Vessel	Extreme weather	Delayed transit time	Break down of ship parts	Collision, non delivery	Remote	High costs, HMS damger
49	Vessel	Machinery problems	Potential delay	Bad weather	Extreme delay	remote	Huge operational costs
50	Vessel	Offloading of vessel	Sensitive operation	Change of weather	Abortion of offloading	Extremely remote	Delay of delivery, collision with plattforr
51	Vessel	Equipment broken during offloading	Reduced offloading	Change of weather	Abortion of offloading	Remote	Delay of delivery, collision with plattforr
52	Vessel and installatio	Vessel is fully loaded	Problems when offloading	Installation is fully loaded	Not able to load on or off	Remote	Delay, potential risk of operational stop
53	Vessel and installatio	Installation waiting on priority delivery	Another installation have a greater need	Change of sailingplan	Delayed delivery	Remote	potential stop or reduction of productior
54	Vessel and installatio	Installation waiting on priority delivery	Another installation have a greater need	Change of sailingplan	Delayed delivery	Extreme remote	Stop of production
55	Vessel and installatio	Installation is fully Loaded	No room for new cargo	Arrival of supply vessel	No delivery of cargo	Extreme remote	Delay, potential risk of operational stop
56	Base handling	Delayed delivery from supplier	Base personell works to make up for lost tim	Inattention, too effective treatment of cargo	Cargo is destroyed	Extremely remote	New ordering of equipment
57	Vessel	Delayed vessel	Personnel trying to make up for lost time	Lack of sea fastening control	Cargo not seafastened properly	Extremely remote	Broken equipment, risk of operaional stc
58	Vessel	Cargo is not seafastened properly	Extreme weather	Cargo loosens	Cargo is destroyed	Extremely remote	Risk of operational delay
59	Vessel	Cargo is not seafastened properly	Extreme weather	Cargo loosens	Cargo is broken and needs repair	Extremely remote	Risk of operational delay

Appendix B – Dependency and incident diagrams

Dependency and influence diagram Scenario 1: Delayed cargo from supplier	Extra treatment of cargo	Vessel departure is delayed	WOW	Crane equipment down	Not able to fix equipment
Transporational queue: Cargo is late till base	+ +	+			
Extra treatment of cargo		+			
Vessel departure is delayed			+		
WOW					
Crane equipment down					+

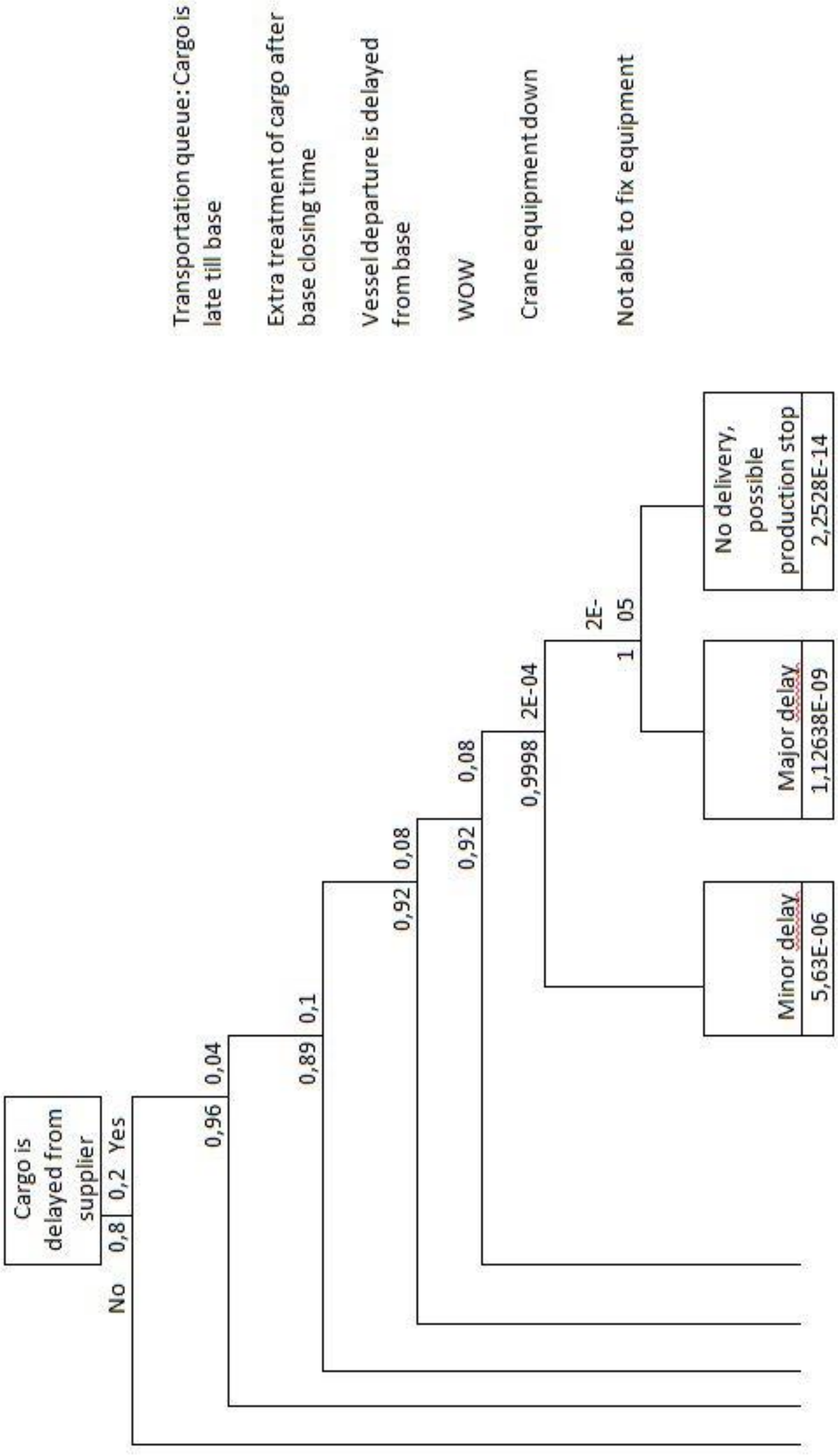
Simple dependency and influence diagram for Scenario 2: Badly marked Cargo	Congestion	Inattentive base crew	Cargo misdirected to wrong ship	Mistake not discovered	Urgent need for this equipment
Cargo arriving late at base					
Congestion		+	+	+	
Inattentive base crew			+	+	
Cargo misdirected to wrong ship					
Mistake not discovered					

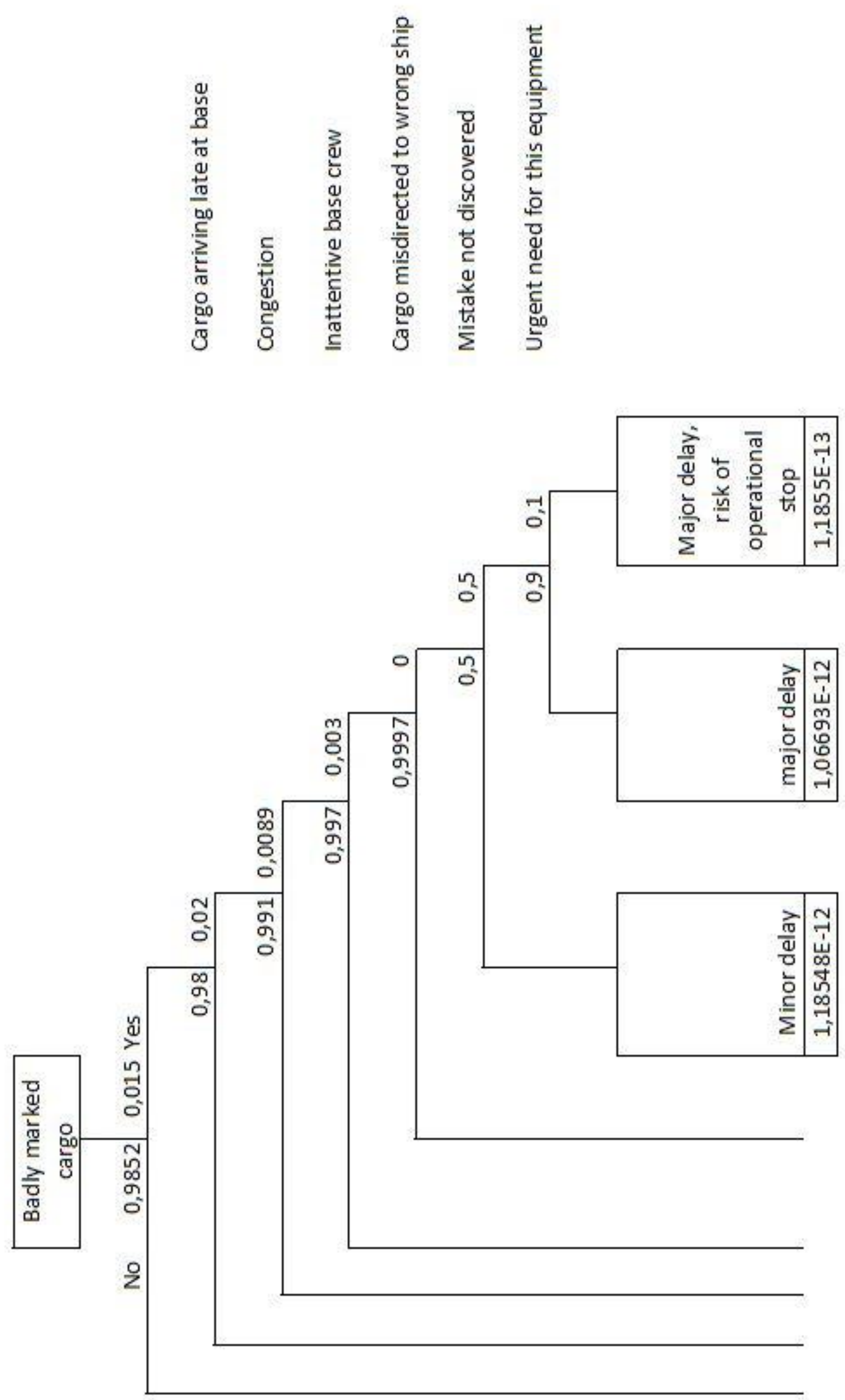
Simple dependency and influence diagram for Scenario 3: Cargo arriving late at base	Cargo is priority delivery	Cargo of medium size: sent with helicopter	WOW	Extreme weather at sea
Cargo does not get on waiting vessel		+		
Cargo is priority delivery		+		
Cargo of medium size: sent with helicopter				
WOW				+

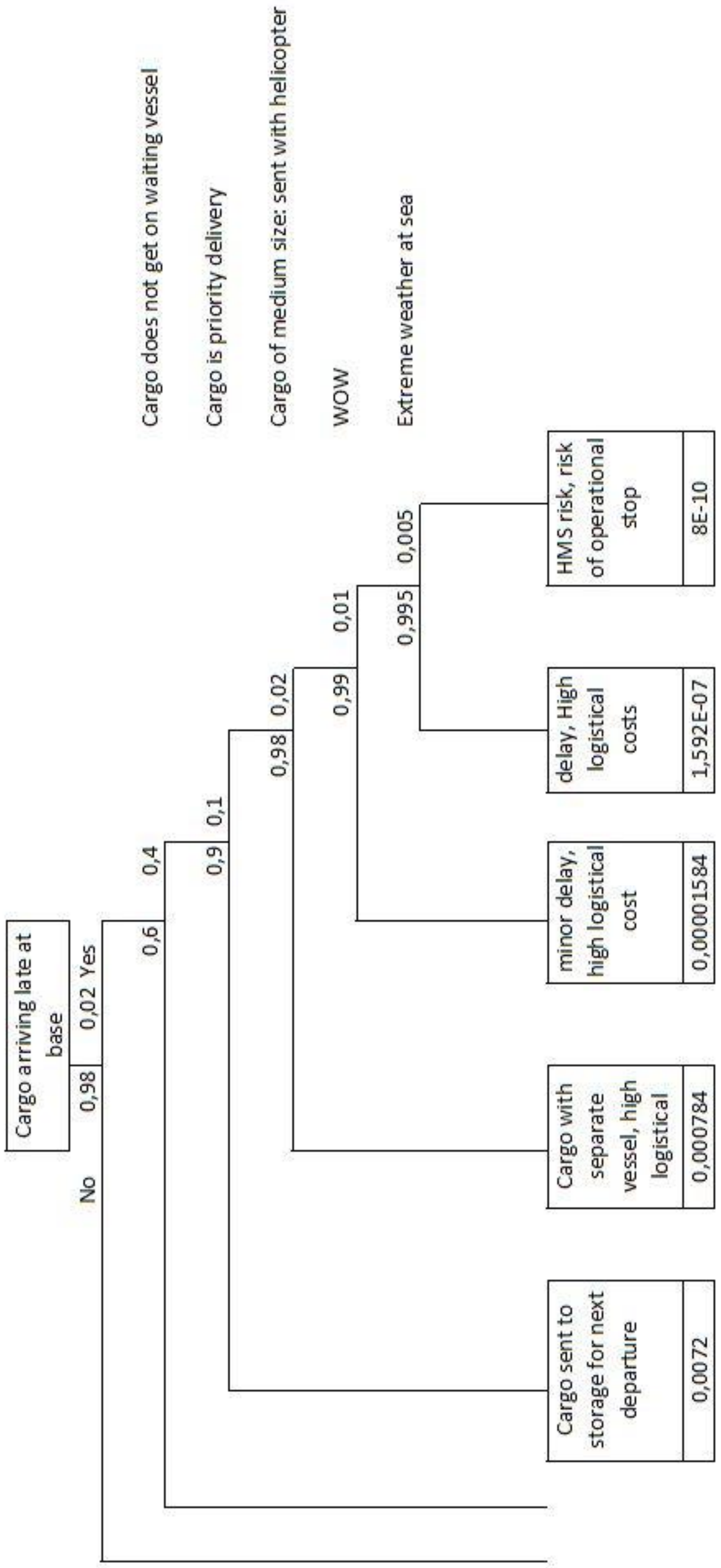
Simple dependency and influence diagram for Scenario 4: Extreme weather	Cargo loosens	Cargo is damaged and needs repair	Waiting on platform	No possibilities for repair at platform	not on near-by installations	Needed equipment is not on base	Not able to repair on base
Cargo is not sea fasten properly	++	+					
Cargo loosens		++					
Cargo is damaged and needs repair				+			
Waiting on platform							
No possibilities for repair at platform							
Needed equipment not on near-by installations						+	
Needed equipment is not on base							

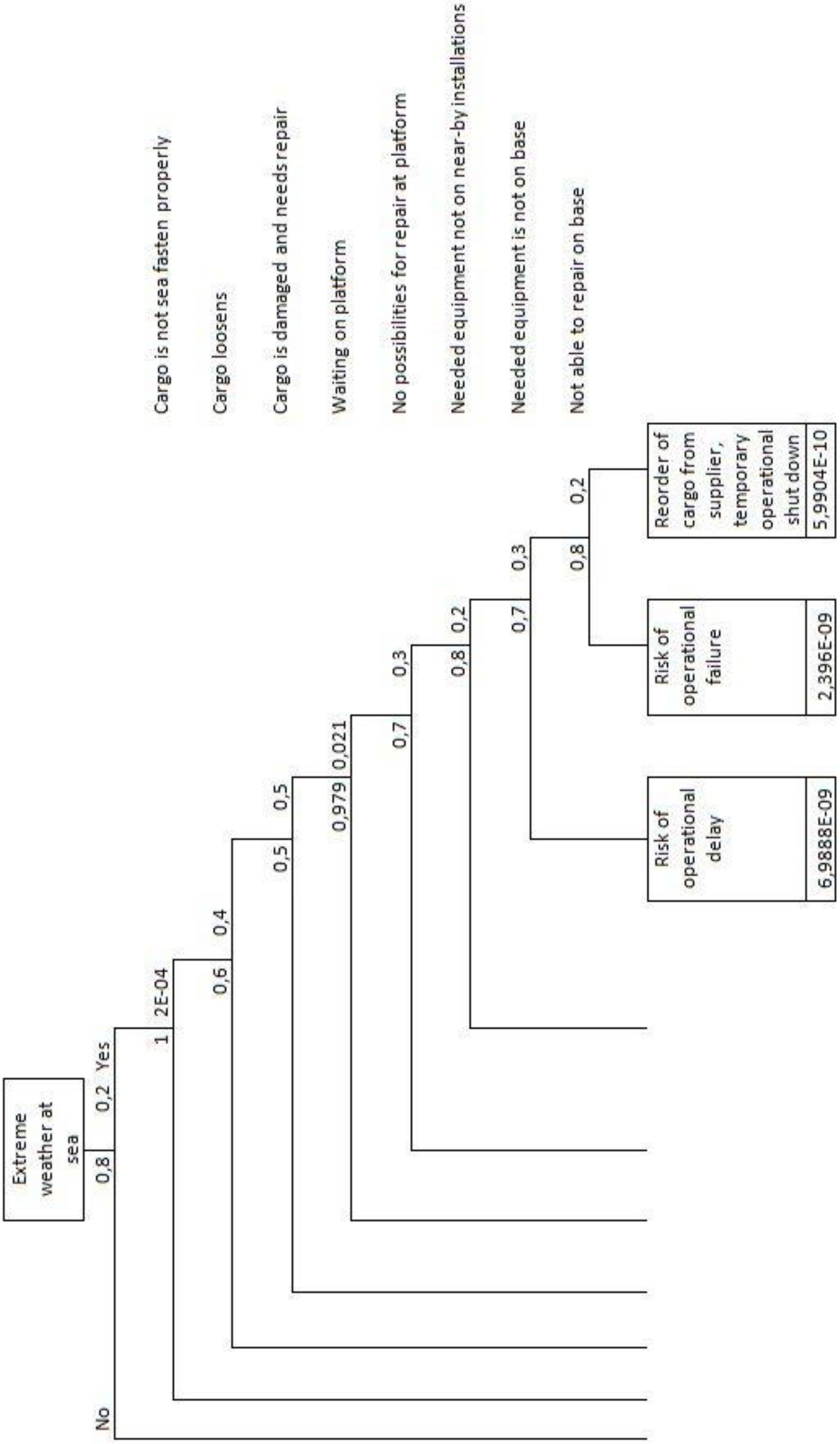
Simple dependency and influence diagram for Scenario 5: change in operational needs at installation	Needed equipment not in storage	Equipment not at near-by installations	Equipment is ordered from supplier	Equipment is delayed till base	Need for priority delivery	Rental of separate supply vessel	extreme weather
Need for different equipment	+	+	+				
Needed equipment not in storage			+		+		
Equipment not at near-by installations							
Equipment is ordered from supplier					+		
Equipment is delayed till base					+	+	+
Need for priority delivery						+	
Rental of separate supply vessel							

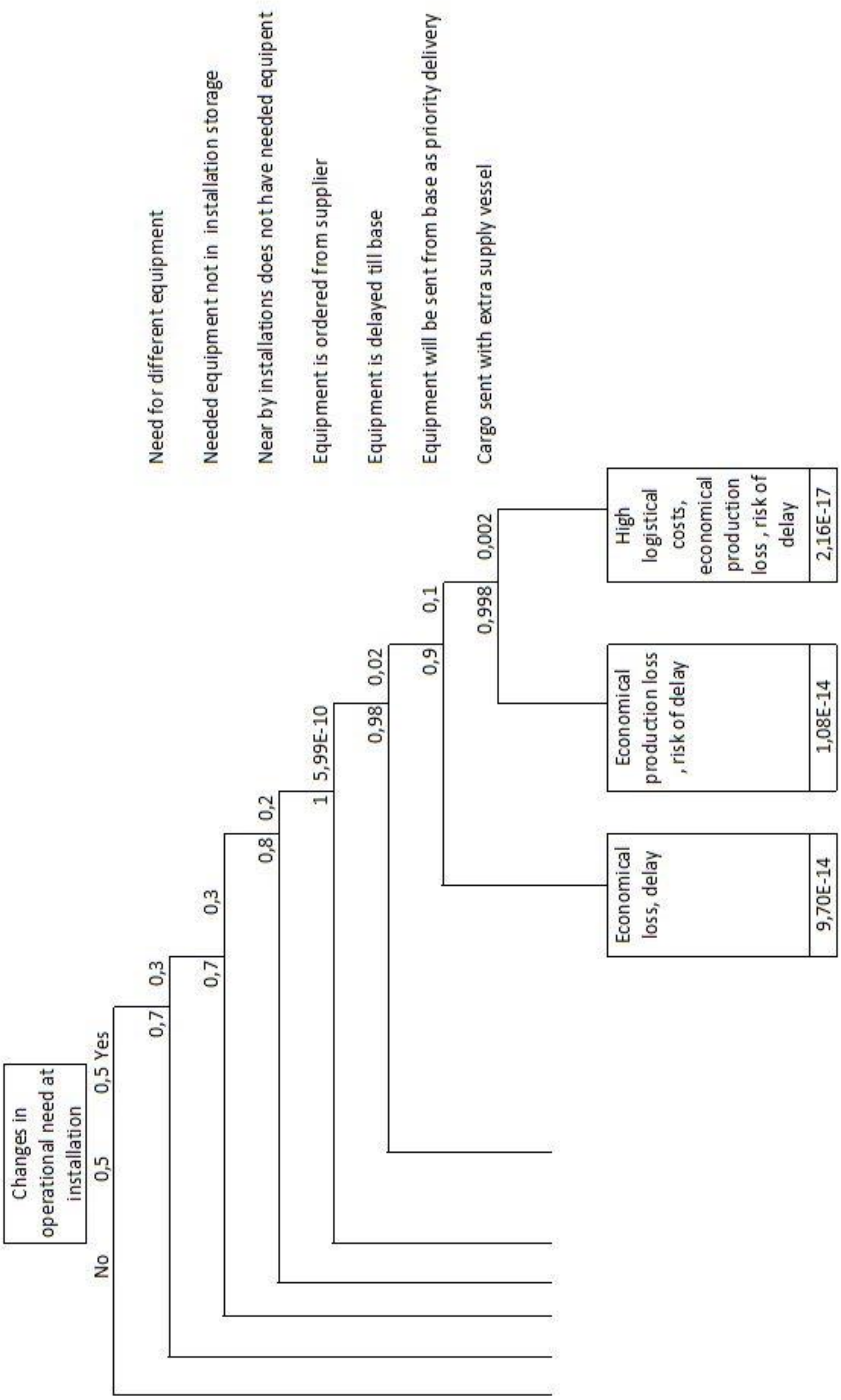
Appendix C –Event tree analysis




Badly marked cargo
Cargo arriving late at base
Congestion
Inattentive base crew
Cargo misdirected to wrong ship
Mistake not discovered
Urgent need for this equipment
0,015 Yes
0,9852
No
0,02
0,98
0,0089
0,991
0,003
0,997
0
0,9997
0,5
0,5
0,1
0,9
Major delay, risk of operational stop
1,1855E-13
major delay
1,06693E-12
Minor delay
1,18548E-12


Cargo arriving late at base
Cargo does not get on waiting vessel
Cargo is priority delivery
Cargo of medium size: sent with helicopter
WOW
Extreme weather at sea
No
0,98
0,02 Yes
0,6
0,4
0,9
0,1
0,98
0,02
0,99
0,01
0,995
0,005
Cargo sent to storage for next departure
0,0072
Cargo with separate vessel, high logistical
0,000784
minor delay, high logistical cost
0,00001584
delay, High logistical costs
1,592E-07
HMS risk, risk of operational stop
8E-10


Extreme weather at sea
Cargo is not sea fasten properly
Cargo loosens
Cargo is damaged and needs repair
Waiting on platform
No possibilities for repair at platform
Needed equipment not on near-by installations
Needed equipment is not on base
Not able to repair on base
0,2 Yes
0,8
No
2E-04
1
0,4
0,6
0,5
0,5
0,021
0,979
0,3
0,7
0,2
0,8
0,3
0,7
0,2
0,8
Reorder of cargo from supplier, temporary operational shut down
5,9904E-10
Risk of operational failure
2,396E-09
Risk of operational delay
6,9888E-09


Changes in operational need at installation
Need for different equipment
Needed equipment not in installation storage
Near by installations does not have needed equipent
Equipment is ordered from supplier
Equipment is delayed till base
Equipment will be sent from base as priority delivery
Cargo sent with extra supply vessel
No
0,5
0,5 Yes
0,7
0,3
0,7
0,3
0,8
0,2
1
5,99E-10
0,98
0,02
0,9
0,1
0,998
0,002
Economical loss, delay
9,70E-14
Economical production loss , risk of delay
1,08E-14
High logistical costs, economical production loss , risk of delay
2,16E-17

Appendix D – Restrictive matrices

		This cannot happen											
	Transit to base	Queue	Closed roads	Closed tunnels	Collision	Collision	Destroyed under transport	Damaged under transport	Engine problems	break down of vital part of trailer	Extreme weather	Driving wrong	Slippery roads
If this happens	Queue	1											
	Closed roads		1										
	Closed tunnels			1									
	Collision				1	1							
	Collision				1	1							
	Destroyed under transport	1	1	1	1	1	1	1	1	1	1	1	1
	Damaged under transport						1	1					
	Engine problems								1	1			
	break down of vital part of trailer								1	1			
	Extreme weather										1		
	Driving wrong											1	
	Slippery roads										1		1

		This cannot happen																									
	At base	Poor marking of cargo	Poor treatment of cargo	Poor treatment of cargo	Early arrival at base	Delayed cargo from supplier	Delayed cargo from supplier	Collision in base area	Collision in base area	Extra treatment of cargo at base after opening hours	Early departure from base	Delayed departure from base	Vessel waiting on late cargo	Collision in harbour	Collision in harbour	Improper loading of ship	Late arrival of vessel till base	Late arrival of crew	Waiting on weather base	Break down on vital parts of the ship	Congestion	Change of sailing plan: Priority deliveries	Labour strike at base	Labour strike at base	Delayed cargo from supplier	Delayed cargo from supplier	Delayed cargo from supplier
If this happens	Poor marking of cargo	1																									
	Poor treatment of cargo		1	1																							
	Poor treatment of cargo		1	1																							
	Early arrival at base				1	1	1			1															1	1	1
	Delayed cargo from supplier				1	1	1				1														1	1	1
	Delayed cargo from supplier				1	1	1				1														1	1	1
	Collision in base area							1	1																		
	Collision in base area							1	1																		
	Extra treatment of cargo at base after opening hours									1	1		1				1	1	1								
	Early departure from base									1	1	1															
	Delayed departure from base										1	1															
	Vessel waiting on late cargo										1		1														
	Collision in harbour													1	1												
	Collision in harbour													1	1												
	Improper loading of ship															1											
	Late arrival of vessel till base																1										
	Late arrival of crew																	1									
	Waiting on weather base																		1								
	Break down on vital parts of the ship																			1							
	Congestion																				1						
	Change of sailing plan: Priority deliveries																					1					
	Labour strike at base																						1	1			
	Labour strike at base																						1	1			
	Delayed cargo from supplier				1	1	1				1	1	1									1			1	1	1
	Delayed cargo from supplier				1	1	1				1	1	1	1								1			1	1	1
	Delayed cargo from supplier				1	1	1				1	1	1	1			1	1	1			1			1	1	1

		This cannot happen																															
	Transit to installation	Change of sailingplan: priority deliveries	Extra call for supply ship	Machinery problems	Machinery down	Break down of vital parts of the ship	Fire onboard	Fire onboard	Man over board	Sickness onboard	Waiting on weather installation	Waiting on weather base	Waiting on platform	Extreme weather	Collision (with other vessels)	Collision (with other vessels)	Grounding	Grounding	Ships nearby in distress	Early departure from base	Early departure from other installations	Delayed departure from base	Delayed departure from other installations	Too low tide at base	Late arrival of vessel	Early arrival of vessel	Waiting on weather installation	Collision in harbour	Collision in harbour	Labour strike at base	Labour strike at base	Late offloading	Late onloading
If this happens	Change of sailingplan: priority deliveries	1																															
	Extra call for supply ship		1																														
	Machinery problems			1	1																												
	Machinery down			1	1																												
	Break down of vital parts of the ship					1																											
	Fire onboard						1	1																									
	Fire onboard						1	1																									
	Man over board								1																								
	Sickness onboard									1																							
	Waiting on weather installation										1																						
	Waiting on weather base											1																					
	Waiting on platform												1																				
	Extreme weather													1																			
	Collision (with other vessels)														1	1																	
	Collision (with other vessels)														1	1																	
	Grounding																1																
	Grounding			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Ships nearby in distress																		1														
	Early departure from base																			1		1											
	Early departure from other installations																				1												
	Delayed departure from base																			1		1											
	Delayed departure from other installations																				1		1										
	Too low tide at base																							1									
	Late arrival of vessel																							1	1	1							
	Early arrival of vessel																							1	1	1							
	Waiting on weather installation																										1						
	Collision in harbour																											1	1				
	Collision in harbour	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Labour strike at base																													1	1		
	Labour strike at base	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Late offloading																															1	
	Late onloading																																1

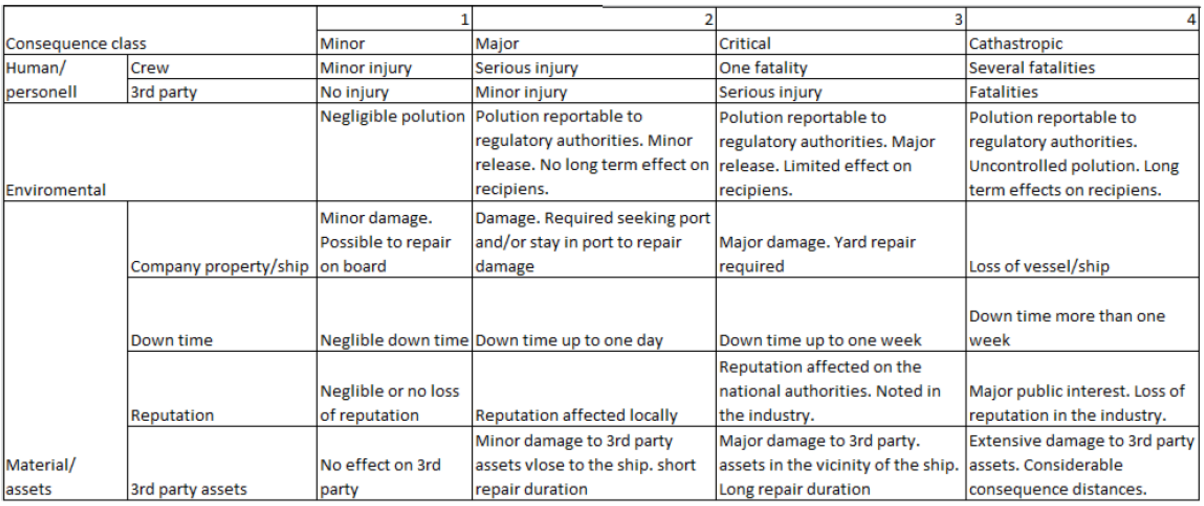
		This cannot happen																				
	At installation	Waiting on plattform	Extreme weather	Extreme weather	Abort of loading due to bad weather	Crane equipment down	Crane equipment down	Break-down of equipment	Break-down of vital equipment	Break-down of vital equipment	Night-closed installations	Delay to night closed installations	Poor placement of already delivered equipment	Full deck	Full deck	Wrong delivery because of bad marking	Collision with installation	Collision with installation	Collision with installation	Labour strike	Labour strike	Extra lay time at installations for supply ship
If this happens	Waiting on plattform	1																				
	Extreme weather		1	1																		
	Extreme weather		1	1																		
	Abort of loading due to bad weather				1																	
	Crane equipment down					1																
	Crane equipment down	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Break-down of equipment							1	1	1												
	Break-down of vital equipment							1	1	1												
	Break-down of vital equipment							1	1	1												
	Night-closed installations										1											
	Delay to night closed installations											1										
	Poor placement of already delivered equipment												1									
	Full deck													1	1							
	Full deck	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				1	1	1
	Wrong delivery because of bad marking															1						
	Collision with installation																1	1	1			
	Collision with installation																1	1	1			
	Collision with installation																1	1	1			
	Labour strike																			1	1	
	Labour strike	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Extra lay time at installations for supply ship																					1

		This cannot happen																
	Return transit	Urgent return due to storage shorrtage at installation	Early departure from installation	Delayed departure from installations	Waiting on weather base	Machinery problems	Machinery down	Break down of vital parts of the ship	Fire onboard	Fire onboard	Man over board	Sickness onboard	Extreme weather	Collision (with other vessels)	Collision (with other vessels)	Grounding	Grounding	Ships nearby in distress
If this happens	Urgent return due to storage shorrtage at installation	1																
	Early departure from installation		1	1														
	Delayed departure from installations		1	1														
	Waiting on weather base				1													
	Machinery problems					1	1											
	Machinery down					1	1											
	Break down of vital parts of the ship							1										
	Fire onboard								1	1								
	Fire onboard								1	1								
	Man over board										1							
	Sickness onboard											1						
	Extreme weather												1					
	Collision (with other vessels)													1	1			
	Collision (with other vessels)													1	1			
	Grounding															1	1	
	Grounding															1	1	
	Ships nearby in distress																	1

Appendix E - DNV Consequence classifications

	Consequence classification	Quantification
1	🟩 Minor	Does not degrade system beyond acceptable limits. Nuisance vary
2	🟨 Major	Degrades system beyond acceptable limits - can be counteracted
3	🟥 Critical	Degrades system beyond acceptable limits - Creates safety hazard
4	🟥 Catastrophic	Can result in death or injury or prevent performance of intended mission

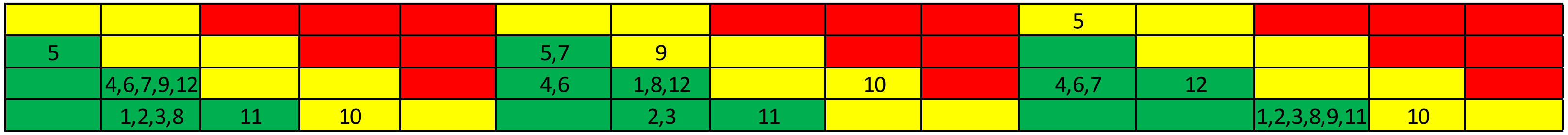
Frequency levels			
Level	Description	Indicated frequency (per vessel year)	Definition
a	Frequent	>0,5	Will occur frequently
b	Probable	0,5-0,05	May occur several times
c	Occasional	0,05-0,005	Likely to occur during lifetime
d	Remote	0,005-0,0005	unlikely to occur during lifetime
e	Improbable	0,0005>	So unlikely that this event might not be experienced



		1	2	3	4
Consequence class		Minor	Major	Critical	Cathastropic
Human/ personell	Crew	Minor injury	Serious injury	One fatality	Several fatalities
	3rd party	No injury	Minor injury	Serious injury	Fatalities
Enviromental		Negligible polution	Polution reportable to regulatory authorities. Minor release. No long term effect on recipiens.	Polution reportable to regulatory authorities. Major release. Limited effect on recipiens.	Polution reportable to regulatory authorities. Uncontrolled polution. Long term effects on recipiens.
Material/ assets	Company property/ship	Minor damage. Possible to repair on board	Damage. Required seeking port and/or stay in port to repair damage	Major damage. Yard repair required	Loss of vessel/ship
	Down time	Neglible down time	Down time up to one day	Down time up to one week	Down time more than one week
	Reputation	Neglible or no loss of reputation	Reputation affected locally	Reputation affected on the national authorities. Noted in the industry.	Major public interest. Loss of reputation in the industry.
	3rd party assets	No effect on 3rd party	Minor damage to 3rd party assets vlose to the ship. short repair duration	Major damage to 3rd party. assets in the vicinity of the ship. Long repair duration	Extensive damage to 3rd party assets. Considerable consequence distances.

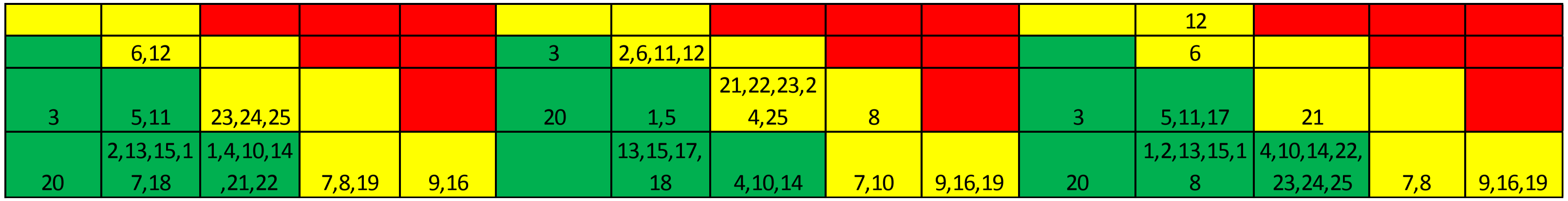
Appendix F – Risk matrices

Transportatio to base



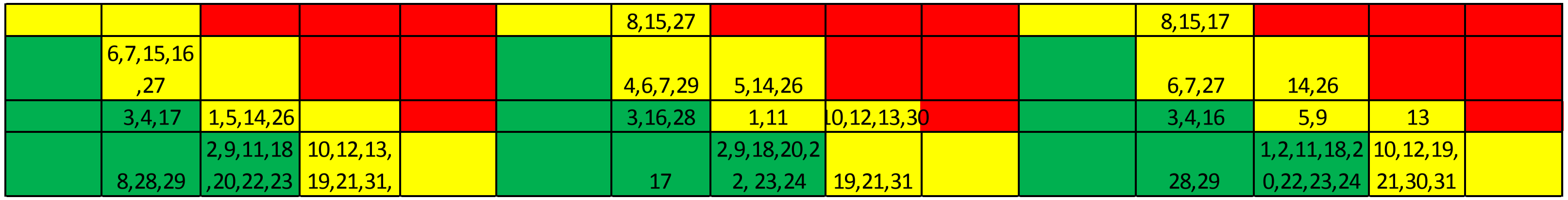
🟨	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟨 5	🟨	🟥	🟥	🟥
🟩 5	🟨	🟨	🟥	🟥	🟩 5,7	🟨 9	🟨	🟥	🟥	🟩	🟨	🟨	🟥	🟥
🟩	🟩 4,6,7,9,12	🟨	🟨	🟥	🟩 4,6	🟩 1,8,12	🟨	🟨 10	🟥	🟩 4,6,7	🟩 12	🟨	🟨	🟥
🟩	🟩 1,2,3,8	🟩 11	🟨 10	🟨	🟩	🟩 2,3	🟩 11	🟨	🟨	🟩	🟩	🟩 1,2,3,8,9,11	🟨 10	🟨

Base treatment



🟨	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟨	🟨 12	🟥	🟥	🟥
🟩	🟨 6,12	🟨	🟥	🟥	🟩 3	🟨 2,6,11,12	🟨	🟥	🟥	🟩	🟨 6	🟨	🟥	🟥
🟩 3	🟩 5,11	🟨 23,24,25	🟨	🟥	🟩 20	🟩 1,5	🟨 21,22,23,24,25	🟨 8	🟥	🟩 3	🟩 5,11,17	🟨 21	🟨	🟥
🟩 20	🟩 2,13,15,17,18	🟩 1,4,10,14,21,22	🟨 7,8,19	🟨 9,16	🟩	🟩 13,15,17,18	🟩 4,10,14	🟨 7,10	🟨 9,16,19	🟩 20	🟩 1,2,13,15,18	🟩 4,10,14,22,23,24,25	🟨 7,8	🟨 9,16,19

Transit to installation



🟨	🟨	🟥	🟥	🟥	🟨	🟨 8,15,27	🟥	🟥	🟥	🟨	🟨 8,15,17	🟥	🟥	🟥
🟩	🟨 6,7,15,16,27	🟨	🟥	🟥	🟩	🟨 4,6,7,29	🟨 5,14,26	🟥	🟥	🟩	🟨 6,7,27	🟨 14,26	🟥	🟥
🟩	🟩 3,4,17	🟨 1,5,14,26	🟨	🟥	🟩	🟩 3,16,28	🟨 1,11	🟨 10,12,13,30	🟥	🟩	🟩 3,4,16	🟨 5,9	🟨 13	🟥
🟩	🟩 8,28,29	🟩 2,9,11,18,20,22,23	🟨 10,12,13,19,21,31,	🟨	🟩	🟩 17	🟩 2,9,18,20,22, 23,24	🟨 19,21,31	🟨	🟩	🟩 28,29	🟩 1,2,11,18,20,22,23,24	🟨 10,12,19,21,30,31	🟨

Installation handling

🟨	🟨 17,18	🟥 16	🟥	🟥	🟨 9	🟨 17,18	🟥 16	🟥	🟥	🟨	🟨 16,17,18	🟥	🟥	🟥
🟩 7,9	🟨	🟨	🟥	🟥	🟩 7,8,20	🟨 6,14	🟨 3,12	🟥	🟥	🟩	🟨	🟨	🟥	🟥
🟩	🟩 12	🟨	🟨	🟥	🟩	🟩 5,15,19	🟨 1,4,	🟨 2,13	🟥	🟩	🟩 12,14	🟨	🟨 13	🟥
🟩 6,8	🟩 5,10,11,15,20	🟩 1,3,4,14,19,21	🟨 2,13	🟨	🟩	🟩 10,11,21	🟩	🟨	🟨	🟩 6,7,8,9,15,20	🟩 5,10,11,19	🟩 1,3,4,21	🟨	🟨

Return transit from base

🟨	🟨	🟥	🟥	🟥	🟨 14	🟨	🟥	🟥	🟥	🟨 10,14,17	🟨 9	🟥	🟥	🟥
🟩 14,16	🟨 8,9	🟨	🟥	🟥	🟩 6,16	🟨 1,8,9,13	🟨	🟥	🟥	🟩	🟨 8,13	🟨	🟥	🟥
🟩 15	🟩 13	🟨	🟨	🟥	🟩 7,15	🟩 4,5	🟨	🟨 3,12	🟥	🟩 6,7,15,16	🟩	🟨 11	🟨	🟥
🟩 6,7,10,17	🟩 1,4,5	🟩 2,11	🟨 3,12	🟨	🟩 10,17	🟩	🟩 2,11	🟨	🟨	🟩	🟩 1,4,5	🟩 2	🟨 3,12	🟨

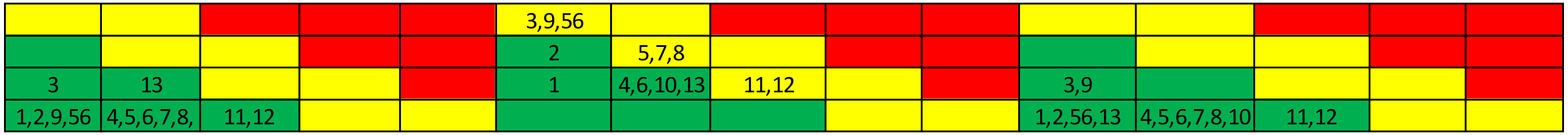
From the PHA analysis:

These tables correspond with appendix A

Supplier and transit

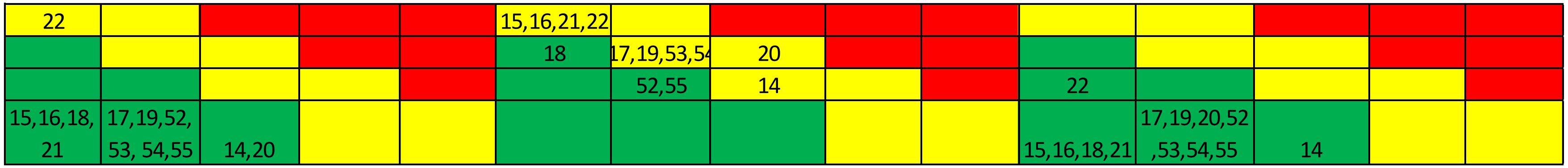
🟨	🟨	🟥	🟥	🟥	🟨 25,34,36	🟨	🟥	🟥	🟥	🟨 25,34,36	🟨	🟥	🟥	🟥
🟩 34	🟨	🟨	🟥	🟥	🟩 24	🟨 32	🟨	🟥	🟥	🟩	🟨	🟨	🟥	🟥
🟩 25	🟩 33	🟨	🟨	🟥	🟩 40,41	🟩 27,29,31,33,35,37,	🟨 23,26,28	🟨	🟥	🟩	🟩 33,35	🟨	🟨	🟥
🟩 24,36,40,41	🟩 27,29,30,31,	🟩 23,26,28,38	🟨	🟨	🟩	🟩 30	🟩 38	🟨	🟨	🟩 24,40,41	🟩 27,29,30,31,32,37,39	🟩 23,26,28,38	🟨	🟨

Cargo and base treatment



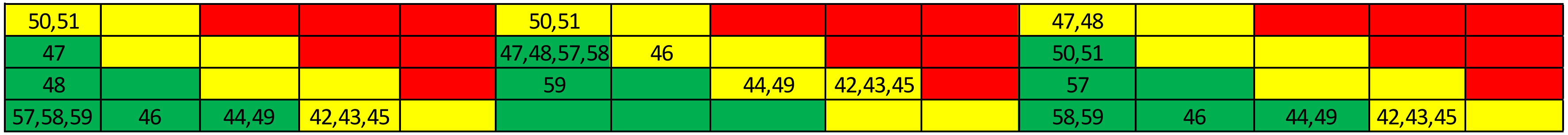
🟨	🟨	🟥	🟥	🟥	🟨 3,9,56	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥
🟩	🟨	🟨	🟥	🟥	🟩 2	🟨 5,7,8	🟨	🟥	🟥	🟩	🟨	🟨	🟥	🟥
🟩 3	🟩 13	🟨	🟨	🟥	🟩 1	🟩 4,6,10,13	🟨 11,12	🟨	🟥	🟩 3,9	🟩	🟨	🟨	🟥
🟩 1,2,9,56	🟩 4,5,6,7,8,	🟩 11,12	🟨	🟨	🟩	🟩	🟩	🟨	🟨	🟩 1,2,56,13	🟩 4,5,6,7,8,10	🟩 11,12	🟨	🟨

Installation



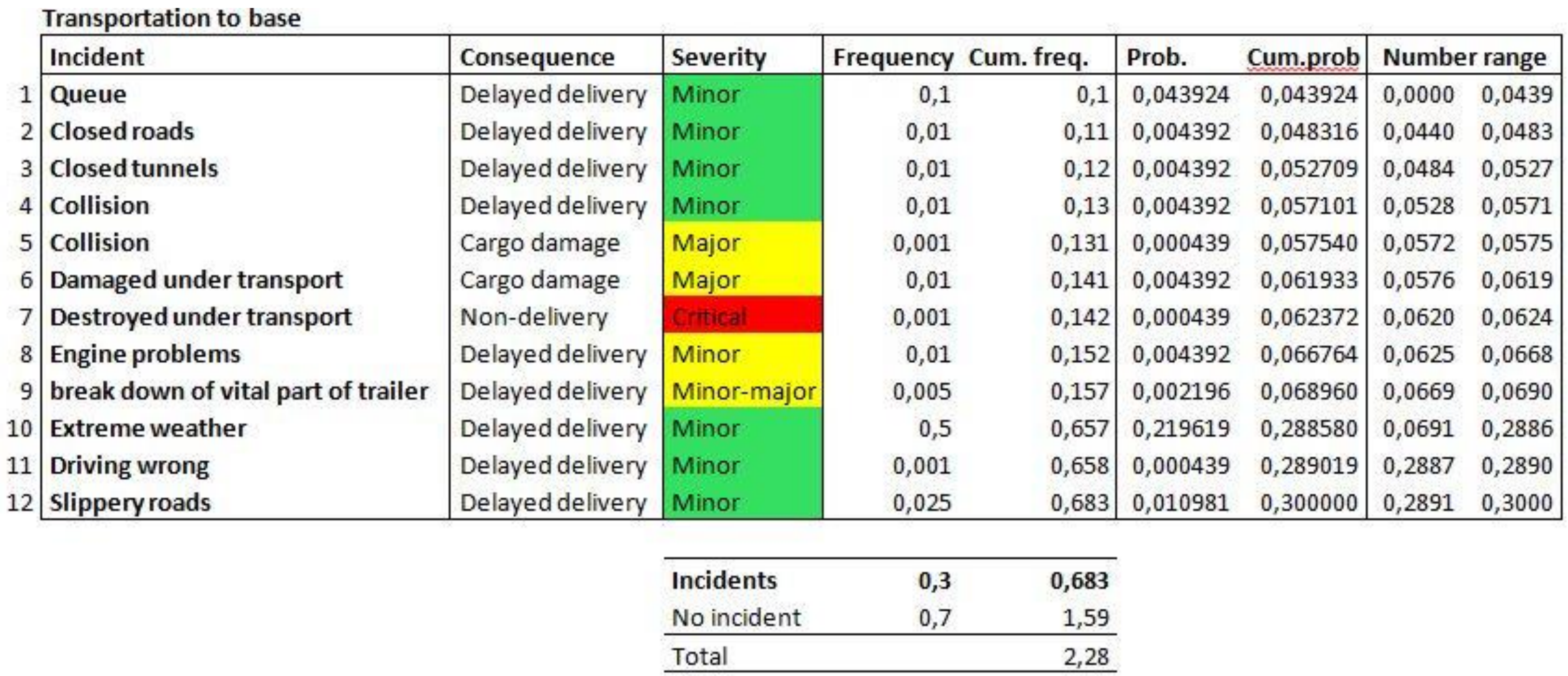
🟨 22	🟨	🟥	🟥	🟥	🟨 15,16,21,22	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥
🟩	🟨	🟨	🟥	🟥	🟩 18	🟨 17,19,53,54	🟨 20	🟥	🟥	🟩	🟨	🟨	🟥	🟥
🟩	🟩	🟨	🟨	🟥	🟩	🟩 52,55	🟨 14	🟨	🟥	🟩 22	🟩	🟨	🟨	🟥
🟩 15,16,18, 21	🟩 17,19,52, 53, 54,55	🟩 14,20	🟨	🟨	🟩	🟩	🟩	🟨	🟨	🟩 15,16,18,21	🟩 17,19,20,52 ,53,54,55	🟩 14	🟨	🟨

Vessel



🟨 50,51	🟨	🟥	🟥	🟥	🟨 50,51	🟨	🟥	🟥	🟥	🟨 47,48	🟨	🟥	🟥	🟥
🟩 47	🟨	🟨	🟥	🟥	🟩 47,48,57,58	🟨 46	🟨	🟥	🟥	🟩 50,51	🟨	🟨	🟥	🟥
🟩 48	🟩	🟨	🟨	🟥	🟩 59	🟩	🟨 44,49	🟨 42,43,45	🟥	🟩 57	🟩	🟨	🟨	🟥
🟩 57,58,59	🟩 46	🟩 44,49	🟨 42,43,45	🟨	🟩	🟩	🟩	🟨	🟨	🟩 58,59	🟩 46	🟩 44,49	🟨 42,43,45	🟨

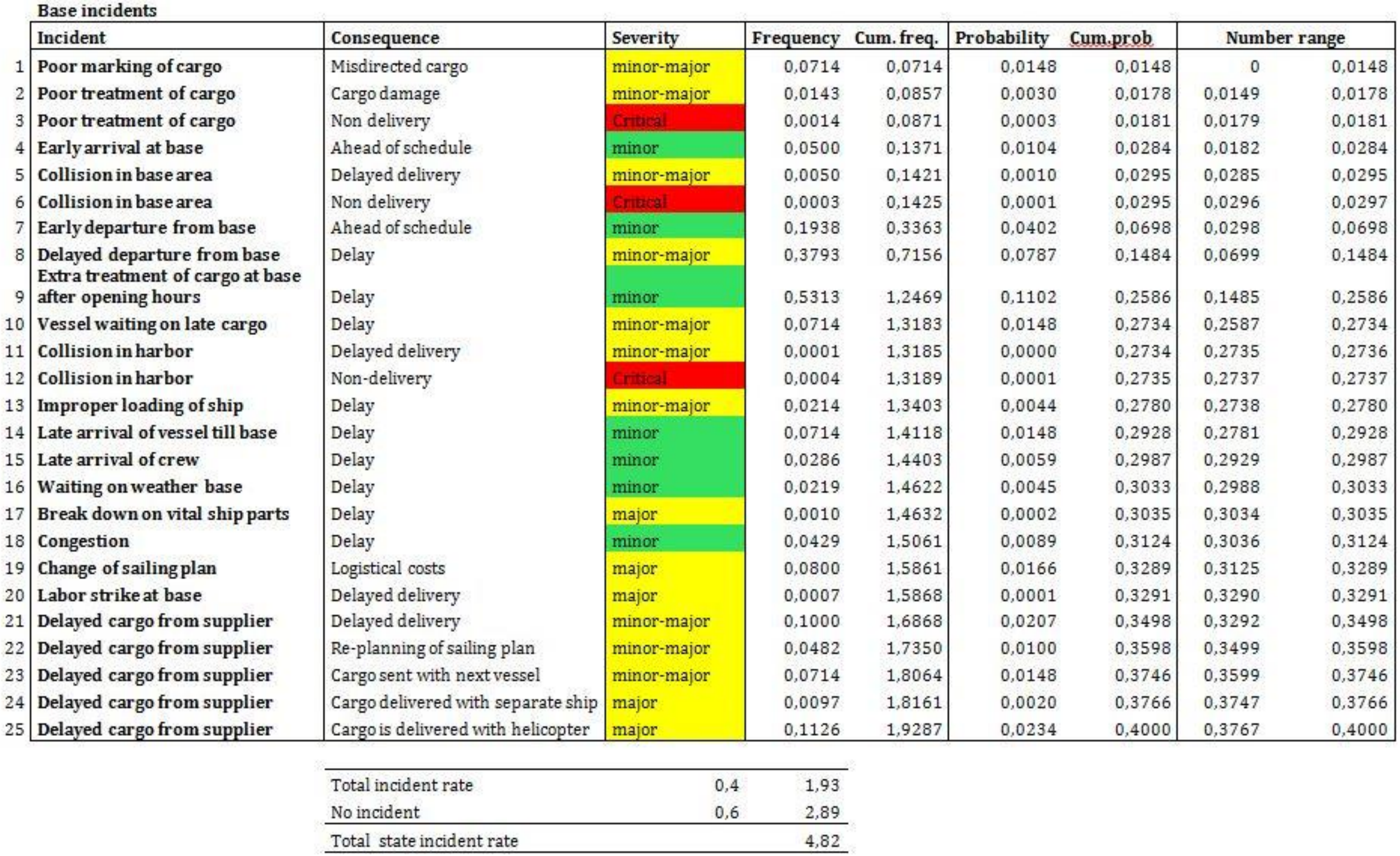
Appendix G - Event frequencies and probabilities



Transportation to base

	Incident	Consequence	Severity	Frequency	Cum. freq.	Prob.	Cum.prob	Number range	
1	**Queue**	Delayed delivery	Minor	0,1	0,1	0,043924	0,043924	0,0000	0,0439
2	**Closed roads**	Delayed delivery	Minor	0,01	0,11	0,004392	0,048316	0,0440	0,0483
3	**Closed tunnels**	Delayed delivery	Minor	0,01	0,12	0,004392	0,052709	0,0484	0,0527
4	**Collision**	Delayed delivery	Minor	0,01	0,13	0,004392	0,057101	0,0528	0,0571
5	**Collision**	Cargo damage	Major	0,001	0,131	0,000439	0,057540	0,0572	0,0575
6	**Damaged under transport**	Cargo damage	Major	0,01	0,141	0,004392	0,061933	0,0576	0,0619
7	**Destroyed under transport**	Non-delivery	Critical	0,001	0,142	0,000439	0,062372	0,0620	0,0624
8	**Engine problems**	Delayed delivery	Minor	0,01	0,152	0,004392	0,066764	0,0625	0,0668
9	**break down of vital part of trailer**	Delayed delivery	Minor-major	0,005	0,157	0,002196	0,068960	0,0669	0,0690
10	**Extreme weather**	Delayed delivery	Minor	0,5	0,657	0,219619	0,288580	0,0691	0,2886
11	**Driving wrong**	Delayed delivery	Minor	0,001	0,658	0,000439	0,289019	0,2887	0,2890
12	**Slippery roads**	Delayed delivery	Minor	0,025	0,683	0,010981	0,300000	0,2891	0,3000

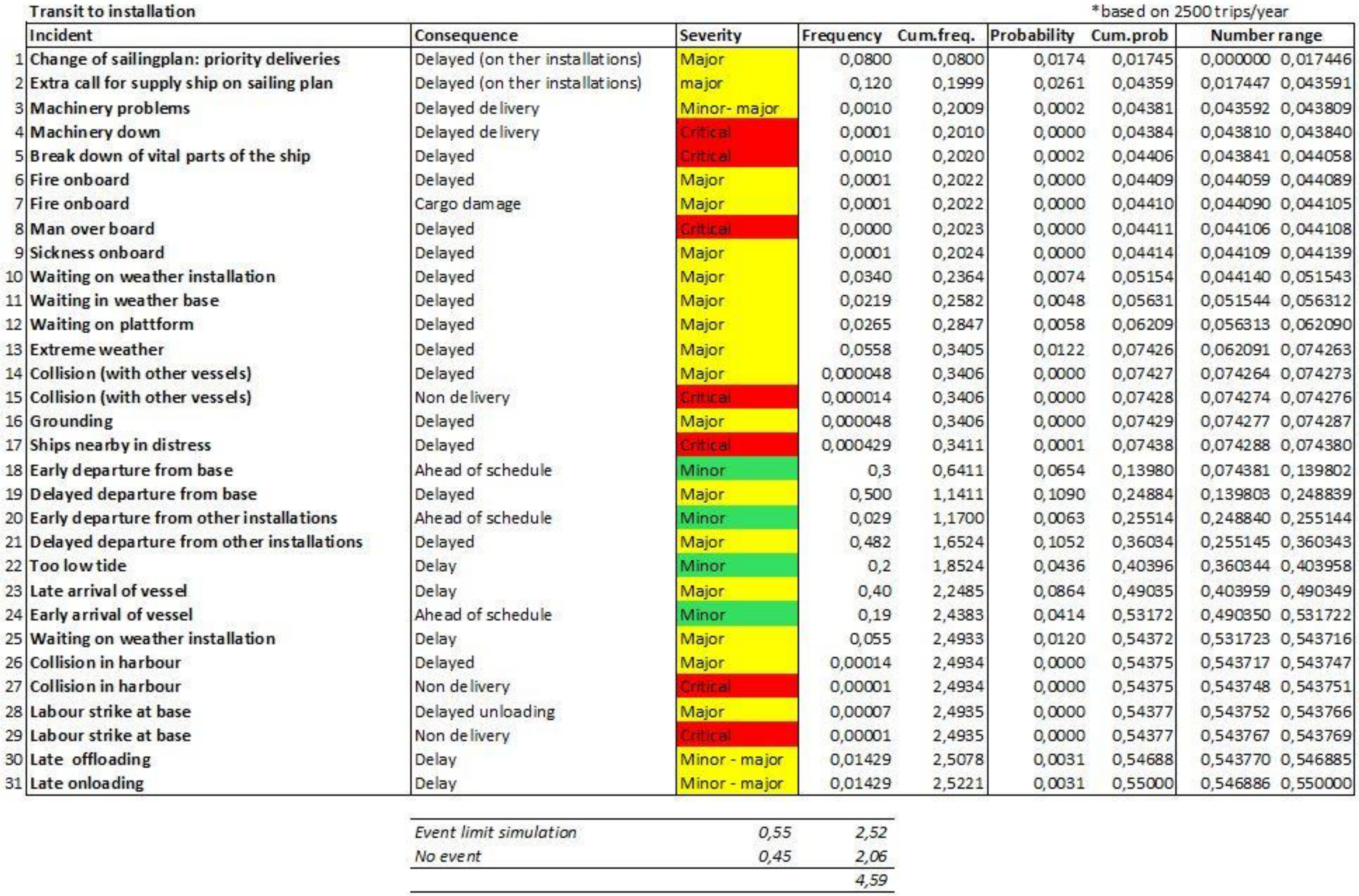
Incidents	**0,3**	**0,683**
No incident	0,7	1,59
Total		2,28



Base incidents

	Incident	Consequence	Severity	Frequency	Cum. freq.	Probability	Cum.prob	Number range	
1	**Poor marking of cargo**	Misdirected cargo	🟨 minor-major	0,0714	0,0714	0,0148	0,0148	0	0,0148
2	**Poor treatment of cargo**	Cargo damage	🟨 minor-major	0,0143	0,0857	0,0030	0,0178	0,0149	0,0178
3	**Poor treatment of cargo**	Non delivery	🟥 Critical	0,0014	0,0871	0,0003	0,0181	0,0179	0,0181
4	**Early arrival at base**	Ahead of schedule	🟩 minor	0,0500	0,1371	0,0104	0,0284	0,0182	0,0284
5	**Collision in base area**	Delayed delivery	🟨 minor-major	0,0050	0,1421	0,0010	0,0295	0,0285	0,0295
6	**Collision in base area**	Non delivery	🟥 Critical	0,0003	0,1425	0,0001	0,0295	0,0296	0,0297
7	**Early departure from base**	Ahead of schedule	🟩 minor	0,1938	0,3363	0,0402	0,0698	0,0298	0,0698
8	**Delayed departure from base**	Delay	🟨 minor-major	0,3793	0,7156	0,0787	0,1484	0,0699	0,1484
9	**Extra treatment of cargo at base after opening hours**	Delay	🟩 minor	0,5313	1,2469	0,1102	0,2586	0,1485	0,2586
10	**Vessel waiting on late cargo**	Delay	🟨 minor-major	0,0714	1,3183	0,0148	0,2734	0,2587	0,2734
11	**Collision in harbor**	Delayed delivery	🟨 minor-major	0,0001	1,3185	0,0000	0,2734	0,2735	0,2736
12	**Collision in harbor**	Non-delivery	🟥 Critical	0,0004	1,3189	0,0001	0,2735	0,2737	0,2737
13	**Improper loading of ship**	Delay	🟨 minor-major	0,0214	1,3403	0,0044	0,2780	0,2738	0,2780
14	**Late arrival of vessel till base**	Delay	🟩 minor	0,0714	1,4118	0,0148	0,2928	0,2781	0,2928
15	**Late arrival of crew**	Delay	🟩 minor	0,0286	1,4403	0,0059	0,2987	0,2929	0,2987
16	**Waiting on weather base**	Delay	🟩 minor	0,0219	1,4622	0,0045	0,3033	0,2988	0,3033
17	**Break down on vital ship parts**	Delay	🟨 major	0,0010	1,4632	0,0002	0,3035	0,3034	0,3035
18	**Congestion**	Delay	🟩 minor	0,0429	1,5061	0,0089	0,3124	0,3036	0,3124
19	**Change of sailing plan**	Logistical costs	🟨 major	0,0800	1,5861	0,0166	0,3289	0,3125	0,3289
20	**Labor strike at base**	Delayed delivery	🟨 major	0,0007	1,5868	0,0001	0,3291	0,3290	0,3291
21	**Delayed cargo from supplier**	Delayed delivery	🟨 minor-major	0,1000	1,6868	0,0207	0,3498	0,3292	0,3498
22	**Delayed cargo from supplier**	Re-planning of sailing plan	🟨 minor-major	0,0482	1,7350	0,0100	0,3598	0,3499	0,3598
23	**Delayed cargo from supplier**	Cargo sent with next vessel	🟨 minor-major	0,0714	1,8064	0,0148	0,3746	0,3599	0,3746
24	**Delayed cargo from supplier**	Cargo delivered with separate ship	🟨 major	0,0097	1,8161	0,0020	0,3766	0,3747	0,3766
25	**Delayed cargo from supplier**	Cargo is delivered with helicopter	🟨 major	0,1126	1,9287	0,0234	0,4000	0,3767	0,4000

Total incident rate	0,4	1,93
No incident	0,6	2,89
Total state incident rate		4,82



Transit to installation *based on 2500 trips/year

	Incident	Consequence	Severity	Frequency	Cum.freq.	Probability	Cum.prob	Number range	
1	**Change of sailingplan: priority deliveries**	Delayed (on ther installations)	Major	0,0800	0,0800	0,0174	0,01745	0,000000	0,017446
2	**Extra call for supply ship on sailing plan**	Delayed (on ther installations)	major	0,120	0,1999	0,0261	0,04359	0,017447	0,043591
3	**Machinery problems**	Delayed delivery	Minor- major	0,0010	0,2009	0,0002	0,04381	0,043592	0,043809
4	**Machinery down**	Delayed delivery	Critical	0,0001	0,2010	0,0000	0,04384	0,043810	0,043840
5	**Break down of vital parts of the ship**	Delayed	Critical	0,0010	0,2020	0,0002	0,04406	0,043841	0,044058
6	**Fire onboard**	Delayed	Major	0,0001	0,2022	0,0000	0,04409	0,044059	0,044089
7	**Fire onboard**	Cargo damage	Major	0,0001	0,2022	0,0000	0,04410	0,044090	0,044105
8	**Man over board**	Delayed	Critical	0,0000	0,2023	0,0000	0,04411	0,044106	0,044108
9	**Sickness onboard**	Delayed	Major	0,0001	0,2024	0,0000	0,04414	0,044109	0,044139
10	**Waiting on weather installation**	Delayed	Major	0,0340	0,2364	0,0074	0,05154	0,044140	0,051543
11	**Waiting in weather base**	Delayed	Major	0,0219	0,2582	0,0048	0,05631	0,051544	0,056312
12	**Waiting on plattform**	Delayed	Major	0,0265	0,2847	0,0058	0,06209	0,056313	0,062090
13	**Extreme weather**	Delayed	Major	0,0558	0,3405	0,0122	0,07426	0,062091	0,074263
14	**Collision (with other vessels)**	Delayed	Major	0,000048	0,3406	0,0000	0,07427	0,074264	0,074273
15	**Collision (with other vessels)**	Non delivery	Critical	0,000014	0,3406	0,0000	0,07428	0,074274	0,074276
16	**Grounding**	Delayed	Major	0,000048	0,3406	0,0000	0,07429	0,074277	0,074287
17	**Ships nearby in distress**	Delayed	Critical	0,000429	0,3411	0,0001	0,07438	0,074288	0,074380
18	**Early departure from base**	Ahead of schedule	Minor	0,3	0,6411	0,0654	0,13980	0,074381	0,139802
19	**Delayed departure from base**	Delayed	Major	0,500	1,1411	0,1090	0,24884	0,139803	0,248839
20	**Early departure from other installations**	Ahead of schedule	Minor	0,029	1,1700	0,0063	0,25514	0,248840	0,255144
21	**Delayed departure from other installations**	Delayed	Major	0,482	1,6524	0,1052	0,36034	0,255145	0,360343
22	**Too low tide**	Delay	Minor	0,2	1,8524	0,0436	0,40396	0,360344	0,403958
23	**Late arrival of vessel**	Delay	Major	0,40	2,2485	0,0864	0,49035	0,403959	0,490349
24	**Early arrival of vessel**	Ahead of schedule	Minor	0,19	2,4383	0,0414	0,53172	0,490350	0,531722
25	**Waiting on weather installation**	Delay	Major	0,055	2,4933	0,0120	0,54372	0,531723	0,543716
26	**Collision in harbour**	Delayed	Major	0,00014	2,4934	0,0000	0,54375	0,543717	0,543747
27	**Collision in harbour**	Non delivery	Critical	0,00001	2,4934	0,0000	0,54375	0,543748	0,543751
28	**Labour strike at base**	Delayed unloading	Major	0,00007	2,4935	0,0000	0,54377	0,543752	0,543766
29	**Labour strike at base**	Non delivery	Critical	0,00001	2,4935	0,0000	0,54377	0,543767	0,543769
30	**Late offloading**	Delay	Minor - major	0,01429	2,5078	0,0031	0,54688	0,543770	0,546885
31	**Late onloading**	Delay	Minor - major	0,01429	2,5221	0,0031	0,55000	0,546886	0,550000

Event limit simulation	*0,55*	*2,52*
No event	*0,45*	*2,06*
		4,59

At installation

*based on 2500 trips/year

	Incident	Consequence	Severity	Freq.	Cum. freq.	Probability	Cum. prob	Number range	
1	**Waiting on platform**	Delayed delivery	Major	0,02650	0,02650	0,02912	0,0291	0,000000	0,029122
2	**Extreme weather**	Delayed delivery	Major	0,05580	0,08230	0,06133	0,0905	0,029123	0,090455
3	**Extreme weather**	Non- delivery from this vessel	Catastrophic	0,00003	0,08232	0,00003	0,0905	0,090456	0,090486
4	**Abort of loading due to bad weather**	Delayed delivery	Major	0,07143	0,15375	0,07851	0,1690	0,090487	0,168997
5	**Crane equipment down**	Delayed delivery	Major	0,01429	0,16804	0,01570	0,1847	0,168998	0,184699
6	**Crane equipment down**	Non-delivery	Critical	0,00014	0,16818	0,00016	0,1849	0,184700	0,184856
7	**Break-down of equipment**	Reduced production at installation	Critical	0,00001	0,16820	0,00002	0,1849	0,184857	0,184872
8	**Break-down of vital equipment**	Priority delivery	Major	0,00001	0,16821	0,00002	0,1849	0,184873	0,184888
9	**Break-down of vital equipment**	Production stop	Catastrophic	0,00001	0,16822	0,00002	0,1849	0,184889	0,184903
10	**Night-closed installations**	Delayed delivery	Major	0,01429	0,18251	0,01570	0,2006	0,184904	0,200605
11	**Delay to night closed installations**	Re-planning of sailing plan	Major	0,01429	0,19680	0,01570	0,2163	0,200606	0,216308
12	**Poor placement of already delivered equipment**	Delayed delivery	Major	0,01429	0,21108	0,01570	0,2320	0,216309	0,232010
13	**Full deck**	Delayed delivery	Major	0,02857	0,23965	0,03140	0,2634	0,232011	0,263414
14	**Full deck**	Non-delivery	Critical	0,00071	0,24037	0,00079	0,2642	0,263415	0,264199
15	**Wrong delivery - bad marking**	Delayed delivery	Major	0,00143	0,24180	0,00157	0,2658	0,264200	0,265769
16	**Collision with installation**	Delayed delivery	Major	0,00003	0,24182	0,00003	0,2658	0,265770	0,265801
17	**Collision with installation**	Possible production stop at installation	Critical	0,00001	0,24184	0,00002	0,2658	0,265802	0,265816
18	**Collision with installation**	Reduced production at installation	Critical	0,00001	0,24185	0,00002	0,2658	0,265817	0,265832
19	**Labor strike**	Delayed delivery	Major	0,00007	0,24192	0,00008	0,2659	0,265833	0,265911
20	**Labor strike**	Non-delivery of cargo	Critical	0,00001	0,24194	0,00002	0,2659	0,265912	0,265926
21	**Extra lay time at installations for supply ship**	Delayed delivery	minor - major	0,03100	0,27294	0,03407	0,3000	0,265927	0,300000

Total	0,3	0,2729
No events	0,7	0,6369
Total state incident rate		0,9098

Return transit *based on 2500 trips/year

	Incident	**Consequence**	**Severity**	**Frequency**	**Cumulative freq.**	**Probability**	**Cum.prob**	**Number range**	
1	**Urgent return due to storage shorrtage at installation**	Ahead of schedule	Major	0,02588	0,02588	0,023086	0,023086	0	0,02309
2	**Early departure from installation**	Ahead of schedule	minor	0,02891	0,05479	0,025791	0,048877	0,023096	0,048877
3	**Delayed departure from installations**	Delayed	minor-major	0,48096	0,53575	0,429074	0,477950	0,048878	0,477950
4	**Waiting on weather base**	Delayed	minor-major	0,02187	0,55762	0,019509	0,497459	0,477951	0,497459
5	**Machinery problems**	Delayed delivery	Major	0,00100	0,55862	0,000892	0,498351	0,497460	0,498351
6	**Machinery down**	Delayed delivery	Critical	0,00014	0,55876	0,000127	0,498478	0,498352	0,498478
7	**Break down of vital parts of the ship**	Delayed	Critical	0,00100	0,55976	0,000892	0,499370	0,498479	0,499370
8	**Fire onboard**	Delayed	Major	0,00014	0,55990	0,000127	0,499498	0,499371	0,499498
9	**Fire onboard**	HMS damage	Critical	0,00007	0,55997	0,000064	0,499562	0,499499	0,499562
11	**Man over board**	Delayed	Critical	0,00001	0,55999	0,000013	0,499574	0,499563	0,499574
12	**Sickness onboard**	Delayed	Minor	0,00014	0,56013	0,000127	0,499702	0,499575	0,499702
13	**Extreme weather**	Delayed	Minor - major	0,05580	0,61593	0,049780	0,549482	0,499703	0,549482
14	**Collision (with other vessels)**	Delayed	Major	0,00005	0,61598	0,000042	0,549524	0,549483	0,549524
15	**Collision (with other vessels)**	Non delivery	Critical	0,00003	0,61601	0,000025	0,549550	0,549525	0,549550
16	**Grounding**	Delayed	Major	0,00005	0,61606	0,000042	0,549592	0,549551	0,549592
17	**Grounding**	Non delivery	Critical	0,00003	0,61608	0,000025	0,549618	0,549593	0,549618
18	**Ships nearby in distress**	Delayed	Critical	0,00043	0,61651	0,000382	0,550000	0,549619	0,550000

Total incidents	0,55	0,61651305
No incidents	0,45	0,50441977
		1,12093282

Appendix H – MATLAB script

The model consists of 12 main MATLAB scripts.
- main.m
- simulation.m
- 9 triangularcalculation.m
- report.m

Model tutorial
The main program starts the simulation
The simulation program runs the triangular calculation programs
When the simulation is complete, the report program is run.

```
%MAIN
%The program that runs the simulation

t = 0; %for en runde i simulator
T = 0; %sum runder
Ttot = 8760;
simulationruns = 0;
Totaldelaytransport = 0;
Totaldelaybase = 0;
Totaldelaytransit = 0;
Totaldelayinst1= 0;
Totaldelaytransit2 = 0;
Totaldelayinst2 = 0;
Totaldelaytransit3 = 0;
Totaldelayinst3 = 0;
Totaldelayreturn = 0;
Totalsimdelay = 0 ; %Total delay for all runs

time = zeros(simulationruns,1);
run_delay = zeros(simulationruns,1);
transport_delay = zeros(simulationruns,1);
base_delay = zeros(simulationruns,1);
transit_delay = zeros(simulationruns,1);
installation1_delay = zeros(simulationruns,1);
transit2_delay = zeros(simulationruns,1);
installation2_delay = zeros(simulationruns,1);
transit3_delay = zeros(simulationruns,1);
installation3_delay = zeros(simulationruns,1);
return_delay = zeros(simulationruns,1);
simruns = zeros(simulationruns,1);

events = zeros(simulationruns,9);
event_chain = zeros(simulationruns,9);
storage = zeros(simulationruns,9);
vessel = zeros(simulationruns,9);
heli = zeros(simulationruns,9);

while T<Ttot
   run simulation
```

```
   T=t+T;
   disp(['Simulation number: ' num2str(simulationruns)]);
   disp(['Time for this run: ' num2str(t)]);
   disp(['The delay for this run was: ' num2str(Totaldelay)]);
   disp(' ')
   disp(['Total time used in the simulator: ' num2str(T)]);
   disp(' ')

   events(simulationruns,1:9)= [x1 x2 x3 x4 x5 x6 x7 x8 x9];
   event_chain(simulationruns,1:9)= [y1 y2 y3 y4 y5 y6 y7 y8 y9];


   Totaldelaytransport = Totaldelaytransport + delaytransport ;
   Totaldelaybase = Totaldelaybase + delaybase ;
   Totaldelaytransit = Totaldelaytransit + delaytransit ;
   Totaldelayinst1= Totaldelayinst1 + delayinst1;
   Totaldelaytransit2 = Totaldelaytransit2 + delaytransit2;
   Totaldelayinst2 = Totaldelayinst2 + delayinst2;
   Totaldelaytransit3 = Totaldelaytransit3 + delaytransit3;
   Totaldelayinst3 = Totaldelayinst3 + delayinst3;
   Totaldelayreturn = Totaldelayreturn + delayreturn;
   Totalsimdelay = Totalsimdelay + Totaldelay;

end

   run report
```

```
%SIMULATION
%This program runs the calculations

simulationruns = simulationruns + 1;

        run triangulartransport;
        run triangularbase;
        run triangulartransit;
        run triangulartreatment;
        run triangulartransit2;
        run triangulartreatment2;
        run triangulartransit3;
        run triangulartreatment3;
        run returnbase;

t;
Totaldelay;

nr = simulationruns;
simruns(simulationruns) = nr;

time(simulationruns,1) = t;
run_delay(simulationruns,1) = Totaldelay;
transport_delay(simulationruns,1) = delaytransport;
base_delay(simulationruns,1) = delaybase;
transit_delay(simulationruns,1) = delaytransit;
installation1_delay(simulationruns,1) =delayinst1;
transit2_delay(simulationruns,1) = delaytransit2;
installation2_delay(simulationruns,1) =delayinst2;
transit3_delay(simulationruns,1) = delaytransit3;
installation3_delay(simulationruns,1) =delayinst3;
return_delay(simulationruns,1) = delayreturn;

return
```

```
% Triangulartransport
% Incidents and delays for transport to base

format long

x1 = rand(1);
y1 = rand(1);

pd = makedist('Triangular', 'a',10, 'b',14,'c', 20);

ndeliveries = 1000;
transporttid = 0;

delayx = 0; %delay for hendelse x
delayy = 0;
delay=0;
Totaldelay=0;
t=0;

if x1<=0.3&&y1>=0.3;

   for nloops = 1:ndeliveries;
    r = random(pd);
    delayx = r + delayx;
   end

    delayx = delayx/ndeliveries;
    transporttid = delayx + transporttid;
    delaytransport = transporttid - 14;

elseif x1<=0.3&&y1<=0.3;

   for nloops = 1:ndeliveries;
        ry=random(pd);
        delayy = ry + delayy;
    end

    for nloops = 1:ndeliveries;
         rx = random(pd);
         delayx = rx + delayx;
    end

   if x1<=0.0575&&x1>=0.0528 %restrictive 1: collision
       if y1<=0.0575&&y1>=0.0528
           delayy=0;
       end
   end

   if x1<=.0624&&x1>=.0576 %restrictive 2: damage
      if  y1<=0.0624&&y1>=0.0576
          delayy=0;
      end
   end
```

```
    if x1<=0.0690&&x1>=0.625 %restrictive: break down
       if  y1<=.0690&&y1>=.0625
           delayy=0;
       end
    end

 delayx = delayx/ndeliveries;
 delayy = delayy/ndeliveries;
 delay = (delayx + delayy);

 transporttid = delay;
 delaytransport = transporttid - 14;

else

    transporttid = 14;
    delaytransport = 0;
end

Totaldelay = Totaldelay + delaytransport;
t = transporttid;
```

```
% TRIANGULARBASE
% Incidents and delays for base treatment

pd = makedist('Triangular', 'a',2, 'b',4,'c', 12);
format long
x2 = rand(1);
y2 = rand(1);

ntrips = 1000;
basetid = 0; %basedelay  - pass på at den ikke blir null hver gang!
delayx = 0;%delay for denne hendelsen
delayy=0;
delay=0;
basetid = 0;

if x2<=0.4&&y2>=0.4

    if x2>=.3599 && x2<=.3746 %last på lager
        delay = delay + 24;
        basetid = delay + basetid;
        delaybase = basetid - 4;
        storage(simulationruns,2)= [1];

    elseif x2>=.3747 && x2<=.3766 %prioritet: skip
        delay = 0;
        basetid = 4;
        delaybase = basetid - 4;
        vessel(simulationruns,2)= [1];


    elseif x2>=.3767 && x2<=.4000 %prioritet helikopter
        delay = 0;
        basetid = 4;
        delaybase = basetid - 4;
        heli(simulationruns,2)= [1];

    else

        for nloops = 1:ntrips;
         r = random(pd);
         delayx = r + delayx;
        end

       delay = delayx/ntrips;

       if delay<=4 %
       basetid = 4;
       delaybase = basetid - 4;
       else
       basetid = delay + basetid;
       delaybase = basetid - 4;
       end

    end
```

```
elseif x2<=0.4&&y2<=0.4

    if x2>=.3599 && x2<=.3746 %hendelse: vente til neste skip
        delayx = delayx + 24;
        storage(simulationruns,2)= [1];

        for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
        end

        delayy = delayy/ntrips;
        delayx;

    elseif x2>=.3747 && x2<=.3766 %Prioritet skip
        delayx = 0;
        vessel(simulationruns,2)= [1];

        for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
        end

        delayy = delayy/ntrips;
        delayx;

    elseif x2>=.3767 && x2<=.4 %Prioritet helikopter
        delayx = 0;
        heli(simulationruns,2)= [1]; % Tall til matrise

        for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
        end

        delayy = delayy/ntrips;
        delayx;

    else
        for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
        end

        for nloops = 1:ntrips;
        rx = random(pd);
        delayx = rx + delayx;
        end

        delayx = delayx/ntrips;
        delayy = delayy/ntrips;
    end
```

```
     if x2>=0.3292&&x2<=0.4 %Restrictive 1: Delayed cargo from supplier
        if y2>=0.3292&&y2<=0.4
         delayy=0;
        end
     end

     if x2>=0.2735&&x2<=0.2738 %Restrictive 2: collision in harbor
         if y2>=0.2735&&y2<=0.2738
          delayy=0;
         end
     end

     if x2>=0.1398&&x2<=0.2586 %restrictive 3; Arrival base
         if y2>=0.1398&&y2<=0.2586
          delayy=0;
         end
     end

     if x2>=0.0285&&x2<=0.0297 %restrictive 4: collision base
         if y2>=0.0285&&y2<=0.0297
          delayy=0;
         end
     end

      if x2>=0.0149&&x2<=0.0181 %restrictive 5: poor cargo treatment
         if y2>=0.0149&&y2<=0.0181
          delayy=0;
         end
      end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

   delayx;
   delayy;
   delay = delayx + delayy;

       if delay<=4
       basetid = 4;
       delaybase = basetid - 4;
       else
       basetid = delay + basetid;
       delaybase = basetid - 4;
       end

else
    basetid = 4;
    delaybase=0;
end

Totaldelay = Totaldelay + delaybase;
t = transporttid + basetid;
```

```
%TRIANGULAR TRANSIT
%Incidents and delays for transit to the first installation

format long
pd = makedist('Triangular', 'a',8, 'b',12,'c', 20);
x3 = rand(1);
y3 = rand(1);

ntrips = 1000;
transittid = 0;
delayx = 0;
delayy = 0;
delay = 0;

if x3<=0.55 && y3>=0.5

     for i = 1:ntrips;
         r = random(pd);
         delayx = r + delayx;
     end

     delay = delayx/ntrips;
     transittid = delay + transittid;
     delaytransit = transittid - 12;

elseif x3<=0.55 && y3<=0.5

    for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
    end

    for nloops = 1:ntrips;
         rx = random(pd);
         delayx = rx + delayx;
    end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if x3>=0.043592&&x3<=0.043840 %restrictive 1: Machinery problems
      if y3>=0.043592&&y3<=0.043840
          delayy=0;
      end
   end

   if x3>=0.044059&&x3<=0.044105 %restrictive 2: Fire
      if y3>=0.044059&&y3<=0.044105
          delayy=0;
      end
   end
```

```
   if x3>=0.074264&&x3<=0.074276 %restrictive 3: Vessel collision
      if y3>=0.074264&&y3<=0.074276
          delayy=0;
      end
   end

    if x3>=0.074381&&x3<=0.248839 %restrictive 4: Base departure
      if y3>=0.074381&&y3<=0.248839
          delayy=0;
      end
   end

   if x3>=0.403959&&x3<=0.531722%restrictive 5: Early/late vessel arrival
      if y3>=0.403959&&y3<=0.531722
          delayy=0;
      end
   end

   if x3>=0.543717&&x3<=0.543751 %restrictive 6: inst collision
      if y3>=0.543717&&y3<=0.543751
          delayy=0;
      end
   end

   if x3>=0.543752&&x3<=0.55 %restrictive 7: strike
      if y3>=0.543752&&y3<=0.55
          delayy=0;
      end
   end

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 delayx = delayx;
 delayy = delayy;
 delay = (delayx + delayy)/(2*ntrips);

transittid = delay + transittid;
delaytransit = transittid - 12;

else
        transittid = 12;
        delaytransit=0;
end

Totaldelay = Totaldelay + delaytransit;
t = transporttid + basetid + transittid;
```

```
%Triangulartreatment
%Incidents and disruptions in the transit on the first installation

format long
x4 = rand(1);
y4 = rand(1);
pd = makedist('Triangular', 'a',0.5, 'b',2,'c', 10);

ntrips = 1000;
delayinst1 = 0;
delayx = 0;
delayy = 0;
delay = 0;
treatmenttime = 0;

if x4<=0.3&&y4>=0.3

    for nloops = 1:ntrips;
    r = random(pd);
    delayx = r + delayx;
    end

treatmenttime = delayx/ntrips;
delayinst1 = treatmenttime - 2;

elseif x4<=0.3&&y4<=0.3

    for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
    end

    for nloops = 1:ntrips;
         rx = random(pd);
         delayx = rx + delayx;
    end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if x4>=0.029123&&x4<=0.090486 %Restrictive 1: Weather
      if y4>=0.029123&&y4<=0.090486
         delayy=0;
      end
  end

if x4>=0.168998&&x4<=0.184856 %Restrictive 2: Crane
      if y4>=0.168998&&y4<=0.184856
         delayy=0;
      end
end
```

```
  if x4>=0.184857&&x4<=0.184903 %Restrictive 3: Equipment break down
      if y4>=0.184857&&y4<=0.184903
         delayy=0;
      end
  end

  if x4>=0.232011&&x4<=0.264199 %Restrictive 4: Full deck
      if y4>=0.232011&&y4<=0.264199
         delayy=0;
      end
  end

   if x4>=0.265770&&x4<=0.265832 %Restrictive 5: Collision
      if y4>=0.265770&&y4<=0.265832
         delayy=0;
      end
   end

    if x4>=0.265833&&x4<=0.265926 %Restrictive 6: Strike
      if y4>=0.265833&&y4<=0.265926
         delayy=0;
      end
    end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

delayx = delayx;
delayy = delayy;
delay = (delayx + delayy)/(2*ntrips);

treatmenttime = delay + treatmenttime;
delayinst1 = treatmenttime - 2;

else
    treatmenttime = 2;
    delayinst1 = 0;
end


Totaldelay = Totaldelay + delayinst1;
t = transporttid + basetid + transittid + treatmenttime;
```

```
% Triangulartransit2
% Incidents and delays for transit to the second installation

format long
x5 = rand(1);
y5 = rand(1);
pd = makedist('Triangular', 'a',2, 'b',4,'c', 10);

ntrips = 1000;
transit2tid = 0;
delayx = 0;
delayy = 0;
delay = 0;

if x5<=.55 && y5>=0.3

        for nloops = 1:ntrips;
            r = random(pd);
            delayx = r + delayx;
        end

delay = delayx/ntrips;
transit2tid= (delay + transit2tid);
delaytransit2= transit2tid - 4;

elseif x5<=0.55 && y5<=0.3

    for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
    end

    for nloops = 1:ntrips;
         rx = random(pd);
         delayx = rx + delayx;
    end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if x5>=0.043592&&x5<=0.043840 %restrictive 1: Machinery problems
      if y5>=0.043592&&y5<=0.043840
          delayy=0;
      end
   end

   if x5>=0.044059&&x5<=0.044105 %restrictive 2: Fire
      if y5>=0.044059&&y5<=0.044105
          delayy=0;
      end
   end

   if x5>=0.074264&&x5<=0.074276 %restrictive 3: Vessel collision
      if y5>=0.074264&&y5<=0.074276
          delayy=0;
      end
   end

   if x5>=0.248840&&x5<=0.360343 %restrictive 4: installation departure
      if y5>=0.248840&&y5<=0.360343
          delayy=0;
      end
   end

   if x5>=0.403959&&x5<=0.531722%restrictive 5: Early/late vessel arrival
      if y5>=0.403959&&y5<=0.531722
          delayy=0;
      end
   end

   if x5>=0.543717&&x5<=0.543751 %restrictive 6: inst collision
      if y5>=0.543717&&y5<=0.543751
          delayy=0;
      end
   end

   if x5>=0.543752&&x5<=0.55 %restrictive 7: strike
      if y5>=0.543752&&y5<=0.55
          delayy=0;
      end
   end
delayx = delayx;
 delayy = delayy;
 delay = (delayx + delayy)/(2*ntrips);

transit2tid = delay + transit2tid;
delaytransit2 = transit2tid - 4;

else
   transit2tid = 4;
   delaytransit2=0;
end

Totaldelay = Totaldelay + delaytransit2;
t = transporttid + basetid + transittid + treatmenttime + transit2tid;
```

```
% Triangulartreatment2
% Incidents and disruptions in the transit on the second installation

format long
x6 = rand(1);
y6 = rand(1);
pd = makedist('Triangular', 'a',0.5, 'b',2,'c', 10);

ntrips = 1000;
delayinst2 = 0;
delayx = 0;
delayy = 0;
delay = 0;

if x6<=0.3&&y6>=0.3

    for nloops = 1:ntrips;
    r = random(pd);
    delayx = r + delayx;
    end

treatmenttime2 = delayx/ntrips;
delayinst2 = treatmenttime2 - 2;

elseif x6<=0.3&&y6<=0.3

    for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
    end

    for nloops = 1:ntrips;
         rx = random(pd);
         delayx = rx + delayx;
    end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if x6>=0.029123&&x6<=0.090486 %Restrictive 1: Weather
      if y6>=0.029123&&y6<=0.090486
         delayy=0;
      end
  end

if x6>=0.168998&&x6<=0.184856 %Restrictive 2: Crane
      if y6>=0.168998&&y6<=0.184856
         delayy=0;
      end
end

  if x6>=0.184857&&x6<=0.184903 %Restrictive 3: Equipment break down
      if y6>=0.184857&&y6<=0.184903
         delayy=0;
      end
  end
```

```
  if x6>=0.232011&&x6<=0.264199 %Restrictive 4: Full deck
      if y6>=0.232011&&y6<=0.264199
         delayy=0;
      end
  end

   if x6>=0.265770&&x6<=0.265832 %Restrictive 5: Collision
      if y6>=0.265770&&y6<=0.265832
         delayy=0;
      end
   end

    if x6>=0.265833&&x6<=0.265926 %Restrictive 6: Strike
      if y6>=0.265833&&y6<=0.265926
         delayy=0;
      end
    end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

delayx = delayx/ntrips;
delayy = delayy/ntrips;
delay = (delayx + delayy);

treatmenttime2 = delay + treatmenttime2;
delayinst2 = treatmenttime2 - 2;

else
    treatmenttime2 = 2;
    delayinst2 = 0;
end

Totaldelay = Totaldelay + delayinst2;
t = transporttid + basetid + transittid + treatmenttime + transit2tid +
treatmenttime2;
```

```
%TRIANGULARTRANSIT3
%Incidents and disruptions in the transit to the third installation

format long
x7 = rand(1);
y7 = rand(1);
pd = makedist('Triangular', 'a',2, 'b',6,'c', 12);

ntrips = 1000;
transit3tid = 0;
delayx = 0;
delayy = 0;
delay = 0;

if x7<=0.55 && y7>=0.3

        for nloops = 1:ntrips;
            r = random(pd);
            delayx = r + delayx;
        end

   delay = delayx/ntrips;
   transit3tid= delay + transit3tid;
   delaytransit3= transit3tid - 6;

elseif x7<=0.55 && y7<=0.3

    for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
    end

    for nloops = 1:ntrips;
         rx = random(pd);
         delayx = rx + delayx;
    end

  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

   if x7>=0.043592&&x7<=0.043840 %restrictive 1: Machinery problems
      if y7>=0.043592&&y7<=0.043840
          delayy=0;
      end
   end

   if x7>=0.044059&&x7<=0.044105 %restrictive 2: Fire
      if y7>=0.044059&&y7<=0.044105
          delayy=0;
      end
   end
```

```
   if x7>=0.074264&&x7<=0.074276 %restrictive 3: Vessel collision
      if y7>=0.074264&&y7<=0.074276
          delayy=0;
      end
   end



   if x7>=0.248840&&x7<=0.360343 %restrictive 4: installation departure
      if y7>=0.248840&&y7<=0.360343
          delayy=0;
      end
   end

   if x7>=0.403959&&x7<=0.531722%restrictive 5: Early/late vessel arrival
      if y7>=0.403959&&y7<=0.531722
          delayy=0;
      end
   end

   if x7>=0.543717&&x7<=0.543751 %restrictive 6: inst collision
      if y7>=0.543717&&y7<=0.543751
          delayy=0;
      end
   end

   if x7>=0.543752&&x7<=0.55 %restrictive 7: strike
      if y7>=0.543752&&y7<=0.55
          delayy=0;
      end
   end

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 delayx = delayx;
 delayy = delayy;
  delay = (delayx + delayy)/(2*ntrips);

transit3tid = delay + transit3tid;
delaytransit3 = transit3tid - 6;

else
   transit3tid = 6;
   delaytransit3=0;
end


Totaldelay = Totaldelay + delaytransit3;
t = transporttid + basetid + transittid + treatmenttime + transit2tid +
treatmenttime2 + transit3tid;
```

```
% Triangulartreatment3
% Incidents and disruptions in the transit on the third installation

format long
x8 = rand(1);
y8 = rand(1);
pd = makedist('Triangular', 'a',0.5, 'b',2,'c', 10);

ntrips = 1000;
delayinst3 = 0;
delayx = 0;
delayy = 0;
delay = 0;

if x8<=0.3&&y8>=0.3

    for nloops = 1:ntrips;
    r = random(pd);
    delayx = r + delayx;
    end

treatmenttime3 = delayx/ntrips;
delayinst3 = treatmenttime3 - 2;

elseif x8<=0.3&&y8<=0.3

    for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
    end

    for nloops = 1:ntrips;
         rx = random(pd);
         delayx = rx + delayx;
    end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if x8>=0.029123&&x8<=0.090486 %Restrictive 1: Weather
      if y8>=0.029123&&y8<=0.090486
         delayy=0;
      end
  end

if x8>=0.168998&&x8<=0.184856 %Restrictive 2: Crane
      if y8>=0.168998&&y8<=0.184856
         delayy=0;
      end
end

  if x8>=0.184857&&x8<=0.184903 %Restrictive 3: Equipment break down
      if y8>=0.184857&&y8<=0.184903
         delayy=0;
      end
  end
```

```
  if x8>=0.232011&&x8<=0.264199 %Restrictive 4: Full deck
      if y8>=0.232011&&y8<=0.264199
         delayy=0;
      end
  end

   if x8>=0.265770&&x8<=0.265832 %Restrictive 5: Collision
      if y8>=0.265770&&y8<=0.265832
         delayy=0;
      end
   end

    if x8>=0.265833&&x8<=0.265926%Restrictive 6: Strike
      if y8>=0.265833&&y8<=0.265926
         delayy=0;
      end
    end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


delayx = delayx/ntrips;
delayy = delayy/ntrips;
delay = (delayx + delayy);

treatmenttime3 = delay + treatmenttime3;
delayinst3 = treatmenttime3 - 2;

else
    treatmenttime3 = 2;
    delayinst3 = 0;
end

Totaldelay = Totaldelay + delayinst3;
t = transporttid + basetid + transittid + treatmenttime + transit2tid +
treatmenttime2 +transit3tid + treatmenttime3;
```

```
% returntransit
% Incidents and disruptions in the transit to the third installation

format long
x9 = rand(1);
y9 = rand(1);
pd = makedist('Triangular', 'a',10, 'b',12,'c', 18);

ntrips = 1000;
returntransittid = 0;
delayx = 0;
delayy = 0;
delay = 0;

if x9<=0.55 && y9>=0.5

        for nloops = 1:ntrips;
            r = random(pd);
            delayx = r + delayx;
        end

delay = delayx/ntrips;
returntransittid = (delay + returntransittid);
delayreturn= returntransittid - 12;

elseif x9<=0.55 && y9<=0.5

    for nloops = 1:ntrips;
        ry=random(pd);
        delayy = ry + delayy;
    end

    for nloops = 1:ntrips;
         rx = random(pd);
         delayx = rx + delayx;
    end

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if x9>=0.023096&&x9<=0.477950 %Restrictive 1: departure
      if y9>=0.023096&&y9<=0.477950
         delayy=0;
      end
  end

if x9>=0.497460&&x9<=0.498351 %Restrictive 2: Machinery
      if y9>=0.497460&&y9<=0.498351
         delayy=0;
      end
end
```

```
if x9>=0.499371&&x9<=0.499562 %Restrictive 1: departure
      if y9>=0.499371&&y9<=0.499562
         delayy=0;
      end
  end

if x9>=0.549483&&x9<=0.549550 %Restrictive 2: Machinery
      if y9>=0.549483&&y9<=0.549550
         delayy=0;
      end
end

if x9>=0.549551&&x9<=0.549618 %Restrictive 2: Machinery
      if y9>=0.549551&&y9<=0.549618
         delayy=0;
      end
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

delayx = delayx;
delayy = delayy;
delay = (delayx + delayy)/(2*ntrips);

returntransittid = delay + returntransittid;
delayreturn = transittid - 12;

else
   returntransittid = 12;
   delayreturn=0;
end

Totaldelay = Totaldelay + delayreturn;
t = transporttid + basetid + transittid + treatmenttime + transit2tid +
treatmenttime2 + transit3tid + treatmenttime3 + returntransittid ;
```

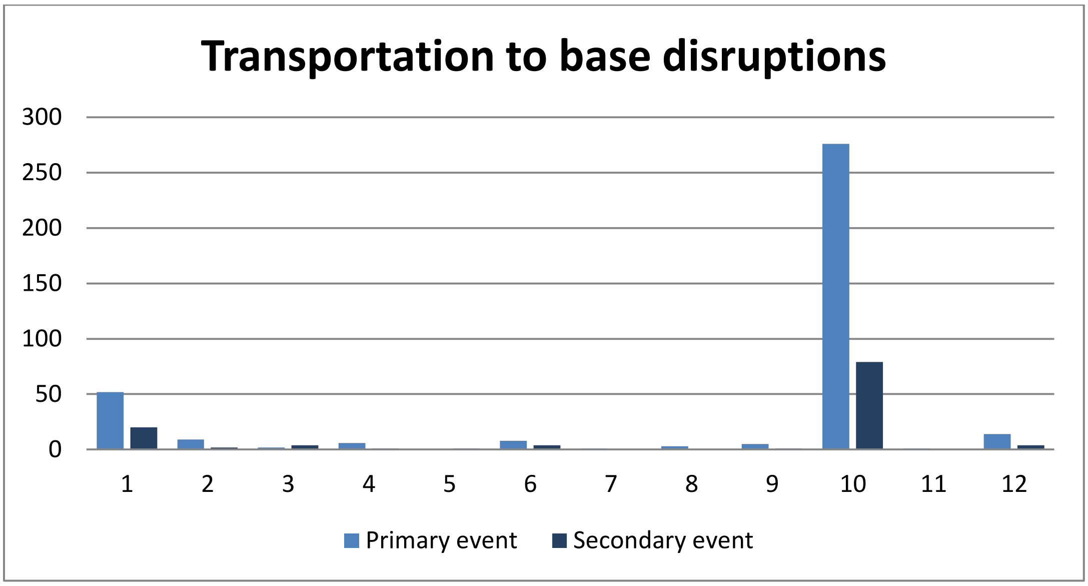
```
%report

disp(['The simulation is over and it ran: ' num2str(simulationruns) '
times']);
disp(' ')
disp(['Total time simulated in the chain was: ' num2str(T)]);
disp(['Total delay was: ' num2str(Totalsimdelay)]);
disp(' ')

disp(['The transportational delay was: ' num2str(Totaldelaytransport)]);
disp(['The base delay was: ' num2str(Totaldelaybase)]);
disp(['The transit delay to the first installation was: '
num2str(Totaldelaytransit)]);
disp(['The treatment delay at the first installation was: '
num2str(Totaldelayinst1)]);
disp(['The transit delay to the second installation was: '
num2str(Totaldelaytransit2)]);
disp(['The treatment delay at the second installation was: '
num2str(Totaldelayinst2)]);
disp(['The transit delay to the third installation was: '
num2str(Totaldelaytransit3)]);
disp(['The treatment delay at the third installation was: '
num2str(Totaldelayinst3)]);
disp(['The transit delay for the return to the base was: '
num2str(Totaldelayreturn)])
disp(' ')

%matrixes

time;
run_delay;
transport_delay;
base_delay;
transit_delay;
installation1_delay;
transit2_delay;
installation2_delay;
transit3_delay;
installation3_delay;
return_delay;
simruns;
events;
storage;
vessel;
heli;
```

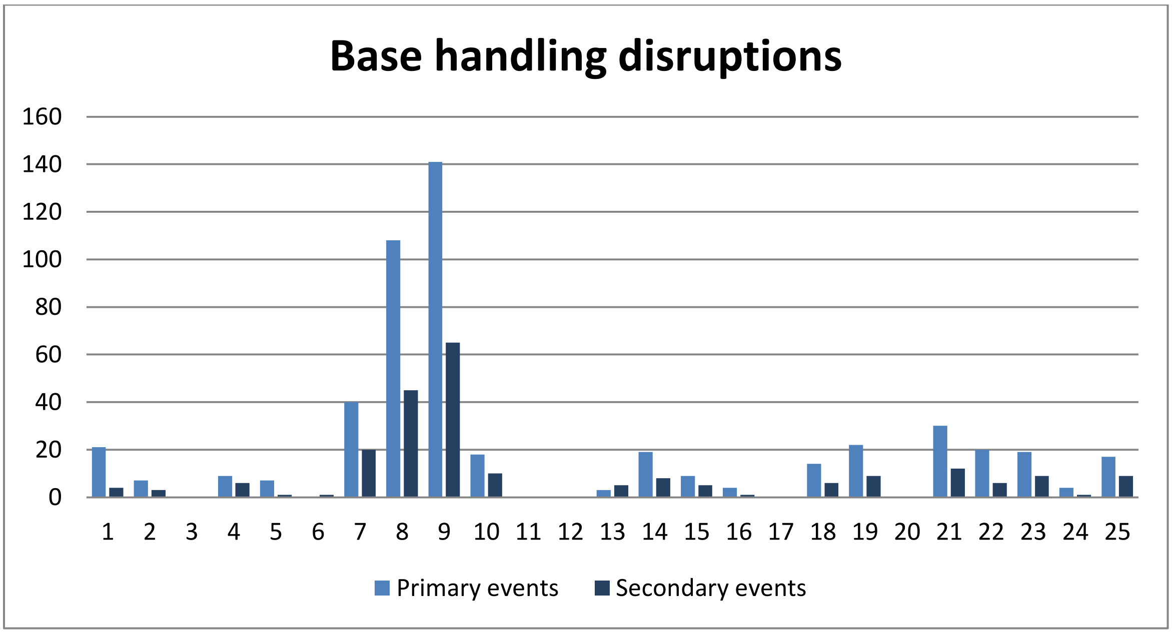
```
%charts
figure(1)%forsinkelse i de forskjellige simuleringsrundene
subplot(2,2,1)
bar(simruns',run_delay');
title('Total delay in the different runs');
xlabel('Simulation runs');
ylabel('Duration [h]') ;

subplot(2,2,2)
bar(simruns',time'); %hvor lenge en simulering varer
title('Duration of the different simulation runs');
xlabel('Number of simulations');
ylabel('Duration [h]') ;

subplot(2,2,3)
bar(simruns',[transport_delay base_delay transit_delay installation1_delay
transit2_delay installation2_delay transit3_delay installation3_delay
return_delay], 1); %
title('');
xlabel('Delay distributions of the different states');
ylabel('Duration supply chain delivery') ;
legend('Transport', 'Base', 'Transit1', 'Installation1', 'Transit2',
'Installation2', 'Transit3', 'Installation3', 'return transit base');

subplot(2,2,4)
pie([Totaldelaytransport Totaldelaybase Totaldelaytransit Totaldelayinst1
Totaldelaytransit2 Totaldelayinst2 Totaldelaytransit3 Totaldelayinst3
Totaldelayreturn])
title('Average delay distribution')
legend('Transport', 'Base', 'Transit1', 'Installation1', 'Transit2',
'Installation2', 'Transit3', 'Installation3', 'return transit base');

figure(2)
bar(simruns',run_delay'); %totalforsinkelse- bytte bar med hist?
title('Total delay in the different runs');
xlabel('Simulation runs');
ylabel('Duration [h]') ;

figure(3)
bar(simruns',time'); %hvor lenge en simulering varer
title('Duration of the different simulation runs');
xlabel('Number of simulations');
ylabel('Duration [h]') ;

figure(4)
bar(simruns', [transport_delay base_delay transit_delay installation1_delay
transit2_delay installation2_delay transit3_delay installation3_delay
return_delay], 1); %
title('');
xlabel('Delay distributions of the different states');
ylabel('Duration supply chain delivery') ;
legend('Transport', 'Base', 'Transit1', 'Installation1', 'Transit2',
'Installation2', 'Transit3', 'Installation3', 'return transit base');
```

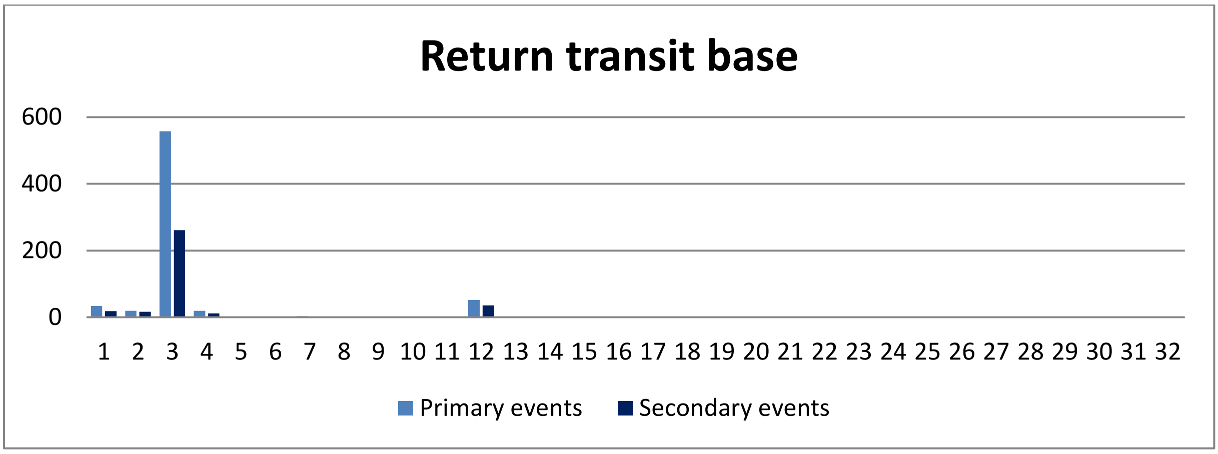
```
figure(5)
pie([Totaldelaytransport Totaldelaybase Totaldelaytransit Totaldelayinst1
Totaldelaytransit2 Totaldelayinst2 Totaldelaytransit3 Totaldelayinst3
Totaldelayreturn])
title('Average delay distribution')
legend('Transport', 'Base', 'Transit1', 'Installation1', 'Transit2',
'Installation2', 'Transit3', 'Installation3', 'return transit base');

%excel
xlswrite('events.xls',events, 'Ark1');
xlswrite('events.xls',event_chain, 'Ark2');

allmatrixes = ([transport_delay base_delay transit_delay
installation1_delay transit2_delay installation2_delay transit3_delay
installation3_delay return_delay]);
xlswrite('delay.xls', allmatrixes);

xlswrite('priority.xls',storage, 'Ark1');
xlswrite('priority.xls',heli, 'Ark2');
xlswrite('priority.xls',vessel, 'Ark3');
```

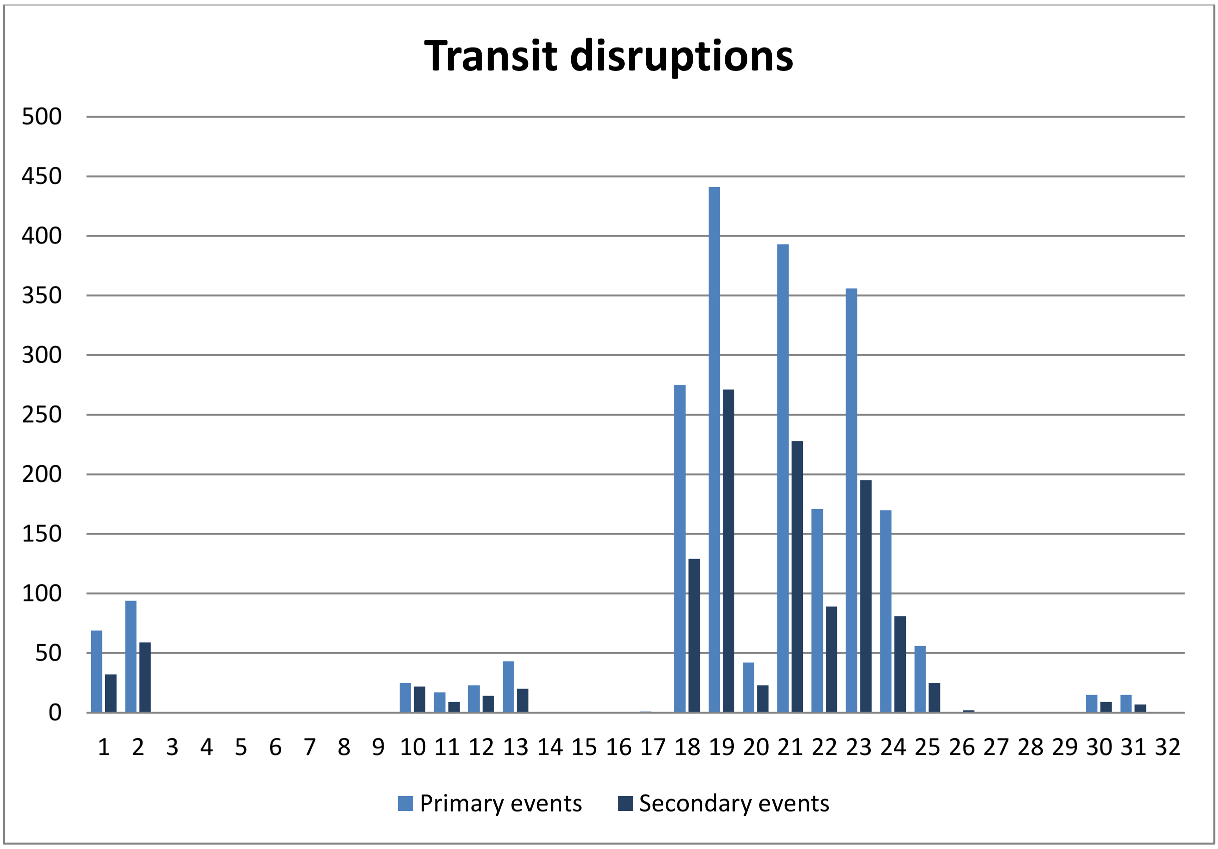
Appendix I – Delay distribution for 10 years

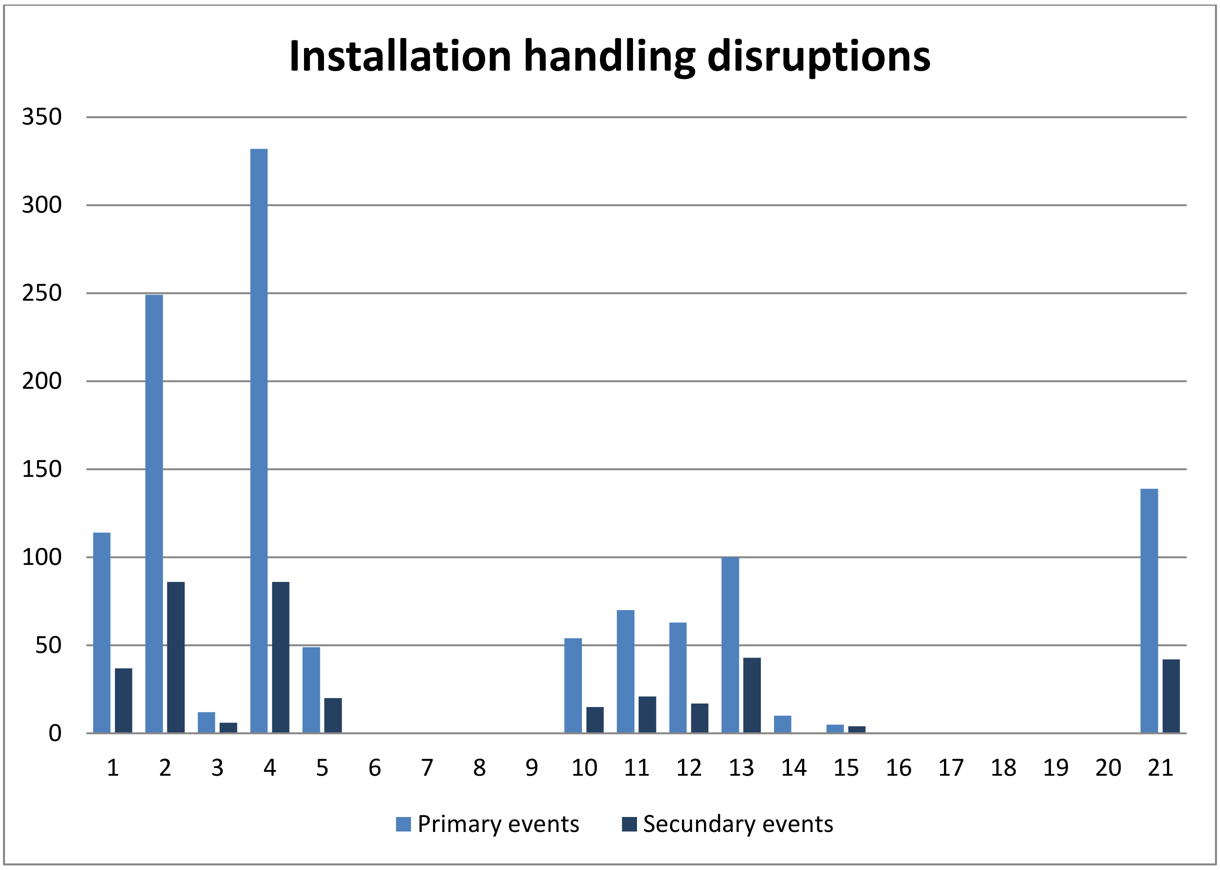
These tables coincides with figure 26 in section 9.3






Return transit base
600
400
200
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Primary events
Secondary events


Transit disruptions
500
450
400
350
300
250
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Primary events
Secondary events


Installation handling disruptions
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Primary events
Secundary events