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Shared Spare Parts Management in Offshore Remote Locations: A Model to Improve Logistics and Reduce Carbon Emissions.

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Abstract

The management of spare parts poses significant challenges, particularly in offshore remote locations. The combination of the remoteness of these locations and harsh environmental conditions adds complexity to the process of timely delivery of spare parts. As a result, lead times are prolonged and operational downtime is increased, leading to substantial financial losses for companies

The lack of simulation models limits the practical application of sharing spare parts strategy, hindering understanding of their potential benefits, costs, and challenges. This gap hinders the implementation of the concept of sharing spare parts management and prevents their adoption in real-world scenarios

To address this gap, a simulation model was developed to manage spare parts across three offshore locations in the Barents Sea. The focus lies in exploring the benefits of sharing spare parts strategy among platforms, particularly regarding lead times, CO_2 emissions, carbon tax costs, and reuse of spare parts among these platforms.

The study follows a quantitative approach using AnyLogic software for simulation. Various factors, including storage capacities, vessel speed, carbon emissions, and carbon tax costs, were incorporated into the model. The research design consists of four stages: conceptualization, model structuring, parameterization, and validation. A case study approach is used, with data from three common equipment types across three criticality classes.

Through a comparison between the baseline scenario and the solution scenario, the results demonstrate the effectiveness of the proposed concept of sharing spare parts. It reduced trips to the onshore warehouse by 42%, decreased total traveling time, CO_2 emissions, and carbon tax costs by 48.6% each, and optimized lead times and inventory management. These results underscore the potential benefits of sharing spare parts systems, providing a pathway for more efficient and sustainable spare parts management in offshore operations.

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Acronyms

CO_2 Carbon Dioxide. 1

BOE Barrel of Oil Equivalent. 1

CAPEX Capital Expenditure. 1

CCS Carbon Capture and Storage. 1

CTV Crew Transfer Vessels. 1

DES Discrete Event Simulation. 1

ETS Emissions Trading System. 1

EU ETS European Union Emissions Trading System. 1

FPSO Floating Production Storage and Offloading. 1

GIS Geographic Information System. 1

HSE Health, Safety, and Environment. 1

IAM Institute of Asset Management. 1

ISO International Organization for Standardization. 1

LNG Liquefied Natural Gas. 1

MTBF Mean Time Between Failures. 1

MTTF Mean Time To Failure. 1

NCS Norwegian Continental Shelf. 1

NORSOK	Norsk Sokkels Konkurranseposisjon. 1
OPEX	Operating Expense. 1
OREDA	Offshore and Onshore Reliability Data. 1
PDO	Plan for Development and Operation. 1
SDS	System Dynamics Simulation. 1
SOV	Service Operation Vessels. 1

Chapter 1

Introduction

This thesis explores innovative strategies for spare parts management in offshore remote locations in the Barents Sea, with a focus on efficiency, carbon reduction, and cost saving. It uses simulation modeling to explore a shared spare parts strategy among platforms, aiming to balance operational demands with environmental accountability in the oil and gas industry.

1.1 Background & Motivation

The offshore industry plays a crucial role in meeting global energy demands, particularly in the oil & gas sector. However, it faces numerous operational challenges, among which efficient spare parts management. Effective and efficient spare parts management remains a critical aspect of operations in the oil & gas industry, as it is a key challenge in ensuring smooth operations and minimizing downtime, especially in offshore remote locations. The management of spare parts inventory influences operational efficiency, and any disruptions can potentially lead to extended downtime and subsequent substantial financial losses [1]. Moreover, due to the remote location of oil & gas platforms in areas like the Barents Sea, there is an additional challenge of logistics and lead time involved in the transport of spare parts. Besides these factors, the logistics process also contributes to CO_2 emissions, raising significant environmental concerns.

There are some researches demonstrating the potential benefits of cooperative inventory pooling systems, as shared inventory systems can help reduce overall inventory levels, thus reducing logistic costs and associated CO_2 emissions [2]. However, managing spare parts in offshore remote locations in the Barents Sea presents additional complexity in the implementation of such systems, due to the long distances between offshore platforms and onshore warehouses and among the platforms themselves, as shown in Figure 1.1.

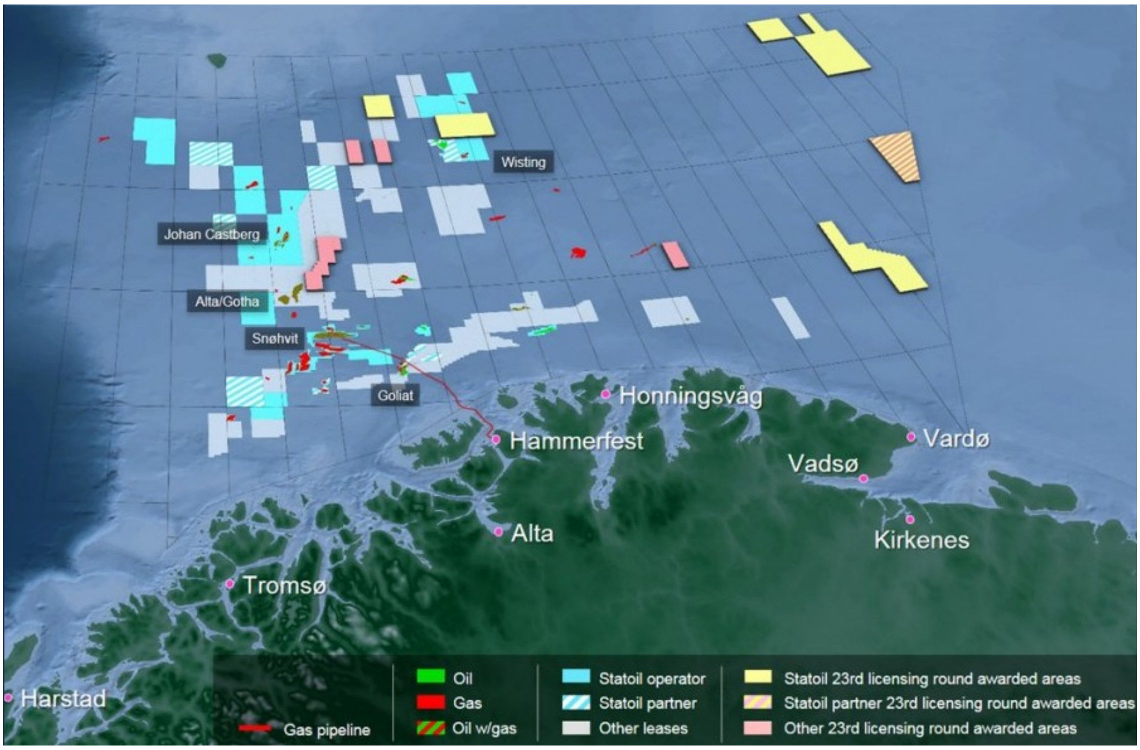


Figure 1.1: *Overview of offshore platforms in the Barents Sea [3].*

In the face of these complexities associated with offshore operations and the unique challenges posed by remote locations in the Barents Sea, conventional analytical approaches often fall short in addressing the dynamic nature of variables involved, such as unpredictable weather conditions affecting transportation, various location of the platforms, and stochastic demand for various spare parts. Therefore, a more sophisticated and adaptable method is required, leading to the adoption of a simulation-based approach.

Simulation modeling provides an opportunity to explore various scenarios under several conditions, providing valuable insights into spare parts management. This approach can bridge existing gaps and provide a comprehensive understanding of managing spare parts in offshore remote locations in the Barents Sea. Hence, this thesis aims to explore and enhance the efficiency of spare parts management while also striving for reduced carbon dioxide emissions.

1.2 Thesis Main Objective

The purpose of the thesis is to reconsider the current management strategy of offshore spare parts practices and explore their challenges, especially in harsh environments such as the Barents Sea.

In addition, assessing the implementation of a new strategy of spare parts management more efficiently by sharing spare parts among the platforms in the Barents Sea. As well as explore and analyze its impacts on the lead time, logistics supply, CO_2 emission related to transportation, and costs. This includes the possibility of reusing the spare parts and equipment in other remote locations, enhancing the sustainability of offshore operations.

1.3 Research Question

The main research question of this thesis revolves around; *"How can a shared spare parts strategy be implemented across multiple platforms in remote offshore locations, and what potential advantages might this approach offer?"*

This question aims to explore the practicalities and advantages of a shared system, focusing on operational, environmental, and economic aspects.

1.4 Method

The main methodology adopted in this thesis to achieve the objective is simulation modeling, chosen for its ability to replicate complex systems and analyze various scenarios in different environments. The primary software used for developing this model is AnyLogic, a comprehensive simulation software widely used across varied industries.

AnyLogic provides a flexible platform for creating models using a variety of modeling languages and methods, including discrete event, agent-based, and system dynamics. Its broad applicability extends to areas such as supply chain, manufacturing, maintenance processes, and warehouse operations, as it gives the opportunity to the users to make informed decisions and optimize processes [4]. This makes it suitable software for the study of spare parts management in offshore remote locations in the Barents Sea.

In this thesis a simulation model was developed for offshore remote locations using AnyLogic as software, to test various scenarios and optimize the management of spare parts in the offshore remote locations. this model aims to predict and analyze the behavior of these scenarios, specifically regarding the availability and delivery of spare parts.

The sharing spare parts scenario is evaluated in order to examine strategies for obtaining spare parts from nearby platforms or the onshore warehouse, considering aspects such as distance and availability of spare parts. The model also includes various factors, including logistics costs, lead times, CO_2 emissions, and the potential for reusing spare parts and equipment among remote locations. This allows for fostering both operational efficiency and environmental sustainability in the management of spare parts in offshore remote locations.

1.5 Delimitation & Assumptions

Asset maintenance inevitably leads to inevitably in consumption of spare parts therefore it is the most important factor needed in this case. Especially in terms of offshore remote, the meaning of spare parts includes all equipment in the platform from pump and drilling equipment to screws and nuts.

However, in this thesis, the simulation model is developed to include three types of equipment classified under three different criticality classes, as per the OREDA (Offshore Reliability Data) handbook's classification. The three different types of equipment were selected as they are existing on each platform, as well as they were chosen from various criticality classes to reflect the varying level of urgency and the status of spare parts demand, and the impact associated with potential equipment failure. The selected types of equipment have been obtained from a relevant master thesis titled "A Multi-Criteria Classification Framework for Spare Parts Management".

The model does not encompass all the onshore warehouses and all offshore platforms in the Barents Sea. Instead, it is limited to one onshore supplier warehouse as a joint inventory for all of the platforms in the Barents Sea. In terms of the platforms, three offshore platforms have been selected to cover long distances in the Barents Sea, and some of the subsea platforms have been excluded because of having another strategy for managing spare parts. As well as choosing only three vessels in the port due to the port capacity and given the coverage of the chosen platforms number. This scope makes the simulation model manageable, user-friendly, and realistic, given that offshore facilities typically do not house all spare parts.

The objective of this thesis is to assess and analyze the current offshore strategies of spare parts management based on best practices and explore a new approach which is sharing spare parts management among the platforms, by integrating them into a simulation model under various scenarios to evaluate their effectiveness across different factors. The goal is to create a model that is intended to be flexible and allows for easy testing of scenarios and experiments, providing clear insights into the anticipated outcomes. However, the users have the opportunity to add, delete, or change the attributes, parameters, variables, and criteria to achieve the desired level of complexity and customization.

The simulation model is developed to run for a specific duration of 5760 hours, representing a period of eight months. This run model time allows for the coverage of all the failures of the chosen equipment within one complete cycle. It's worth noting that the "Personal Learning Edition" of AnyLogic, the software used for simulation, imposes certain limitations that have been considered while developing and implementing the simulation model. One such limitation is the maximum number of agent types, which is set at ten for models using the agent-based method. Additionally, there is a limit of 50000 entries in the source block of the model [5].

Certain data and decisions within the model are estimates, due to the challenges in obtaining precise information and data from various companies and policies, often due to data sensitivity and time constraints. Nevertheless, these estimates should not significantly impact the model's overall performance or data quality, nor hinder the achievement of the thesis's objectives.

1.5.1 Time Limitations

The deadline for completing and submitting this thesis to the University of Stavanger is June 15, 2023, therefore, the scope has been adjusted over time to ensure the research question can be adequately addressed within the given time. This time constraint has influenced the planning and execution of the research activities. The Gantt chart, which can be found in the Appendix A, offers an estimate of the time distribution over this period. It has been designed to accommodate unexpected challenges or unforeseen events, with additional time included.

1.6 Thesis Plan

Planning is the cornerstone of any successful project and is the first crucial step in managerial functions. It involves setting clear objectives, identifying necessary activities, and determining when they should be carried out. By doing so, it provides a roadmap to achieving the desired results.

In the context of this thesis, a Gantt chart has been utilized as a powerful tool for planning and managing the different stages of the research process. The chart provides a comprehensive visual overview of the timeline, depicting tasks' start and end dates and the dependencies between them. The Gantt chart is illustrated in Appendix A.

1.6.1 Thesis Outline

Chapter 2 of this thesis provides a thorough literature review, examining the relationship between asset management, maintenance strategies, and spare parts management. While Chapter 3 focuses on describing the chosen methodology for solving the research problem. In Chapter 4, the necessary data required for the methodology are collected and prepared for analysis. Chapter 5 presents an outlining the approach and analysis conducted in this thesis, including the conceptual and computational modeling for both approaches. Moving further, Chapter 6 is dedicated to presenting and discussing the results derived from these models. Finally, the last chapter, Chapter 7, serves as a conclusion, summarizing the key findings and offering concluding remarks.

Chapter 2

Literature Review

This chapter presents the theoretical basis of the thesis, and it is divided into several sections, which contain an explanation of asset management and its effect on spare parts management. In addition to the study of spare parts, taking into account their challenges, especially in terms of offshore remote locations. Finally, the chapter scrutinizes inventory management from the perspective of priority and importance, taking into account whether it is onshore or offshore.

The primary objective of this chapter is to present a comprehensive overview of asset management, with a particular emphasis on spare parts management. In addition to providing an in-depth understanding of the challenges associated with spare parts management and inventory management. This chapter also seeks to explore a range of different potential options, based on standards, that may serve as alternatives, solutions, or improvements that can be used in order to overcome these challenges.

2.1 Asset Management

Asset management is a crucial process that enables companies to effectively manage their physical and intangible assets, companies usually use all of the activities and procedures of both the systematic and coordinated that are related to asset management to achieve organizational objectives and enhance asset value over time. Figure 2.1 illustrates the relationship between the basic terms of asset management [6].

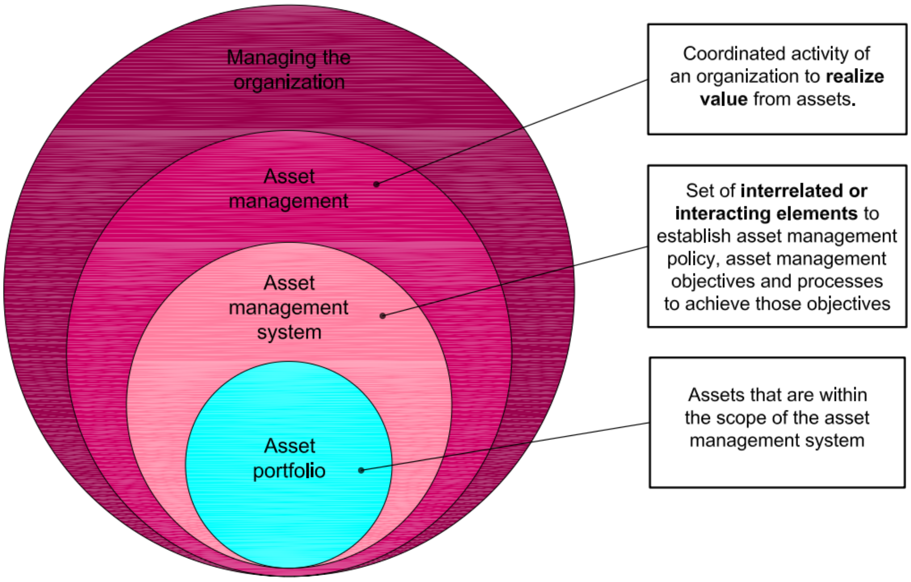


Figure 2.1: *Relationships between key terms [6].*

Some of the key elements that asset management includes are stakeholders, asset management information, and asset management process. An understanding of the needs and expectations of stakeholders is essential to have effective asset management, by having a systematic and structured approach, with clear roles and responsibilities, and a focus on continuous improvement. In addition to ensuring that asset management decisions are aligned with their interests. In terms of asset management information, reliable, correct, and appropriate data, and information are required to gain effective asset management, as well as tools and techniques for analyzing and interpreting this data and information [6].

Figure 2.2 depicts the conceptual asset management model developed by the Institute of Asset Management (IAM), which is a framework that provides a comprehensive overview of asset management. The IAM model is similar to Figure 2.1 which has been mentioned in ISO 55000 standard, in that it includes several key elements related to asset management.

This IAM model shows the IAM's conceptual asset management model, which includes seven elements which are organizational strategic plan, strategy and planning, risk and review, asset management decision-making, organization and people, asset information, and asset life-cycle management. Overall, those elements offer a framework for effective asset management, and they also match up with those listed in the Figure 2.1.

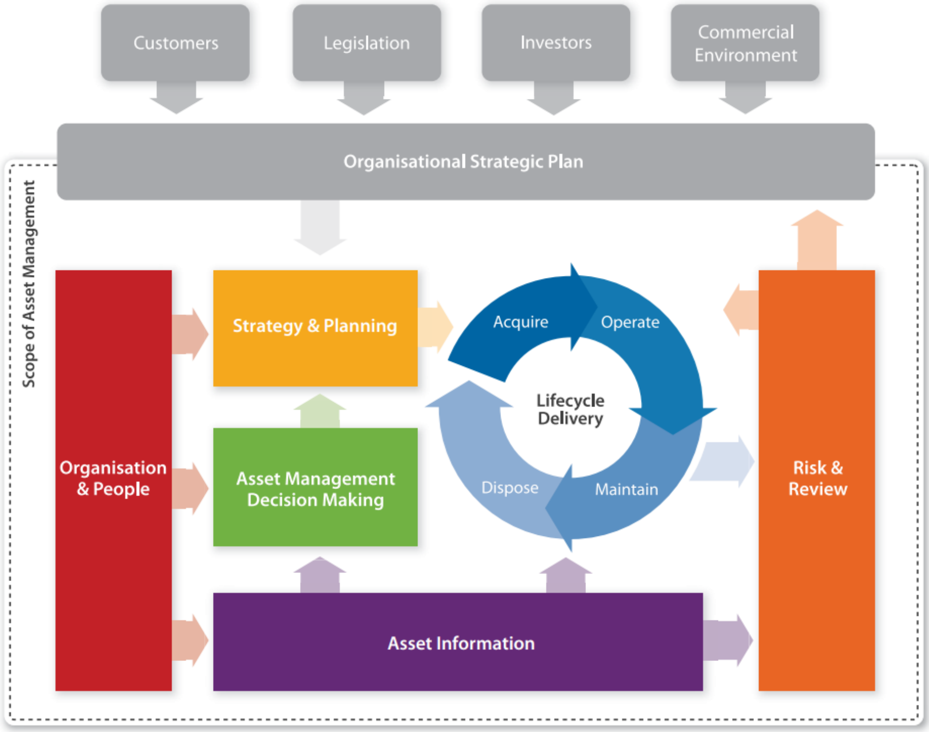


Figure 2.2: *The IAM's conceptual asset management model [7].*

Starting with the organizational strategic plan, which outlines the company's objectives and vision. Strategies and plans are then developed to achieve these goals. Risk identification is crucial to safeguarding the company's ability to achieve its objectives. Asset management decision-making involves making informed choices about assets throughout their life cycle. Organization and people play important roles in asset management, with teams and individuals assuming responsibilities. Asset information is essential to support decision-making. Finally, asset management involves overseeing assets from acquisition to disposal [7].

In general, a comprehensive framework for effective asset management is provided by the IAM's conceptual asset management model. Where each element in this Figure 2.2 represents a key component that contributes to the overall success of an asset management system. Subsequently, asset management is a pivotal factor in the company's success, due to its ability to ensure the effective, efficient, and sustainable use of assets throughout its life cycle. Gaining a thorough understanding of the core concepts of asset management can enable the company to create effective asset management strategies and plans, leading to improve asset performance and amplifying value for the company.

2.1.1 Asset Management in Oil & Gas Sector

Asset management is a structured approach to operating and maintaining asset growth while managing expenses, risks, and performance factors. Overall, the assets within the oil & gas segment are typically complex and expensive to operate and maintain, therefore asset management is a basic preparation for companies in Norway, as it empowers them to make strides in the performance and safety fields, as well as the reliability of their assets while decreasing the cost and increasing the value over the complete asset life cycle. The ultimate goal of asset management is to guarantee that assets provide optimal value to all stakeholders during their lives.

Effective asset management in this sector can help companies to reduce the risk of failure or unplanned downtime. As well as reducing the cost of asset downtime and maintenance, improving asset reliability and performance, and ultimately increasing profitability, where all of which may help companies keep their sustainability in the market.

The oil and gas industry faces unique challenges in asset management especially, in spare parts management due to its complex infrastructure and the high costs associated with equipment downtime. Thus, efficient spare parts management is crucial [8]. Where several Norwegian companies have created frameworks and guidelines for asset management in terms of this sector, regardless of the heavily regulated, with strict environmental and safety requirements, to which the Norwegian oil & gas sector is subject.

Generally, the downtime of assets in the oil & gas sector leads to very costly consequences such as customer dissatisfaction, production delays, public safety risks, or loss of profits. In that case, one key aspect of asset management in the oil & gas sector is maintenance which is just important as in other industries, which leads to extending the lifetime of assets by helping to prevent asset failure or minimizing downtime by ensuring enough spare parts. The main operational maintenance costs as well as daily operational costs of Petroleum, are related to the Norwegian continental shelf (NCS). Downtime is under the unwished list regarding the companies because any breakdown in any asset will affect the operations, which also could lead to an impact on the environment in a negative way as well as the health and safety of the staff. Hence, for safety, effective operation, and concerning the impact on production, companies should conduct maintenance activities following relevant requirements and standards such as NORSOK [9].

2.1.2 Failure rate, MTBF & MTTF

Equipment can fail for various reasons, with the most frequent causes being wear-out, aging, or malfunctions resulting from human mistakes. The average time it takes for a failure to happen is represented by the term mean time between failure (MTBF), which is a measure of the statistical likelihood of a failure occurring. There is an inverse relationship between the mean time to fail and the failure rate shown in the Equation 2.1, which means when the MTBF value goes up, the failure rate goes down, which indicates that the product is more reliable. In a simpler way, the higher MTBF, the more reliable the equipment and the less likely it is to fail frequently. However, as a piece of equipment reaches the end of its life, the chances of failure increase because its parts experience wearing-out from factors like fatigue, oxidation, and other age-related issues [10].

$$\text{MTBF} = \frac{1}{\text{Failure rate}} = \frac{\text{Total operating time}}{\text{Number of failures}} \tag{2.1}$$

Another important metric used to assess the reliability of the equipment and components is the main time to failure (MTTF). MTTF is the average time predicted until a component or piece of equipment fails. This measured period represents how long the equipment can reliably be used before failing. The relationship between the mean time to fail and the failure rate is shown in the Equation 2.2, which describes the failures per million hours(f/mh). MTTF will be equal to MTBF in the case of equipment with no repair or minimal repair time [11].

$$\text{MTTF} = \frac{10^6}{\text{Sum (Failure rate)}} = \frac{\text{Total operating time}}{\text{Number of units}} \tag{2.2}$$

2.1.3 NORSOK Z-008

NORSOK Z-008 is a key standard that covers each aspect of the offshore oil & gas industry, as it gives explanations of the most fundamental concepts for offshore structures, equipment, spare parts management, and assets in a straightforward, simple, and comprehensive manner. As NORSOK Z-008 also describes the essential work processes, including explanations and requirements for each as it is illustrated in Figure 2.3. Some of these processes are managing maintenance activities, making a technical hierarchy, and Spare parts evaluation [12].

The purpose of this standard is to guarantee that the maintenance process is carried out efficiently and effectively, along with effective spare parts management in terms of delivering the right spare parts to the correct place, in order to minimize downtime and enhance asset reliability [12].

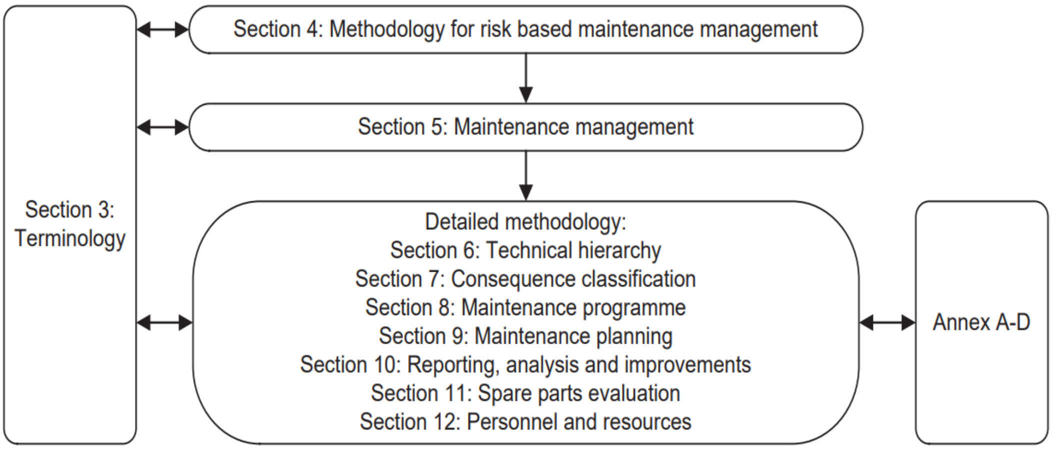


Figure 2.3: *Illustration of structure and content of the NORSOK Z-008 standard [12].*

One of the requirements and guidelines of this standard most relevant to this thesis is the evaluation of spare parts. Whereas, according to the NORSOK Z-008 standard, spare parts should be categorized based on their criticality and frequency of use. The workflow for the evaluation of spare parts is outlined in Figure 2.4. This classification system enables companies to determine the number, location, and lead time of spare parts. It takes into account the demand rate for spare parts, which is often estimated from historical maintenance data and installation-specific data. Consequently, this helps to prioritize efforts of inventory management and improve the availability of spare parts for critical assets [12].

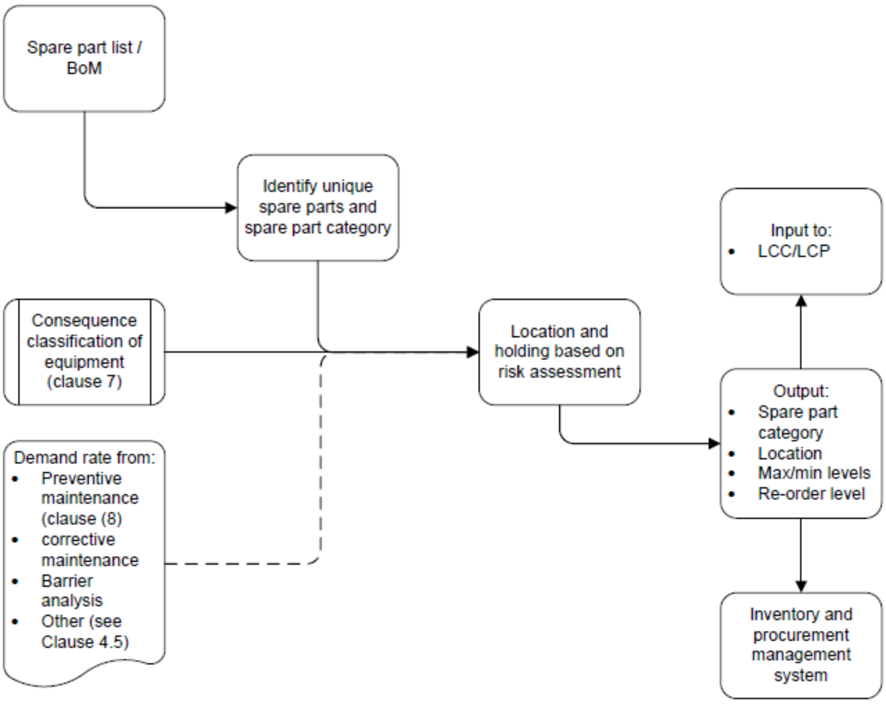
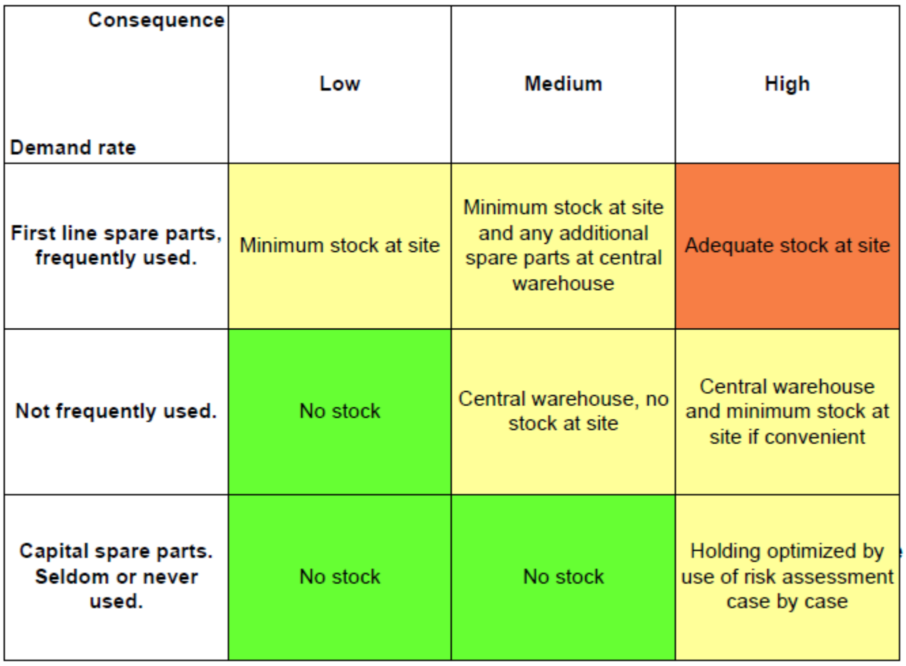


Figure 2.4: *Workflow for the evaluation of spare parts [12].*

An important aspect that the NORSOK Z-008 standard discussed is the optimal location for holding spare parts, which is determined using a risk model as illustrated in Figure 2.5. This risk matrix model balances the consequences of not having the spare parts in place with the demand rate. The ideal location minimizes both the risk and cost associated with spare parts unavailability [12].



Consequence **Demand rate**	**Low**	**Medium**	**High**
First line spare parts, frequently used.	Minimum stock at site	Minimum stock at site and any additional spare parts at central warehouse	Adequate stock at site
Not frequently used.	No stock	Central warehouse, no stock at site	Central warehouse and minimum stock at site if convenient
Capital spare parts. Seldom or never used.	No stock	No stock	Holding optimized by use of risk assessment case by case

Figure 2.5: *Risk evaluation using risk matrix for spare parts [12].*

This standard touches on spare parts inventory optimization enabling companies to establish a systematic approach to managing spare parts inventory levels. This includes determining the optimal reordering points and the order quantities in avoiding under- or overstocking of spare parts. The reorder level is determined based on the demand rate and delivery time, while the order quantity is estimated considering the demand rate, cost per order, and holding cost [13].

Adherence to the guidelines of the NORSOK Z-008 standard allows the companies to improve their spare parts management activities including inventory and reorder levels. Efficient spare parts management helps to lower inventory holding costs and minimize lead time and downtime[13].

2.2 Spare Parts Study

One of the critical tasks in the oil & gas industry is to ensure the smooth and continuous operation of assets. This industry is characterized by its extensive offshore installations in Norway. Furthermore, it requires constant repair and maintenance in order to maintain production efficiency and minimize downtime. In this context, spare parts are important since spare parts let the companies maintain and repair offshore assets in an effective and timely manner.

This section provides an overview of the importance of spare parts in the Norwegian oil & gas industry, their role in maintenance, avoiding preventing downtime, and valuable insights into the challenges and opportunities associated with maintaining offshore equipment context.

2.2.1 Spare Parts & Its Importance

Starting with defining the spare parts and the importance of spare parts and their management. Spare parts are all of the essential equipment and parts that are kept in the warehouse and can be repaired or replaced worn, damaged, or broken parts in assets. In this context, there is a huge need for spare parts management where it takes into consideration determining critical spare parts and establishing a strategy for spare parts in order to identify and control the needed amount in the spare parts inventory, warehouse locations considering the distance to the operation remotes, and the delivery lead time. Management of spare parts helps to minimize downtime and equipment failure [14].

Spare part criticality is a concept used to prioritize the importance of various spare parts based on factors such as their impact on production, safety, and costs. The criticality of spare parts is a measure used in order to prioritize spare part stocking and procurement based on the probable consequences of equipment failure [15].

Several factors affect the management of spare parts, which makes them expensive in general, and the transportation of personnel and necessary spare parts is difficult and expensive, and these factors are manifested in the harsh environment and remote locations. As a result, the availability of spare parts on-site is crucial to minimize the risk of downtime and potential loss of production [14].

2.2.2 Spare Parts Challenges

Considering the importance of spare parts management in the oil & gas industry, it is critical to comprehend the challenges connected with this activity and develop strategies to address these challenges.

The majority of Norwegian oil & gas installations are located offshore, such as Wisting, Johan Castberg, and Goliat in the Barents Sea which are far away from the land. This, combined with harsh environmental conditions, has resulted in challenges related to the delivery, transportation, and storage of spare parts.

The remote locations and harsh weather conditions are making transportation limited across and that lead to being harder to deliver the needed spare parts to the remote locations in a timely and cost-effective manner. Regardless that these remote offshore locations make transportation and logistics more complicated and expensive but there is no irreplaceable for this logistics and transport since the harsh operating conditions in the Barents Sea with the harsh weather conditions and corrosive environment usually lead to increased wear and tear on equipment, making the need for spare parts more frequent.

On the contrary, holding spare parts in remote locations is not a practical solution due to the limited inventory space present there. It is usually reserved for the most critical parts that are most prone to failure. Therefore the spare parts inventory is insufficient in order to satisfy operational needs.

Additionally, the cost of holding spare parts in the inventory is usually high, because it requires storage space that is expensive in the offshore remotes, there are costs associated with maintaining and securing the inventory at these remote locations.

Another contributing factor making it expensive is the possibility of the value of these spare parts depreciating over time, particularly in cases where equipment is replaced or retired before the spare parts are required, and they remain unused. The reason behind this is usually high safety standards since the stringent safety and environmental regulations in Norway require companies to maintain their assets at the highest standards to mitigate safety and environmental risks. Thus, given the asset-intensive nature of petroleum operations, prioritizing financial benefits over safety could potentially lead to increased HSE (Health, Safety, and Environment) threats, hazards, and production loss, resulting in more significant financial harm [14].

Due to the progress witnessed by the world recently, all companies seek to obtain modern equipment and develop their assets to the latest modern technology in order to keep the maximum capacity of production in a safe manner. This obsolescence making a new challenge for spare parts, where over time, spare parts may become obsolete as the equipment is updated or replaced. Holding obsolete spare parts in inventory can be costly, as these spare parts may never be used and then need to be disposed of [16].

2.2.3 Spare Parts Classification

In terms of the oil & gas industry, the need for spare parts and their corresponding strategy are primarily evaluated through consequence classification, supported by reliability, availability, and barrier analysis. This approach, combined with traditional inventory control theory, forms the basis for developing frameworks, inventory policies, and evaluation criteria that ensure efficient spare parts evaluation and control.

Regarding the management of spare parts and the evaluation process, the classification of spare parts is critical. It enables companies to prioritize their spare parts inventory by assessing the potential consequences of equipment failure, in addition, to determining the criticality and importance of each spare part, based on factors such as cost, risk, and material movements, and then establish a suitable spare parts strategy. Such a systematic approach to spare parts classification is essential for creating a cohesive spare parts management policy [14].

According to NORSOK Z-008, the spare parts strategies, including the number of inventories, spare parts quantity, cost, and lead time, must be based on outcomes of the consequence classification as well as any other relevant studies. The criticality and importance of spare parts are closely linked to the significance and criticality of the pieces of equipment or the system they belong to or are intended to repair. However, this approach has been found to be relatively inefficient and costly. In some cases, this conventional approach may lead to the classification of all equipment's spare parts as critical, based on the criticality of the equipment. Therefore, the conventional approach is considered ineffective and impractical in the context of spare parts management [12].

Imagining a case in which a pump is deemed to be highly critical for ensuring production uptime. According to the conventional approach, all spare parts associated with this pump, ranging from screws and nuts to gears and bearings, would be classified as critical as well. But that is necessarily not the case, anyway, this approach has failed to recognize that the majority of the pump's spare parts are probably not critical to the pump's functioning. Hence, such spare parts should not be assigned the same level of criticality as those that are indispensable for pump performance.

On the other hand, suppose that a single spare part such as a shaft of the pump is classified as critical for a piece of equipment that is not considered critical, the pump itself. In such a scenario, it raises the question of whether this spare part should be treated as critically as other highly critical spare parts. Thus, a more nuanced approach is necessary to avoid unnecessary costs and inefficiencies; otherwise, it may result in expensive stock-at-site policies including all its associated spare parts.

As demonstrated in the examples presented, the lower-level framework is necessary as a basis for the classification of spare parts. The significance of this framework for spare parts criticality and consequence analysis cannot be overstated. This actively demonstrates that the framework's level must be below the maintainable item level, in addition, the level should be concerned with spare parts and components that form part of the equipment or system. From the examples given previously, the criticality of a lower-level item classification framework is illustrated, as it allows for the adoption of the current equipment criticality rank as an essential indicator of spare parts criticality. Additionally, the framework's integration with other spare parts characteristics provides a comprehensive understanding of the overall criticality of the spare part situation [9].

OREDA does not specifically provide a unique methodology for classifying spare parts criticality, as it focuses on collecting and analyzing reliability and maintenance data for offshore equipment and components in terms of safety and cost-effectiveness. Companies usually develop and improve their method of categorizing spare parts based on several factors such as cost, lead time, environment, production, impact on safety, and availability. As it is necessary to adapt the spare part classification system to the specific needs and hazards of each installation.

Spare parts are typically divided into three criticality classes based on the equipment's criticality and probability of failure, which include critical, semi-critical, and non-critical.

- The first category is critical which represents the spare parts necessary for the production, operation, or safety of the installation. The unavailability of these critical spare parts could result in massive production losses or significant safety hazards. Therefore having sufficient stock of critical spare parts is important for the continuation of the installation process.
- The second category is considered semi-critical which also represents the important spare parts for the production but may not have the same severe consequences when they are not available. The unavailability of these parts could lead to reduced production or may have minor safety risks.
- The third category is non-critical, which has minimal impact on production. These parts' unavailability may cause small disruptions or delays, but it may never result in significant production losses or safety hazards [16].

While NORSOK Z-008 classifies spare parts into three main categories, as illustrated in Figure 2.5, each of them with its own unique characteristics and importance.

- The first one is capital spare parts, which are also known as insurance spare parts. It is essential in terms of the functioning of the assets regardless of the likelihood of they are not experience any faults during the equipment's lifetime. In some cases, if the capital spare parts are included with the initial order of the system package would that lead to significantly lower costs.
- The second category is operational spare parts, in other words, it is the necessary spare parts in order to maintain the equipment's operational and safety capabilities during its lifetime.
- The third category, consumables are non-specific materials or items that are designed in case of one-time use and are not intended for repair [9, 12].

2.2.4 Consequences of Inefficient Spare Parts Management

As mentioned in the Subsection 2.2.2, one of the challenges that spare parts are facing is inefficient spare parts management, because of the significant impact on the performance and efficiency of companies, particularly in industries with complex and critical equipment such as the oil & gas industry. Some of the main consequences of inefficient spare parts management are touched on and disclosed below.

The consequences of inefficient spare parts management include production delays or may even loss in production with significant costs and significant revenue losses, the danger of obsolescence, and the need for a safety stock policy. The reason for this could be extended periods of downtime when equipment fails, due to the insufficient spare parts inventory, where it takes longer time to require, procure, and transport the needed parts to the assets.

The unavailability of critical spare parts at the right time leads to severe consequences on the safety and environmental performance of companies. In such situations, decisions may be made to continue operation even with parts that are damaged or that need to be replaced, resulting in increased risks of accidents, injuries, and environmental incidents. This could negatively impact the performance, reputation, and financial stability of the company. Using damaged, incompatible, or low-quality parts lead also reduces the equipment's lifespan, as it causes additional wear and tear on the equipment and reduces its overall lifespan.

Inefficient spare parts management can lead to following the strategy of reactive maintenance as repairs only happen when equipment fails, this is more expensive than the other strategies that involve regularly inspecting and replacing parts before the failure happen. In industries where spare parts obsolescence is a significant factor, such as oil & gas, inefficient spare parts management can result in a high risk of inventory holding. This is due to the possibility of spare parts in the inventory becoming obsolete before they are utilized, leading to financial losses for the company, especially if it keeps too many spare parts [16].

It is necessary to keep a balance between the risk and cost of extended downtime caused by delays in obtaining critical spare parts and the associated inventory holding costs to ensure optimal management of spare parts. This approach helps to minimize the impact of obsolescence risks while optimizing inventory costs, and ensuring efficient and effective management of spare parts [17].

2.2.5 Effects of Spare Parts & Its Management on Operation & Asset Availability

In industries with critical and complex assets and equipment specifically the oil & gas industry, there is a significant impact of spare parts on the maintenance operation especially if a company has proper management for those spare parts.

Conversely having inefficient management of spare parts, effective management of spare parts helps to reduce downtime by ensuring the availability of necessary spare parts during critical states. One way to ensure the availability of spare parts is to keep critical and required spare parts in inventory. Therefore, proper spare parts management plays a crucial role in minimizing downtime and ensuring efficient operations.

Effective spare parts management can also help improve maintenance strategies. This happens by providing data on failure rate, failure mechanisms, failure modes, failure cause, for each piece of equipment, the frequency of repairs, and analyzing equipment usage. The maintenance staff can determine which parts have the highest failure rate and are most likely to fail to ensure that those parts are available in sufficient quantity on hand. This would help to plan and execute maintenance activities more effectively such as developing schedules for preventive maintenance in order to identify when it is the right time for equipment replacements and reduce the need for sudden and emergency repairs and increase the efficiency of maintenance operations. Additionally, the combination of spare parts availability and efficient parts management can help reduce costs associated with maintenance by improving inventory levels by reducing the number of unnecessary parts, reducing the need for emergency orders and sudden maintenance operations, and minimizing the risk of obsolete parts. This would assist the company in lowering the amount of money tied up in inventory as well as the costs related to spare parts managing and storing.

Spare parts management encompasses inventory control, procurement, and storage of spare parts to keep optimal levels and ensure timely availability when required. Optimal management of spare parts helps companies avoid excessive costs associated with overstocking or under-stocking of spare parts. While keeping the optimal quantity of spare parts at the right time would support asset maintenance in optimal condition, enhancing overall reliability and reducing the risk of unexpected failures and breakdowns [17].

In conclusion, effective management of spare parts is crucial for oil & gas companies, due to the high cost of offshore equipment and the potential financial impact due to downtime. Therefore, the company should have an overall understanding of equipment requirements, demand variability, lead times, transportation, the cost of inventory holding, and other factors in order to achieve the optimal inventory level. However, the company must gain a balance between spare parts availability and the cost of holding an inventory, considering factors such as loss due to depreciation, harsh environment, withheld capital, obsolescence, and damage. This balance would align with the main objective of the spare parts study, which is to ensure the availability of the right quality spare parts at the right time, place, and cost [14].

2.3 Tool for Modelling

The simulation software that has been used to create and develop a comprehensive and accurate simulation model for spare parts management in the Barents Sea is AnyLogic. It is a sophisticated, accurate, and adaptable simulation software with numerous major characteristics that make it an ideal choice for this topic. AnyLogic is a modeling tool that includes multiple simulation methods as illustrated in the Figure 2.6. It allows for all system dynamics, agent-based modeling, and discrete-event simulation to model the complex interactions among the various physical assets, equipment, and components in the spare parts management process [18].

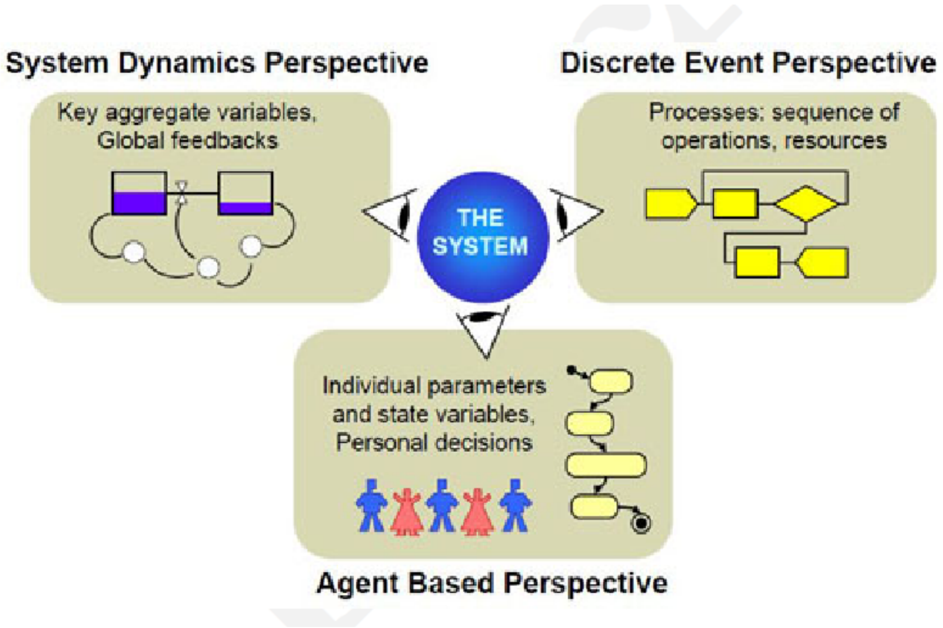


Figure 2.6: *Various methods of simulation [18].*

2.3.1 Discrete Event Simulation (DES)

Starting with discrete event simulation (DES) which is often used for processes that involve discrete entities, since the system considers it as a process that consists of a sequence of operations. It provides a moderate level of abstraction, ignoring specific physical details such as the geometry or acceleration of a car. Industries such as logistics, healthcare, and manufacturing frequently use discrete event simulation [18].

2.3.2 Agent-based Simulation (DES)

While an agent-based simulation is increasingly being used in a variety of applications for processes in which entities exhibit individual behavior rather than a shared behavior. These active entities, or agents, can be anything such as companies, equipment, or other relevant entities within the system being modeled.

State charts are commonly used to define agent behavior in agent-based modeling, as well as they may also be used in other methods of simulation, such as discrete event modeling. By defining the behavior of each individual agent and connecting them in a specified way, the simulation can run and the system's overall dynamics can emerge from the interactions between the individual agents [18].

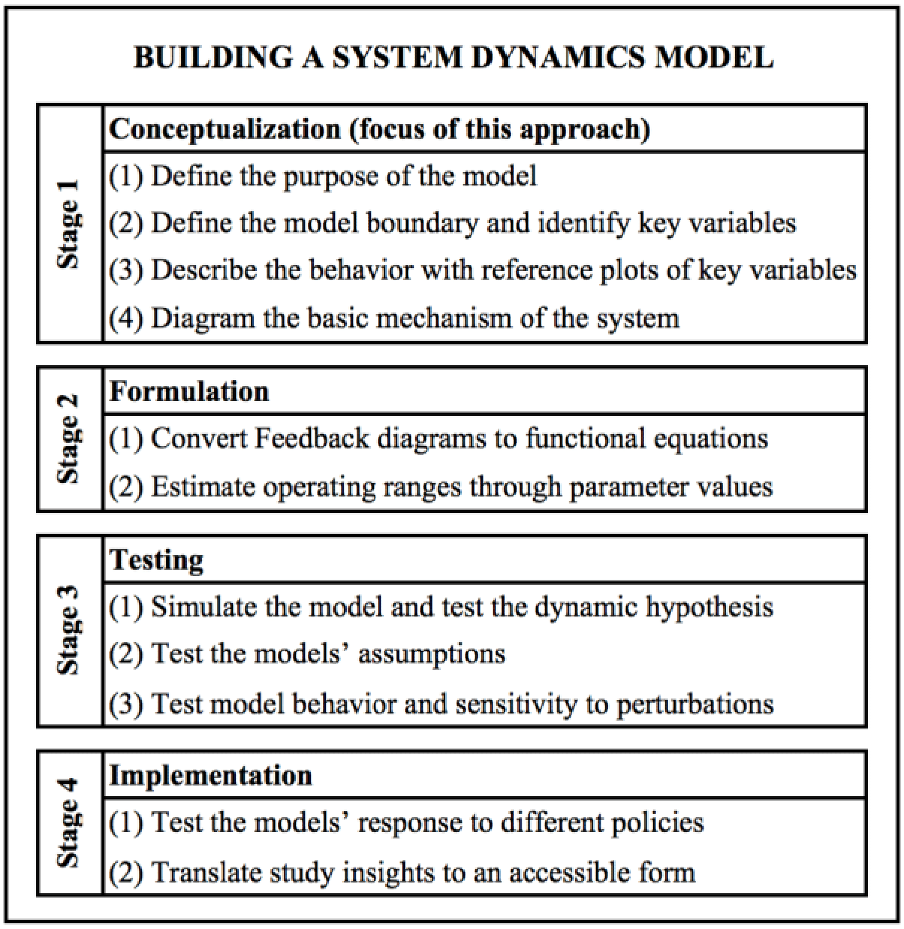
2.3.3 System Dynamics Simulation (SDS)

Lastly, system dynamics simulation (SDS) is often used for processes that involve continuous entities or causal loops. Unlike other modeling methods, such as agent-based modeling, system dynamics focuses on the general representation of a complex system rather than the fine details of individual characteristics, making it suitable for long-term, strategic modeling and simulation [18].

2.3.4 Modeling of System Dynamics

Several phases are taken in the modeling and simulation methodology, involves to create a reliable computational model that accurately describes and predicts the behavior of the model. All the methods are following similar basic phases involved in the process as illustrated in the Figure 2.7.

The initial phase is the conceptualization phase where the system is analyzed as well as the model structure and interfaces are designed. The formulation is the next phase which involves the preparation of the computational model and the model inputs. The third phase is simulation and testing where the base case is run, as well as other scenarios, are run in order to build confidence and validate and validate the model structure. Finally, during the implementation phase, the solution is put into action if the model yields satisfactory results.



BUILDING A SYSTEM DYNAMICS MODEL

Stage 1	**Conceptualization (focus of this approach)**
	(1) Define the purpose of the model
	(2) Define the model boundary and identify key variables
	(3) Describe the behavior with reference plots of key variables
	(4) Diagram the basic mechanism of the system
Stage 2	**Formulation**
	(1) Convert Feedback diagrams to functional equations
	(2) Estimate operating ranges through parameter values
Stage 3	**Testing**
	(1) Simulate the model and test the dynamic hypothesis
	(2) Test the models' assumptions
	(3) Test model behavior and sensitivity to perturbations
Stage 4	**Implementation**
	(1) Test the models' response to different policies
	(2) Translate study insights to an accessible form

Figure 2.7: *Phases of model implementation [19].*

Chapter 3

Methodology

This chapter serves as a comprehensive exploration of the methodology utilized in the development and simulation of the dynamic behavior model. It offers the foundation for a complete understanding of the simulation process and, eventually, contributes to the outcomes reached in this thesis.

3.1 Overview

Modeling and simulation are techniques for creating and modifying high-level representations of complex systems or processes to study, design, develop, improve, or visualize them. Models, which might be mathematical, logical, or physical representations of the entity, system, phenomena, or process which are under research, are created to be used in the process of performing the simulations. The data generated from these simulations can be used for managerial or technical decision-making [20].

Subsequent sections detail the steps of this research method and describe the required data along with their sources and analytical way. In addition to describing the way of developing the simulation model. By detailing the methodology and linking it to the chapters on Data Collection and Analysis, a comprehensive overview of the research approach is provided. This overview supports the investigation into spare part management optimization for offshore remote locations in the Barents Sea.

3.2 Approach

The purpose of this thesis is to improve spare parts management for offshore remote locations in the Barents Sea while minimizing carbon emissions, reducing lead times, and streamlining logistics. Therefore these objectives require the use of numerical data and quantitative methodologies to develop and calibrate a simulation model. The model and simulation try to describe real-world situations to understand the behavior of the spare part management at the offshore remote locations or to predict their behaviors or both. The case study is grounded in mathematical equations and numerical data and relies on variables such as storage capacities, lead times, and carbon emissions. As a result, a quantitative approach is essential.

AnyLogic offers integration capabilities, allowing the software to easily integrate with external data sources, geographic information systems (GIS), and optimization algorithms. This integration facilitates the calibration and validation of simulation models. Additionally, AnyLogic provides built-in visualization tools that enable the creation of interactive simulation models, as it provides a visual representation of the system's performance, which helps to facilitate communication, accelerate decision-making, and aid in the analysis and interpretation of results, especially in this study case it helps in the phase of spare parts planning and management projects before their implementation [18].

3.2.1 Modeling of Case Study

The developed detailed simulation model was made by using AnyLogic, which incorporates the intricacies of spare part management for three offshore remote locations, in the Barents Sea. Where it represents the failure rate of three pieces of equipment onboard, their supply chain, onshore warehouse, and logistics processes involved in spare part management. This model considers factors of transportation modes, onshore and offshore storage capacities, lead times, travel time, carbon emissions, number of travels, components availability, and logistics performance. As it also identifies the optimal scenario for spare part management to contribute to environmental sustainability and operational efficiency [18]. By using simulation modeling, it is possible to analyze the impact of different scenarios and experiments and optimize inventory levels to ensure the availability of critical spare parts while minimizing costs.

3.3 Research Design

In order to provide a clear understanding of the development process, this thesis subdivides the four phases provided in Figure 2.7 into five steps as illustrated in Figure 3.1. These steps help the development of the simulation model by extracting mental models from real-world situations and transforming them into conceptual models. These models are further developed into computational models, resulting in a reliable representation of the system behavior.

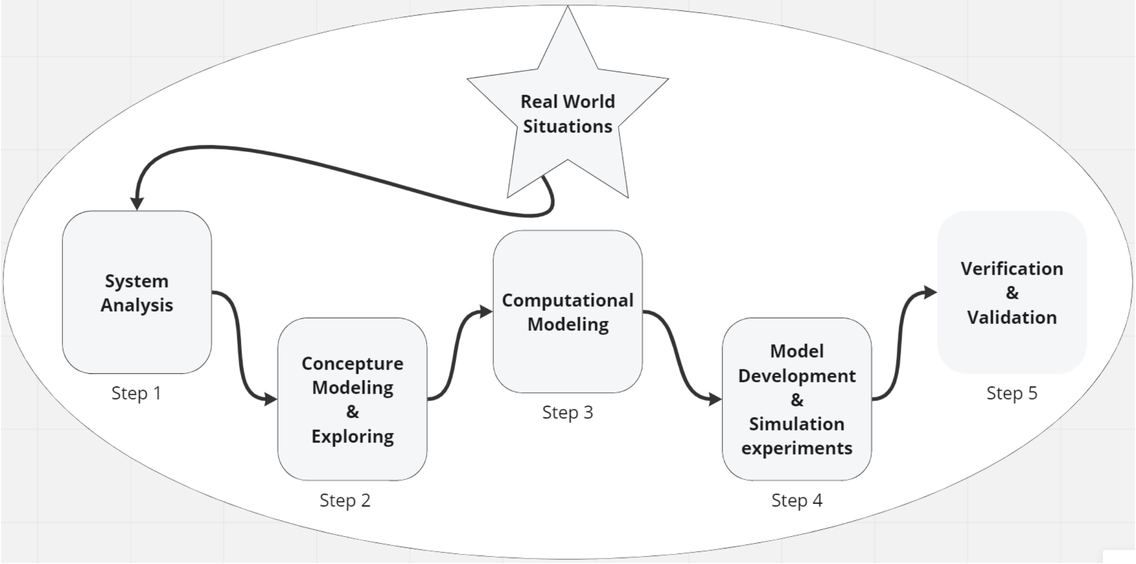


Figure 3.1: *Research method*

Table 3.1 below offers a thorough overview of each step in the research methodology. It provides crucial details, including data requirements and their sources, along with outlines of the analytical approaches implemented. Furthermore, it delineates the validation measures taken to ensure the robustness of the outcomes. The purpose of this table is twofold to detail the systematic progression of the research and to emphasize the rigorous steps taken to ensure the validity and robustness of the outcomes.

Table 3.1: *Research Methodology Stages*

Research Steps	**Data Requirements**	**Data Source**	**Data Analysis**	**Validation**
System Analysis	Needs & Concepts Solutions	Expert Advisor & OREDA	Pugh Matrix & Stakeholders Analysis	Academic Expert
Conceptual Modeling & Exploring	System Workflow & Interactions	literature Reviews	Technical Hierarchy & Sequence Diagrams	Industrial Expert
Computational Modeling	Mathematical Formulations	Literature Reviews & Public Research	Computational Model Analysis	Academic Expert
Modeling Development & Simulation Experiments	Model Parameters & Simulation Scenarios and Experiments	Industry Reports & Public Research	AnyLogic Software	Simulation Verification Techniques with Academic expert
Verification & Validation	Validation Criteria	Figures of Outcomes	Comparison of Outcomes	Domain Expert Review

The subsequent chapter explores the case study, detailing the process of data collection and the indicators used for model development. Where the subsequent chapters cover comprehensively the stages of the model development process, conceptualization, model structuring, parameterization, and validation.

Chapter 4

Data Collection

This chapter describes the way of collecting the required data and explains the utilized data to develop a simulation model to optimize spare part management in offshore remote locations, before going into the model itself in detail. This provides a perspective on certain constraints and assumptions that are being taken into account while creating the model. The data collection process is an essential step in developing a reliable simulation model that accurately represents the real-world scenario and challenges of spare part management in offshore environments. The research objectives are addressed by gathering and using the data in an effective way in the simulation model, which leads to actionable insights and strategies for efficient spare part management.

4.1 Case Study Description

This thesis focuses on the main warehouse located on Hammerfest as a supply hub and three offshore oil & gas platforms located in the Barents Sea, which are Wisting, Johan Castberg, and Goliat. These locations have been selected due to their remote nature, which poses unique challenges in terms of spare parts management.

Three types of equipment were chosen for this study to represent a variety of criticality classes. The centrifugal pump, classified as critical, is essential for platform operations and any failure could have significant implications. The semi-critical gate valve, while not as essential as the pump, still plays a vital role in the operation of the platforms. The electric motor, classified as non-critical, provides an interesting contrast to the other two equipment types as its failure may not pose a direct threat to operations.

A variety of data has been collected to fuel the simulation model, including equipment failure rates, transportation logistics, carbon emission rates from vessel fuel, and the associated carbon tax costs. This rich dataset enables a comprehensive exploration of the potential benefits and implications of implementing a shared spare parts strategy across these three platforms.

The following section provides a comprehensive overview of the data collected and utilized in this study. It begins by explaining the main warehouse and the remote locations situated in the Barents Sea, followed by the selected equipment classified within the diverse criticality classes. Additionally, detailed information regarding the indicators and dataset is provided, establishing a solid foundation for addressing the research questions and objectives outlined in this thesis.

4.1.1 Main Warehouse

The warehouse onshore plays a critical role in supporting offshore platforms in the Barents Sea. As it minimizes downtime by ensuring a continuous supply of spare parts and equipment at a suitable time and helps manage risks by enabling a quick response to emergencies, in addition to improving inventory storage space on platforms.

The Hammerfest warehouse has been named after the city in which it is located, Hammerfest City, that located in the northernmost part of Norway, making it a strategic location to support oil & gas operations in the offshore remotes in the Barents Sea. The Hammerfest warehouse, assets, and other support facilities are referred to as the 'Polar Base' as it is highlighted in Figure 4.1. It has comprehensive resources to meet and provide the needs including material management requirements in addition to the logistics services, and it can accommodate three vessels concurrently. The Hammerfest warehouse has a large building area of approximately 40000 $[m^2]$, offering ample space for storage, equipment, and other necessary resources to support offshore platforms [21].

As a supply hub for offshore remotes in the northernmost, Hammerfest warehouse fulfills the needs of some sectors such as renewable, offshore wind energy, and oil & gas in remote offshore locations in the Barents Sea [22].

Figure 4.1: *Polarbase located at Hammerfest city [21].*

4.1.2 Offshore Remote Locations History

The Barents Sea, characterized by its wealth of oil & gas reserves, is anticipated to be a focal point for future production. Currently, numerous competitive companies operate platforms and engage in production activities within the region [23].

The Norwegian sector of the Barents Sea is home to several oil & gas fields, some of which have been in operation for a long time. It contains five major fields as illustrated in the Figure 4.2, which are Snøhvit (Snow White), Goliat, Johan Castberg, Wisting, and Alta/Gohta. These offshore remote locations are owned by different oil & gas companies and they are either approved for production and activity or planned for future production.

These offshore remote locations are explained and discussed in the following subsections, as well as highlighting their significance to the Norwegian industry. This helps in obtaining the necessary data to incorporate them into the simulation model for analysis and to observe the results of several parameters.

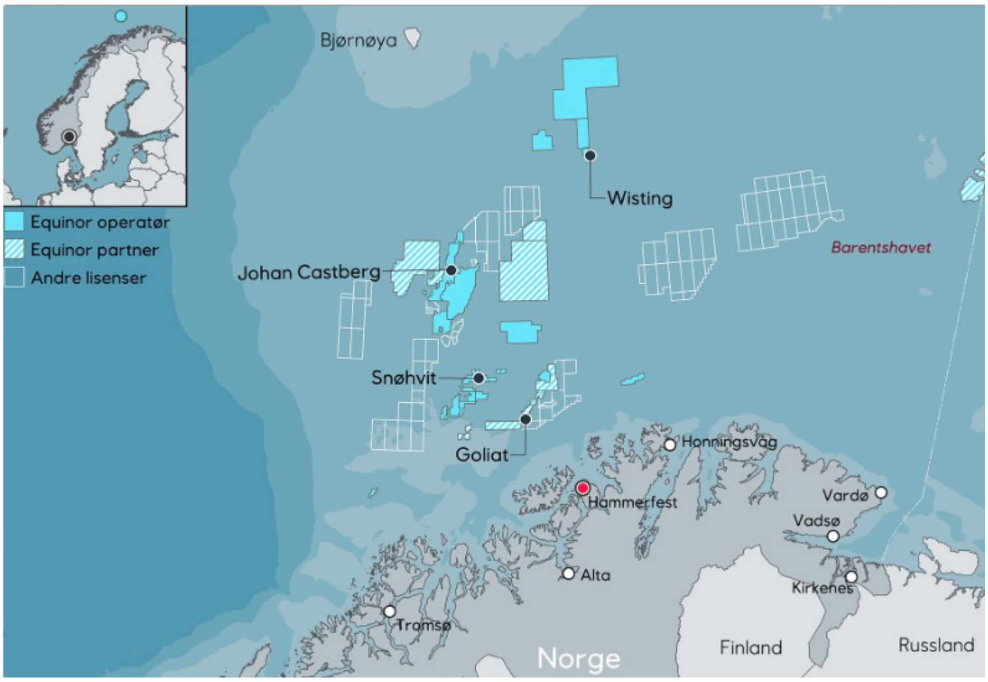


Figure 4.2: *Offshore platforms of interest in the Barents Sea [24].*

4.1.2.1 Goliat:

Goliat is the first oil reservoir in the region to begin production, the field has been discovered in 2000. It is located approximately 85 km north of Hammerfest city, 150 km south of Johan Castberg field, and 180 km south of Wisting field with a water depth is 360-420 m. It is expected to have recoverable reserves equivalent to around 180 million barrels of crude oil (boe).

The Goliat field is operated by the oil company Vår Energi ASA with a 65% stake in the project and the remaining 35% is owned by Equinor Energy AS, both of them have licenses, but Vår Energi ASA is the only current operatorship company.

In 2009, the field underwent development and operation (PDO), during which a cylindrical FPSO (floating production, storage, and offloading) facility with a diameter of 90 m, as illustrated in Figure 4.3, was constructed to facilitate floating, production, storage, and offloading operations. The anticipated duration of oil and gas production from this facility is a minimum of 15 years. The daily oil production capacity is estimated to be 100,000 barrels, while natural gas production is projected to be approximately 3.9 million cubic meters [25].

Figure 4.3: *Goliat platform [25].*

4.1.2.2 Snow White (Snøhvit):

Snow White (Snøhvit) is a field in the Barents Sea, discovered in 1984 by Statoil, now known as Equinor. The platform is located 140 km northwest of Hammerfest city and 100 km south of Johan Castberg field. Snow White is the first offshore natural gas development in the Barents Sea.

The stakeholders of this field who has license are TotalEnergies EP Norge AS with 18.4%, Petro As with 30%, Neptune Energy Norge AS with 12%, Wintershall Dea Norge AS with 2.8% and Equinor Energy AS with 36.8% stake in the project, where Equinor Energy AS is the only current operatorship company.

This field includes three reservoirs Askeladd, Snøhvit, and Albatross as illustrated in Figure 4.4, and comprises remotely controlled seabed infrastructure in the sea between 310 and 340 m deep. Based on the location of the field in the harshest environment which includes sea ice and extreme weather conditions, substantial technological innovations were necessary to develop the field, it saw the approval of the plan for development and operation (PDO) in 2002.

Snøhvit project represented a pioneering initiative in offshore development, as it implemented cutting-edge carbon capture and storage (CCS) technology, as the first of its kind in the Barents Sea. The project involved the injection of carbon dioxide into a subsea reservoir through two dedicated well slots [26].

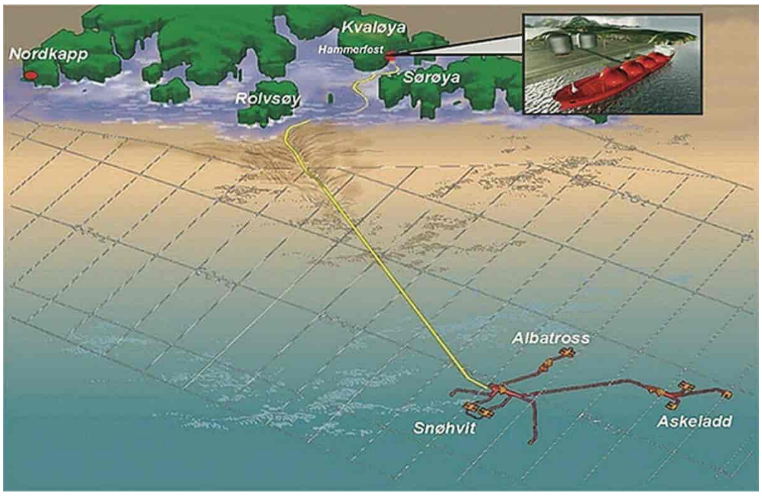


Figure 4.4: *The three structures of Snøhvit platform [27].*

The reserves of the Snøhvit field are estimated at more than 193 billion cubic meters of natural gas, 5.1 million tons of LNG (liquid natural gas), and last of them is 113 million barrels of condensate, which contributes to making Norway one of the major, most reliable, and long-term suppliers of natural gas (LNG) in Europe and beyond, with natural gas production expected to continue for many decades. Electrification will minimize the emission and make reaching near-zero greenhouse gas emissions emitted from production easier [28].

4.1.2.3 Johan Castberg:

Johan Castberg is a new field in the Barents Sea that was discovered in 2011 and is planned for future production. It is located 240 km northwest of Hammerfest city with a water depth of around 370 m and approximately 110 km south of the Wisting field. Johan Castberg field is estimated to contain up to 650 million barrels of oil equivalents. The stakeholders of this field who has license are Vår Energi with 30%, Petro As with 20%, and Equinor Energy AS with 50%, where Equinor Energy AS is the only current operatorship company [29]

The development of the Johan Castberg filed, according to the plan for development and operation (PDO) that was approved in 2018, has included all of the construction of an FPSO vessel Figure 4.5, with considering 200 000 barrels of production of oil in a day. Along with a substantial subsea development consisting of a total of 30 wells spread among 10 subsea templates. The operation of this field is managed by using a main supply base in Hammerfest, as well as vessels to meet and transport its needs such as required spare parts and deliver it aid [30].

Figure 4.5: *Johan Castberg vessel [31].*

4.1.2.4 Wisting:

The field Wisting was discovered in 2014 in the Barents Sea, it is located about 310 km northwest of Hammerfest city, it is lying at a water depth of around 390 - 418 m. This field and is planned for future production as it is estimated to contain around 500 million barrels of oil equivalents.

The stakeholders of the Wisting field are Equinor Energy AS with 35%, Petoro with 20%, Lundin Energy Norway AS with 35%, and INPEX Idemitsu Norge AS with 10%. All these companies have licenses, but Equinor Energy AS is the current operatorship company [32].

The development plan involves the construction of a circular FPSO as shown in the Figure 4.6. FPSO is designed to facilitate floating, production, storage, and offloading operations with an estimated production capacity of around 100,000 barrels of oil per day. Along with the FPSO, it is expected to install a subsea production system comprising several wells and subsea templates in order to support the production process. The Wisting field's operation will most likely involve a primary supply base at Hammerfest, as well as the use of helicopters for moving people and other logistical needs for replacement spare parts [33].

Figure 4.6: *Wisting platform [32].*

In this thesis, Wisting, Goliat, and Johan Castberg fields have been selected as the primary subjects of analysis and involved in the simulation model. These fields were selected because of their different development stages and differing production infrastructures, which provide a diverse and comprehensive insight into the oil & gas activities in the Norwegian Barents Sea.

The excluded fields are Snøhvit and Alta/Gohta from the simulation model. Snøhvit field is a subsea development with an onshore processing plant, which differs significantly from the chosen fields' offshore production infrastructure. Alta/ Gohta is very close to Johan Castberg Field, almost at the same latitude, and can be treated the same in terms of spare parts supply and use. That makes the current status of Snøhvit and Alta/Gohta less suitable for a comprehensive comparative study and both do not align with the specific focus of this thesis.

4.1.3 Equipment Selected for Case

These platforms have similar assets and each platform contains many pieces of equipment and components essential for production, ranging from simple components like screws and nuts to complex machinery such as pumps and drilling equipment. All of this equipment plays a crucial role in keeping production efficient and minimizing asset downtime.

However, this section has concentrated on three types of equipment representing three varieties of criticality classes according to the limitations of the thesis. This approach ensures that the simulation model explores the behavior of the different critical classes for spare part management, leading to more targeted and effective strategies for offshore remote locations.

4.1.3.1 Centrifugal Pump

The centrifugal pump is the first essential piece of equipment included in this thesis in order to develop the model. A generic drawing of the centrifugal pump is provided in Figure 4.7 illustrates the most components every centrifugal pump has in common [9].

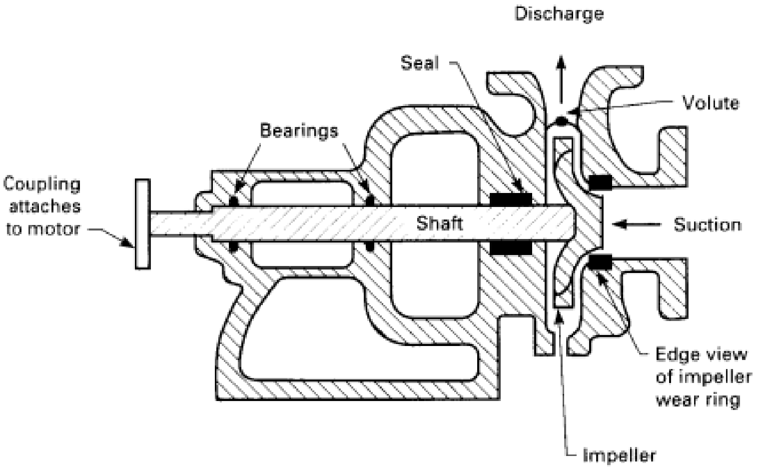


Figure 4.7: *Centrifugal pump component [9] & [34].*

Table 4.1 presents the data used for the centrifugal pump in the developed model. Where it shows the criticality of the pump to be eight which makes it classified in the critical set. Additionally, the MTTF of the centrifugal pump is determined to be 0.04 (years), calculated using Equation 2.2 where the failure rate provided in OREDA, which can be found in the Appendix B. The important aspects of a centrifugal pump are to consider maintenance procedures, timely availability of spare parts, and the pump's impact on system efficiency in the production process.

Table 4.1: *General Information About Centrifugal Pump [9].*

System Summary	
Functional location:	Trip tank pump
Equipment:	Centrifugal pump
Criticality:	8
Maintenance type:	Preventive Maintenance
Technical specification:	High
OREDA MTTF (years):	0.04

4.1.3.2 Electric Motor (DC)

The second piece of equipment included in this thesis is the electric motor and it is incorporated into the developed model. An assembly drawing is provided in Figure 4.8 where it shows what components every electric motor has in common.

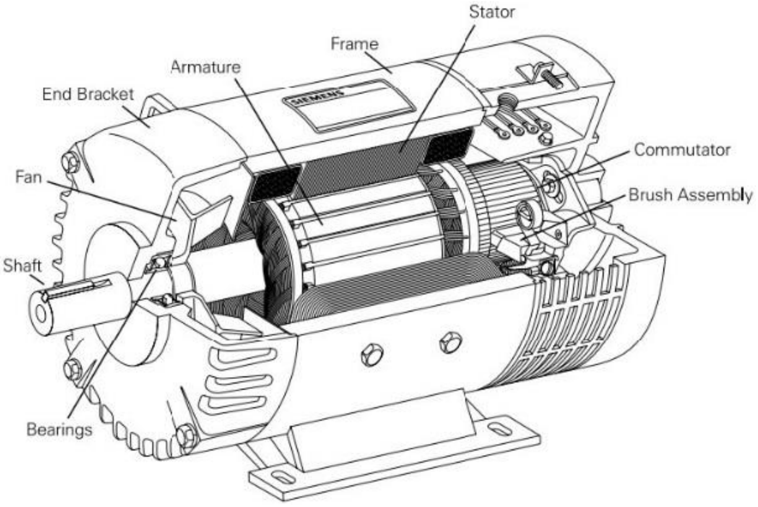


Figure 4.8: *Electric motor (DC) component [9].*

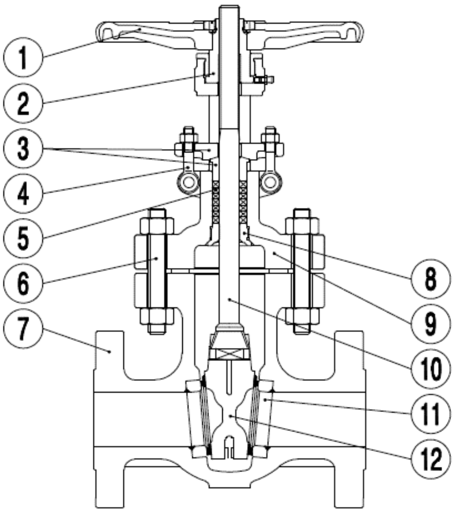
A systems summary in Table 4.2 presents general information about the electric motor, including its criticality rank of six and it is classified in the semi-critical group. Its MTTF is calculated as 0.57 (years), where it can be calculated by using Equation 2.2 and the failure rate obtained from OREDA that can be found in Appendix B. In the thesis, the most critical aspects of the electric motor, such as maintenance procedures, timely spare parts availability, and the electric motor's impact on overall system efficiency in the production process, will be the focus [9].

Table 4.2: *General Information About Electric Motor (DC) [9].*

System Summary	
Functional location:	Tank pump motor
Equipment:	Electrical motor, DC, 690V, 60Hz
Criticality:	6
Maintenance type:	Preventive Maintenance (PM)
Technical specification:	Limited
OREDA MTTF (years):	0.57
Unit price:	111 476.00 Kr

4.1.3.3 Manual Gate Valve

The manual gate valve is an important piece of equipment in regulating and controlling the flow of fluids in piping systems and it is the last piece of equipment included in the model of this thesis. An assembly drawing of a general gate valve has been provided in Figure 4.9 where it illustrates the common components for each manual gate valve.



IT.	DESCRIPTION
1	HANDWHEEL
2	YOKE SLEEVE
3	GLAND FLANGE
4	GLAND EYE BOLT
5	PACKING
6	BONNET BOLT
7	BODY
8	BONNET
9	BACK SEAT
10	STEM
11	SEAT RING
12	WEDGE

Figure 4.9: *Gate valve component [35].*

A summary of general information on the gate valve has been provided in Table 4.3. The manual gate valve has a rank of three in criticality and is classified into the non-critical group. The MTTF of the gate valve has been determined to be 0.14 (years), as indicated in Table 4.3. This value was obtained by applying Equation 2.2 and using its failure rate provided in OREDA, which is available in Appendix B. In this case study, the main objective is to concentrate on the most crucial factors of the manual gate valve, including maintenance procedures, the timely interchangeability of spare parts, and the valve's effect on the system's overall efficiency in terms of production.

Table 4.3: *General Information About Gate Valve [9].*

System Summary	
Functional location:	Isolation valve for filter manifold
Equipment:	Gate valve
Criticality:	3
Maintenance type:	Preventive Maintenance (PM)
Technical specification:	High (all needed docs)
OREDA MTTF (years):	0.14

The data and information about these pieces of equipment, namely the centrifugal pump, electric Motor (DC), and manual gate valve, were obtained from a relevant master thesis titled “A Multi-Criteria Classification Framework for Spare Parts Management”. These three pieces of equipment were chosen for this simulation model as real-life cases of various criticality classes critical, semi-critical, and non-critical. As these three pieces of equipment are considered important components of the oil and gas production process.

There are many pieces of equipment in offshore remote locations that are excluded from this model due to the lack of time. However, by focusing on these three pieces of equipment, the developed model can provide a comprehensive analysis of the spare part management challenges within the three different criticality sets, leading to actionable insights and strategies for improving the efficiency and sustainability of operations.

4.1.4 Vessel

Timely spare parts delivery from onshore warehouses to offshore remote locations requires efficient transportation. The transportation way plays a pivotal role in the overall success of the model presented in this thesis. Among the different kinds of available transportation, vessels are the most reliable and efficient means for this purpose. In particular, two main types of vessels have been identified as the most suitable for the delivery of spare parts to offshore locations, which are Crew Transfer Vessels (CTV) and Service Operation Vessels (SOV).

4.1.4.1 Service Operation Vessels (SOV)

Another type of vessel is SOVs, which are larger, more specialized vessels designed to support offshore operations, including maintenance and repair activities since it has good facilities for carrying and delivering spare parts to remote locations, which allows for faster and more efficient repair of failures. However, it is important to note that the length and speed of SOV can vary depending on the specific design and requirements of each vessel. Some SOVs have a dimension of approximately 80 m in length and a transit speed of around 12-15 [Knots]. Recently, some newer SOVs are designed with secondary fuel hybrid, or fully electric propulsion systems, which lead to a significant reduction in CO_2 emissions, especially when it is idle offshore [36].

4.1.4.2 Crew Transfer Vessels (CTV)

CTVs are mainly utilized for transporting personnel as well as small cargo units between onshore facilities and offshore platforms, and they can also be used in other industries such as wind turbines, for construction, operation, maintenance, and transportation of spare parts. These vessels are smaller and faster, with a size range of 25 to 28 m. However, due to their limited cargo capacity and higher fuel consumption per ton of cargo, they may not be the most efficient option for larger, longer, and more frequent delivery trips [36].

4.1.4.3 Comparing Between CTV and SOV

Table 4.4: *CTV Compared to SOV [36]*

	CTV	***SOV***
CO_2 **emission from the fuel [Kg/h]**	999.1	2775.4
Fuel consumption in transit [l/h]	320	1000
Length of the vessel [meter]	25 - 28	up to 80
Speed [knots]	15 - 25	12 - 22

The master thesis titled " Modelling Analysis of maintenance logistics optimization for a floating wind park: A case study for Utsira Nord " has researched and presented insights into the differences between CTV and SOV in terms of spare parts delivery in the offshore wind industry and maintenance activities in general. The thesis analyzes the fuel consumption for various activities regarding the time spent on the trip and presents the amounts of CO_2 emissions for vessels per hour.

SOVs may be better suited for long-term maintenance trips, where their use of being more limited to transferring spare parts due to their efficient design which prioritizes stability onboard. While in terms of CO_2 emission, it depends on vessels' size, type, and speed, in addition to the type of fuel used, and the distance traveled. According to the master's thesis, CTV emits around 999.1 kg of CO_2, whereas, SOV emits approximately 2775.4 kg of CO_2 as shown in Table 4.4. This makes sense, as larger vessels such as SOV emit more kilograms of CO_2 per hour than other smaller vessels, due to their larger engines and higher fuel consumption [36].

Thus, SOV offers several advantages over CTV for spare parts delivery. Firstly, SOV has larger cargo space, allowing for the transport of a greater volume of spare parts in a single trip. This aligns with the focus on reducing the frequency of trips, which leads to reducing carbon emissions in offshore operations, in addition to improving overall logistics efficiency in spare part management. Secondly, regardless of hourly CO_2 emissions for SOVs, the characteristics of the secondary fuel and less voyage frequency have the potential to considerably reduce CO_2 emissions, and this aligns with the focus on reducing carbon emissions in offshore operations.

4.2 Emissions Control in Norway

Norway employs two key strategies to avoid climate change, which are the carbon tax and the Greenhouse Gas Emission Trading Act to encourage companies to reduce greenhouse gas emissions, particularly from the petroleum and logistics industry. In 1991 was Norway one of the first countries to introduce a carbon tax, it starts by imposing it on the burning of gas, oil, and diesel in petroleum operations, additionally on the CO_2 and natural gas emissions.

Norway also adheres to the Greenhouse Gas Emission Trading Act, which is instituted in 2005. This later led to the accession of Norway to the EU Emissions Trading System (EU ETS) which help to set a lower yearly limit for total greenhouse gas emissions to encourage industrial companies to reduce their emissions. Companies can purchase and sell emission allowances, providing a financial motivation to reduce emissions, but in recent years this has become more expensive [37].

In 2023, the carbon tax in Norway was determined based on the type of fuel:

- NOK 1.78 per standard cubic meter of gas.
- NOK 13.67 per standard cubic meter of natural gas.
- NOK 2.03 per liter of oil or condensate.
- NOK 761 per tonne of CO_2 released from the combustion of natural gas.

However, because of the integration of the carbon tax and the emissions trading system (EST), the operating companies on the NCS pay much higher than other businesses in Norway as well as other countries with petroleum activities

- approximately NOK 1100 per tonne of their CO_2 emissions [37].

It is important to note that this does not limit to direct production activities but extends to other related activities such as vessel and helicopter traffic [37].

4.3 Indicators

This section consolidates the key needs identified for this thesis and expands upon the innovative concepts suggested by academic and industrial expert to address these needs. It concludes with a discussion on spare part supply strategies.

4.3.1 Needs

The primary needs for this thesis revolve around improving the efficiency and sustainability of spare part management in offshore remote locations. By taking into consideration achieving the following aims:

- Reduction of carbon dioxide emissions associated with spare part deliveries.
- Decrease in the traveling time and frequency of trips for delivering spare parts, which enhances operational efficiency and further contributes to emission reduction goal.
- Minimization of carbon tax costs in terms of supply chain logistics.

4.3.2 Suggested Concepts

In response to these needs, three concepts have been proposed by academic and industrial expert that push the boundaries of traditional spare parts management, taking into account the warehouse replenishment time of two to three weeks.

- Using additive manufacturing techniques onboard such as 3-D printing, allows for the possibility of producing certain spare parts directly on offshore platforms.
- Sharing spare parts among different platforms or companies operating in the same region. As It has the potential to reduce overall spare part inventories and associated costs.
- Use of drones to deliver spare parts among different platforms or from the warehouse.

4.3.3 Spare Parts - Supply Strategies

In light of these needs and concepts, two scenarios for spare part supply strategies are considered in this thesis:

- Baseline scenario involves continuing with the approach of keeping spare parts at onshore warehouses and delivering them to offshore platforms as needed.
- Solution scenario that includes a more innovative and sustainable approach that frequently changes spare parts management by implementing one of the concepts presented by the academic and industrial expert.

Chapter 5

Analysis

This chapter covers the analysis for the case study and computational modeling development for managing spare parts more efficiently in remote locations in the Barents Sea by using AnyLogic, taking into account lead time, logistics, carbon emissions, and carbon tax. This has been done by following up the methodology steps represented in Chapter 3 and based on the data and information gathered in Chapter 4.

5.1 System Analysis

System analysis plays a pivotal role in providing a good and comprehensive understanding of the spare parts management system, which includes the dynamics of supplying and transporting the pieces of equipment to offshore remote locations. The system analysis can be completed with the help of the technical hierarchy, understanding the requirements and needs of the stakeholders, and evaluating potential solution concepts. This analysis serves as a basis for developing an effective and accurate simulation model that allows the determination of potential areas for optimization.

5.1.1 Technical Hierarchy

An essential tool in system analysis that allows an understanding of the relationships between the various levels and provides a clear picture of the complexity, structure, and interdependencies of the whole system is the technical hierarchy. Also known as a system of systems that provides an organized way for disassembling the complete system into platforms, its systems, subsystems, equipment, and components as described in Figure 5.1.

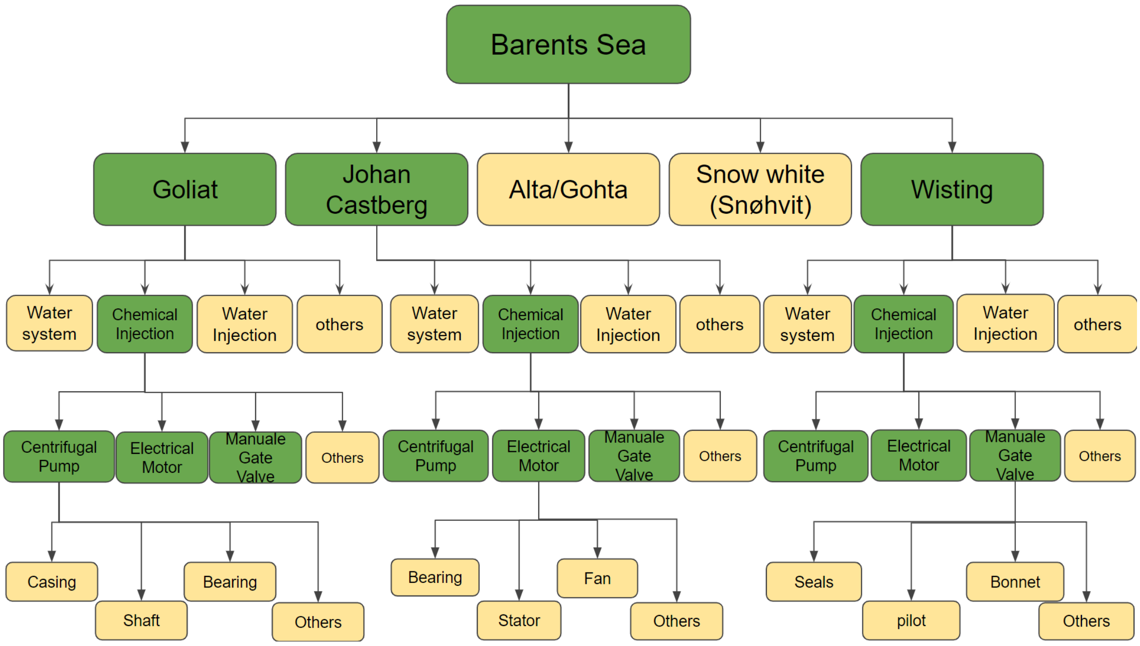


Figure 5.1: *Technical hierarchy.*

Starting at the highest level of the hierarchy is the Barents Sea, which provides the environmental and logistical context for the case study. This includes all offshore remote locations in the Barents Sea. The next level down consists of five platforms which are located in the Barents Sea, they are mentioned in Chapter 4 in detail. Furthermore, each platform is further divided into several systems that are necessary to accomplish the production process. These systems are the functional units of each platform and are integral to the operations of the platform. The equipment level should include all equipment for each of the systems, but for this case, the chemical injection system is taken to be broken down into many pieces of equipment, where the focus is on those mentioned pieces of equipment in Chapter 4, categorized by their criticality classes. The component level, which involves individual components that may require replacement, is less relevant to this case study as the main focus is on the entire equipment.

This helps in understanding interrelationships between these levels to develop the model that represents the processes within the system and explore the different areas for improvement, as each of these pieces of equipment has its own failure rate and other factors that impact the total demand for spare parts from every system on each platform.

5.1.2 Stakeholders Analysis

The main stakeholders of the spare part management system for this case study are the asset owners, the onshore warehouse, the maintenance team, the vessels company, and spare parts suppliers. Each of the presented stakeholders has a critical role to play in the system. These are presented in the Table 5.1 based on their needs requirements, and criteria for each of them.

Table 5.1: *The Needs and Requirements of The Stakeholders.*

Stakeholders	Needs	Requirements	Criteria
Asset owners (Remote Locations)	Reliable equipment performance to ensure continuous operation	Maximum uptime with minimal resources Compliance with environmental and safety regulations	Reliability, Availability, Sustainability, & safety
Onshore warehouse	Inventory management	Storage space and inventory cost optimization Effective management to avoid stockouts or overstocking	Security & Availability
Maintenance team	Obtaining the correct spare parts when needed	Minimal lead time Effective communication with operator(s) and warehouse personnel Easily access to the technical documentation and historical maintenance data	Just in time Reducing CO_2 emissions Better space in the warehouse
Vessels company	Reliable transport	Timely receiving spare parts	Safety & environment sustainability
Spare parts suppliers	Timely delivery of spare parts at reasonable prices	Cooperative with asset owners and warehouses personnel are long-term.	High customer satisfaction Quality

Table 5.1 provides a stakeholder analysis to gain an overview of their needs, requirements, and criteria. This information is crucial because it provides guidance for the development of the simulation model, as it considers the critical needs, requirements, and criteria in the analysis to improve maintenance management.

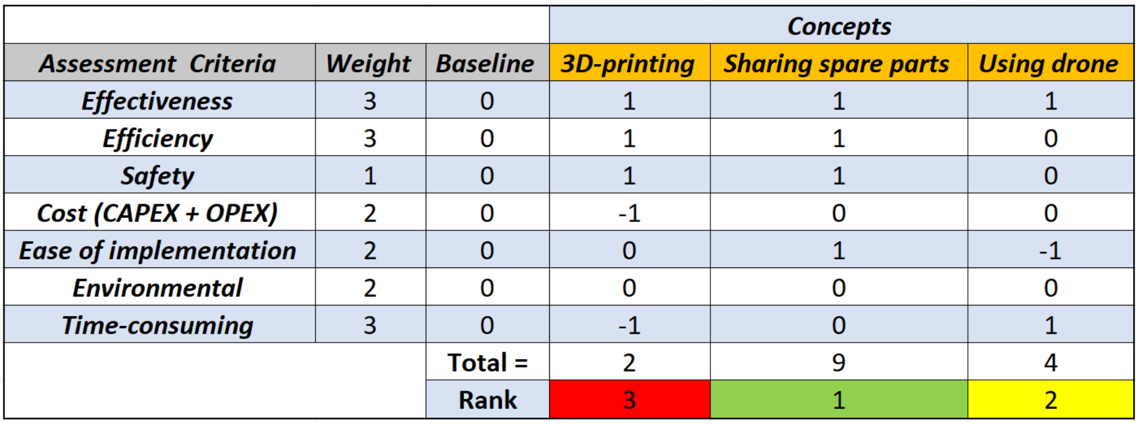
5.1.3 Concept Evaluation

The outlines of these needs, requirements, and criteria for each stakeholder lead to the need for identifying the most suitable solution concepts for optimizing spare parts management. The Pugh Matrix was then utilized to evaluate the solution concepts presented in Subsection 4.3.2 in Chapter 4 against the assessment criteria.

Pugh matrix includes effectiveness, efficiency, safety, cost (CAPEX & OPEX), ease of implementation, environmental impact, and time consumption as Criteria. Each criterion is assigned a weight between one and three for simplicity, with three representing the highest significance. Each concept was assigned a score for each criterion, which was then multiplied by the weight to calculate a weighted score for each concept. The sum of the weighted scores provided an overall score for each concept.

Effectiveness was weighed to three, because the spare parts management system should always ensure delivering the correct parts, to the correct place, with respect to the correct quantity and level of quality. The efficiency of the spare parts management system is also important, as the high efficiency of the spare parts impact on the downtime. Safety as one might seem weird, but there is little to no risk to human life regarding these concepts. Cost, ease of implementation, and environmental got two as the finances and implementation process, and saving emissions are important, but they are maybe not as important as effectiveness and efficiency. In terms of time-consuming, getting three as it is also important to timely deliver the spare parts to avoid long downtime.

Figure 5.2 shows the key criteria for spare parts management along with their weights, the total score, and their rank. The manner of the evaluation of each criterion along with the reason is summarized below



			Concepts		
Assessment Criteria	***Weight***	***Baseline***	***3D-printing***	***Sharing spare parts***	***Using drone***
Effectiveness	3	0	1	1	1
Efficiency	3	0	1	1	0
Safety	1	0	1	1	0
Cost (CAPEX + OPEX)	2	0	-1	0	0
Ease of implementation	2	0	0	1	-1
Environmental	2	0	0	0	0
Time-consuming	3	0	-1	0	1
		Total =	2	9	4
		Rank	3	1	2

Figure 5.2: *Pugh Matrix.*

- **Effectiveness:** All conceptual solutions scored a positive one as they have the ability to successfully manage spare parts and achieve the desired outcome
- **Efficiency:** The 3D printing and sharing of spare parts got a positive one as they can reduce the frequency of physical transport while using drones had no score.
- **Safety:** Both 3D printing and sharing spare parts scored a positive one as they meet safety standards. Using drones received zero due to potential cybersecurity risks of unauthorized access or control of the drones and battery failures during long-distance flights over water.
- **Cost:** Comparing costs was challenging due to the varying among quality and the amount of the products and materials used. However, sharing spare parts and using drones received no score due to the expensive of energy sources (Diesel or electric). While 3D printing scored a negative one due to high regular maintenance, electricity, material costs, and products needed for printing. Additionally, the need for personnel training as it required knowledge and skills from the operator
- **Ease of implementation:** Sharing spare parts received a positive score as it is relatively easy to set up, leveraging existing resources in the Barents Sea. Implementing 3D printing scored zero due to challenges in setup, training, integration, and possibly modifying infrastructure. Using drones received a negative one as it is hard for establishing drone infrastructure including landing pads and recharging/refueling stations both onshore and offshore.
- **Environmental impact:** All solutions are working on improving their environmental regulation and scored a positive one for being emission-conscious.
- **Time-consuming:** 3D printing scored a negative one due to the long time it takes to fully print parts. Sharing spare parts and using drones scored positive, with drones being the fastest option for spare part delivery.

Based on the Pugh matrix analysis shown in Figure 5.2, the concept of sharing spare parts was ranked as the first optimal solution, while the second place went to the concept of using drones, and the third place was occupied by the concept of 3D printing. The Pugh Matrix is an integral part of simulation model development because it helps determine the most effective solution strategies aligned with stakeholder needs, requirements, criteria, and expectations.

5.2 Conceptional and Computational Modeling for Baseline Case

This section describes how the case study problem has been translated into a model which incorporates the key factors identified earlier. This model serves as the framework for analyzing and implementing potential spare parts supply designs in order to optimize spare parts management. It presents a baseline scenario that offers an overview of how the platforms get spare parts supplied.

A sequence diagram, depicted in Figure 5.3, has been used in order to enhance a better understanding of the real-world situation. This diagram helps illustrate the interactions and dependencies within the system, providing valuable insights into its dynamics. Additionally, it also enhances understanding of the simulation model and how it represents the underlying problem, further contributing to overall understanding.

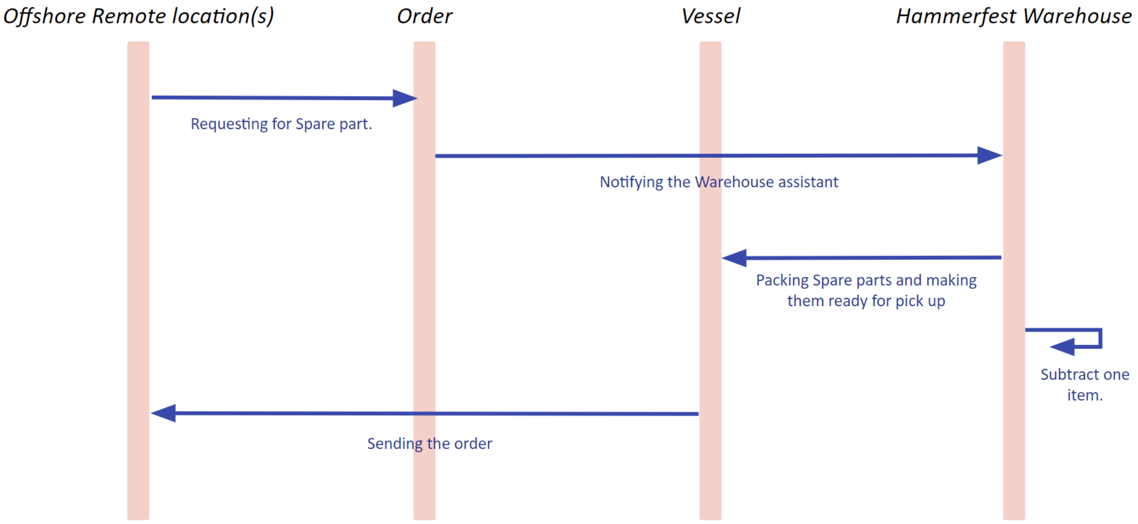
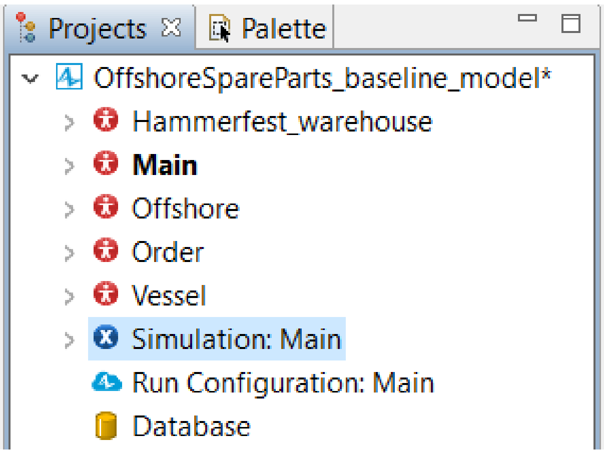


Figure 5.3: *Sequence diagram of the performance for the baseline scenario*

The provided diagram in Figure 5.3 showcases the comprehensive flow of spare parts supply processes for selected remote locations in the Barents Sea. The process begins with equipment failure at one or more of these locations, triggering the need for spare parts based on the failure rate. Where the focus is on those mentioned pieces of equipment in Chapter 4. Subsequently, the platform makes an order for the required spare parts, then the onshore warehouse is notified of the order. Upon receiving the order, the warehouse starts preparing and packaging the requested spare parts. Once the parts are ready, the SOV is notified, prompting the warehouse to subtract the concerned equipment from the warehouse system and update its stock. The vessel then transports the equipment to the designated platform, where it is received and installed into the system. Finally, the vessel sails back to the Polarbase, completing the cycle.

To translate this theoretical concept into a simulation model, the software AnyLogic was used. The simulation model primarily revolves around five agents, as shown in Figure 5.4, each of them is representing the key entities such as platforms, warehouse, spare parts orders, vessels, and the main agent that contains all of them. These agents have their own properties.



OffshoreSpareParts_baseline_model*
- Hammerfest_warehouse
- **Main**
- Offshore
- Order
- Vessel
- Simulation: Main
- Run Configuration: Main
- Database

Figure 5.4: *The project agents.*

The central page for this model is the 'Main' agent, as it functions as a central hub to gather different elements, such as a GIS map, events, parameters, stocks, blocks of discrete events, and other agents representing different entities. All these elements collectively contribute to the creation of the overall simulation model.

Figure 5.5 illustrates the dashboard of the 'Main' agent for the baseline scenario, which is comprised of multiple other agents namely 'offshores', 'hammerfest_warehouse', 'vessels', and 'orders', each of these agents plays a specific role and contributes to the simulation model. Among these agents, 'offshores' and 'vessel' are public agents, the 'hammerfest_warehouse' is a single agent, and the 'orders' is agent type only.

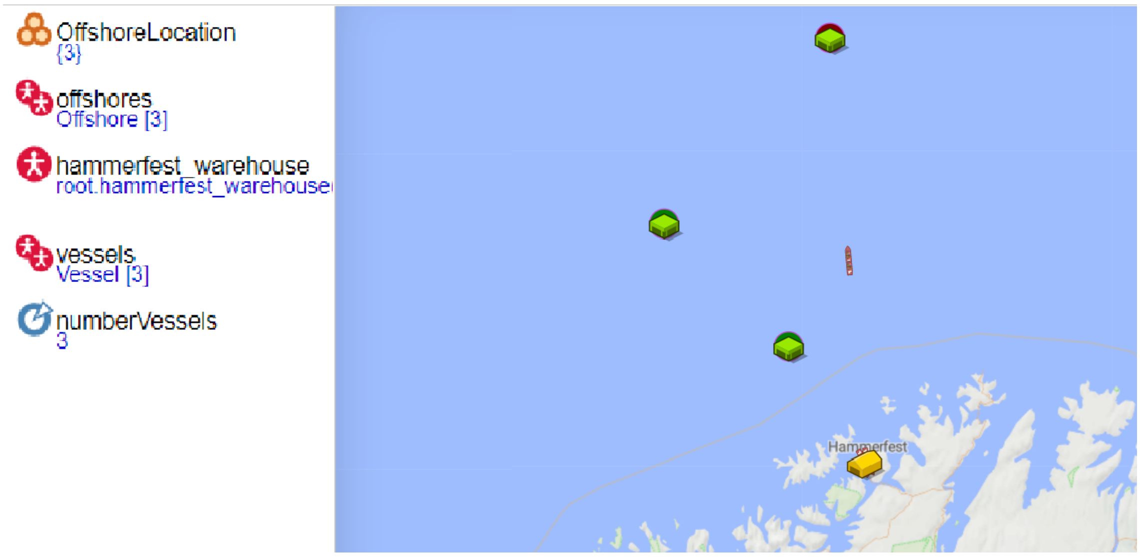


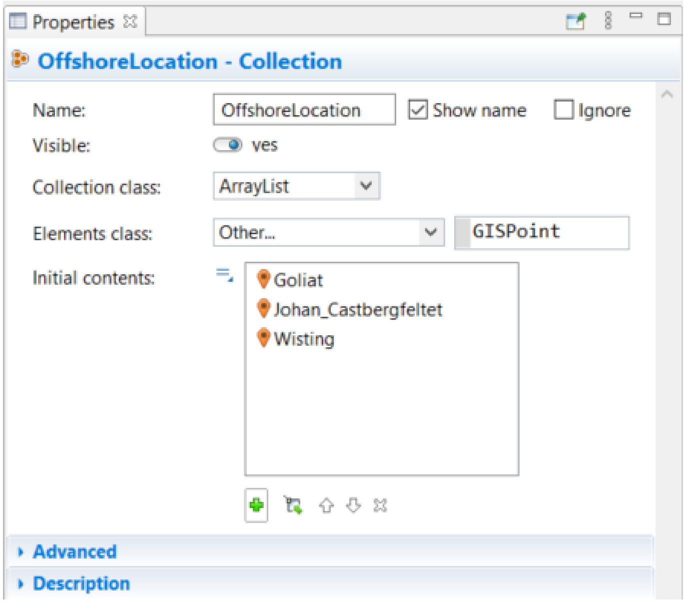
Figure 5.5: *Main agent.*

In the properties of the simulation experiment, as illustrated in Figure C.1 in Appendix C, several important options have been selected to guarantee repeatable and accurate results. For example, the option of fixed seed (reproducible simulation runs) with a fixed seed value of one has been chosen, in order to assures that each simulation run has the same seed value, resulting in consistent time intervals and deterministic outcomes.
By using a constant seed value, simulation results can be reliably reproduced and compared through different runs. These choices in the simulation experiment properties guarantee that the simulation runs consistently and produces reliable and comparable results for the specified time duration.

The number of vessels in the model is determined by the 'numberVessels' parameter, as shown in Figure 5.5. By default, the parameter is set to three vessels, aligning with the capacity of the Polar base as mentioned in Chapter 4.

The integrated GIS functionality is employed, as illustrated in Figure 5.5, to locate the agents 'offshores', 'hammerfest_warehouse', and 'vessels' and automatically determine the route in the model. This is achieved by using the search center on the map (GIS) for looking for the platforms and the warehouse, then converting them to GIS points.
Figure C.2 in Appendix C shows the adjustments needed within the properties of the map (GIS) for the model to function properly and achieve its objectives.

Since these platforms are treated uniformly in terms of ordering and equipment types, a collection has been created, consisting of an array list of GIS points representing the three selected platforms, as shown in Figure 5.6.



OffshoreLocation - Collection

Name: OffshoreLocation ☑ Show name ☐ Ignore
Visible: yes
Collection class: ArrayList
Elements class: Other... GISPoint
Initial contents:
Goliat
Johan_Castbergfeltet
Wisting

Figure 5.6: *Properties of collection*

In the model, orders are represented as agents and are created by remote locations, while the onshore warehouse receives these orders. Also the properties of the "offshores" agent, which include variables such as the number of agents, are modified using code, as shown in Figure C.3 in Appendix C. By utilizing that code, dynamic assignment of values for the initial locations of offshore remote locations can be achieved. On the other hand, selecting initial locations for the warehouse and vessels is simpler and can be done directly from the menu bar.

Moving on to the ’offshores’ agent, it includes a state chart depicted in Figure 5.7. This state chart effectively represents the status of the three chosen pieces of equipment that are installed on the platforms, as all of them have the same equipment type. The default state for all three pieces of equipment is ’working’, indicating their normal operational condition. However, considering that each piece of equipment possesses a distinct failure rate, three transitions have been implemented to change the state accordingly. These three transitions change the status from the ’working’ state to the state that represents which type of equipment failed.

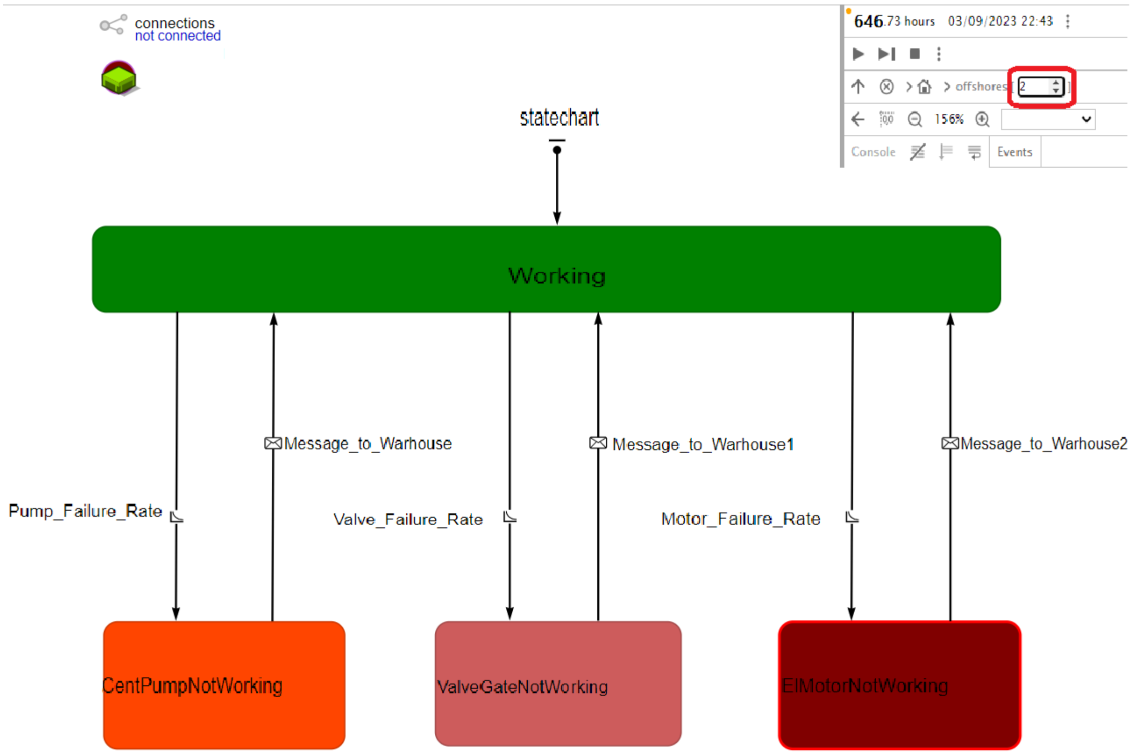


Figure 5.7: *Offshore agent (State chart).*

This state chart consists of multiple transitions that facilitate the change in status from one state to another and play a crucial role in the creation of orders. As they are triggered during the transition between different states, based on the failure rate where the failure rate encompasses all modes and is represented in upper values as the worst possibility as presented in Appendix B. The failure rate has been used in Equation 2.2 to calculate the MTTF for each piece of equipment.

It is worth noting that the orders are created upon entering each of the 'CentPumpNotWorking,' 'ValveGateNotWorking,' and 'ElMotorNotWorking' states, and it would show the specific platform that it gets failed on as marked red in the Figure 5.7 above. Additionally identifying the specific equipment that has failed in the platform as also illustrated in Figure 5.7.

For further details, Table 5.2 below presents a comprehensive summary of all states and transitions, including their associated triggers, codes, and actions with explanations.

Table 5.2: *'Offshore' State Chart.*

Name	Type	Triggered by, code, and explanation
statechart	statechart entry point	–
Working	State	–
Pump_Failure_Rate	Transition	Triggered by: rate. Rate; 1/309.3 times per hour This will be used to create the orders

CentPumpNotWorking	State	Entry action;
		Order order = new Order(this);
		send(order,main.hammerfest_warehouse);
		This code is to create a new order on the entry, associated with this platform. It is also to send the order back to the warehouse agent inside the main agent.
		Exit action;
		main.hammerfest_warehouse.Inventory_CentPump -= 1;
		main.hammerfest_warehouse.No_of_travels_Hammerfest = main.hammerfest_warehouse.No_of_travels_Hammerfest +1
		This code is to subtract one item from the stock that belongs to. The second part of the code is to count the number of travels.

message_ to_Warehouse	Transition	Triggered by: message Message type; string Message; 'equipment is on board' This transition is the receipt of a message called 'equipment is on board' that will change the state of the offshore agent from CentPumpNotWorking to normal working condition
Valve_Failure_Rate	Transition	Triggered by: rate Rate; 1/1459.2 times per hour This will be used to create the orders

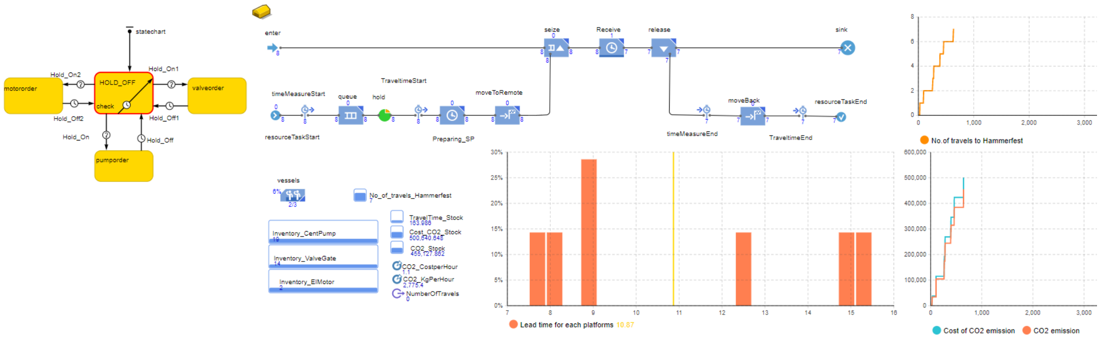
ValveGateNotWorking	State	Entry action;
		Order order = new Order(this);
		send(order,main.hammerfest_warehouse);
		This code is to create a new order on the entry, associated with this platform. It is also to send the order back to the warehouse agent inside the main agent.
		Exit action;
		main.hammerfest_warehouse. Inventory_ValveGate -= 1;
		main.hammerfest_warehouse.No_of_travels_Hammerfest = main.hammerfest_warehouse.No_of_travels_Hammerfest +1
		This code is to subtract one item from the stock that belongs to. The second part of the code is to count the number of travels.

message_ to_Warehouse1	Transition	Triggered by: message Message type; string Message; 'equipment is on board' This transition is the receipt of a message called 'equipment is on board' that will change the state of the offshore agent from ValveGateNotWorking to normal working condition
Motor_Failure_Rate	Transition	Triggered by: rate Rate; 1/309.3 times per hour This will be used to create the orders

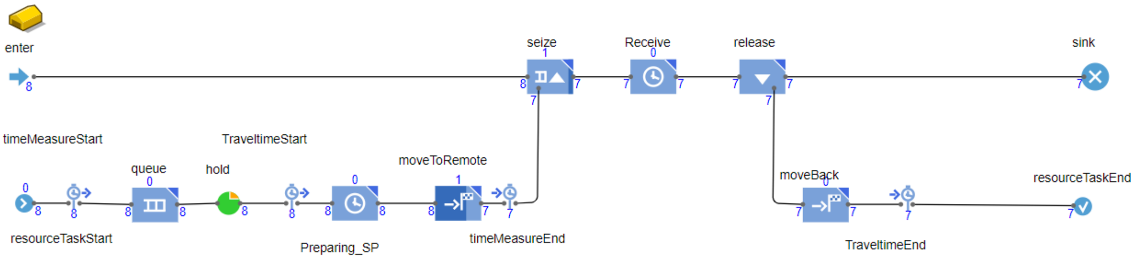
ElMotorNotWorking	State	Entry action;
		Order order = new Order(this);
		send(order,main.hammerfest_warehouse);
		This code is to create a new order on the entry, associated with this platform. It is also to send the order back to the warehouse agent inside the main agent.
		Exit action;
		main.hammerfest_warehouse.Inventory_ElMotor -= 1;
		main.hammerfest_warehouse.No_of_travels_Hammerfest = main.hammerfest_warehouse.No_of_travels_Hammerfest +1
		This code is to subtract one item from the stock that belongs to. The second part of the code is to count the number of travels.

message_ to_Warehouse2	Transition	Triggered by: message Message type; string Message; 'equipment is on board' This transition is the receipt of a message called 'equipment is on board' that will change the state of the offshore agent from ElMotorNotWorking to normal working condition

The codes presented in the Table 5.2 above demonstrate a connection between two agents, the current agent, and the 'hammerfest_warehouse' agent. The 'hammerfest_warehouse' agent is responsible for handling the order once it is received. To obtain a comprehensive understanding of the order processing mechanism, there is wise to look at what the agent 'hammerfest_warehouse' contains.



(a) Hammerfest_warehouse agent.



(b) Discrete event within 'Hammerfest_warehouse'

Figure 5.8: *Hammerfest_warehouse agent overview.*

Figure 5.8 shows an overview inside the 'Hammerfest_warehouse' agent, where there are several things that play a big role to complete this model, such as the flow of discrete event, parameters, and state chart. Starting with Figure 5.8b shows the discrete event process as it is an integral part of the simulation model and describes the flow of spare parts order processing, which is derived from the previous state chart. This discrete event ensures a seamless flow and efficient management of the order within the simulation model.

The order processing begins at the 'Enter' block, where the order is received, and then progresses to the 'Seize' command, which involves seizing a resource from the 'vessels' resource pool associated with the order. However, before seizing the resource, a parallel process is created to initiate the vessel loading as soon as the order is received. This parallel process is initiated by the 'resourceTaskStart' block. To manage the process effectively, a 'hold' block is used to pause the process when the onshore warehouse is close to being empty until it is restocked. To accommodate this hold, a

’queue’ block is placed before the ’hold’ block, with a maximum capacity defined. Additionally, to simulate the time required for packing and preparing the order, a delay labeled ’Preparing_SP’ is introduced.

Once the order is prepared, the vessel begins its journey to the platform, facilitated by the ’moveToRemote’ block, which should be connected to the ’seize’ block. Upon arrival at the platform with the intended spare parts, the vessel undergoes an unpacking process, which is managed by another delay block called ’Receive’. After the vessel is unpacked, it releases the resource using the ’release’ block and subsequently sinks it using the ’sink’ block to signify the completion of this logic. Following the release, the vessel returns to the warehouse using the ’moveBack’ block, which is directly connected to the ’release’ block. Then the process concludes with the ’resourceTaskEnd’ block once the vessel has returned to the warehouse.

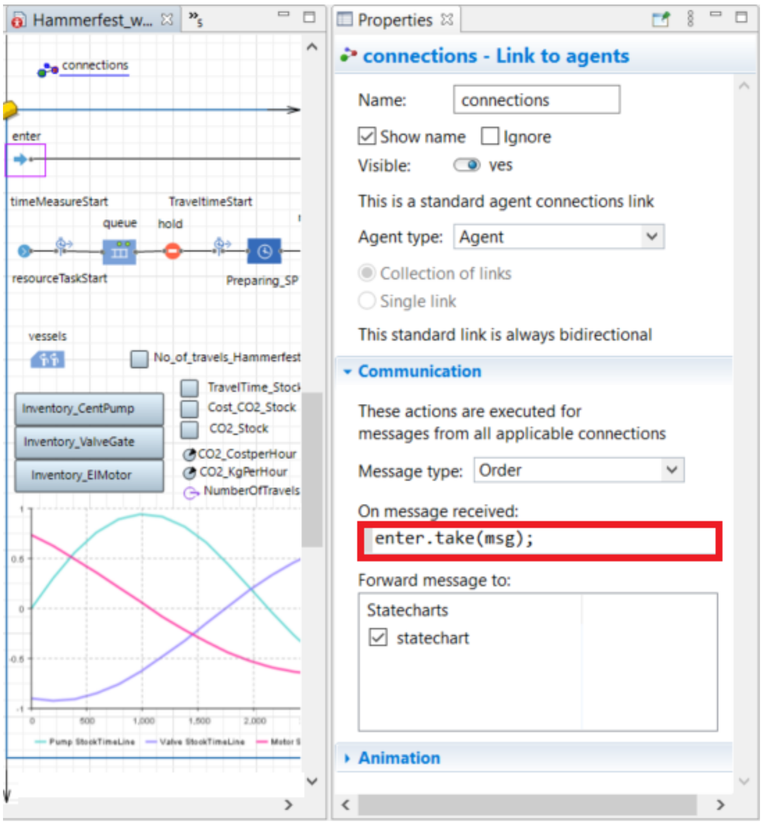
Table 5.3 below to understand the properties, actions, and codes of these blocks involved in order processing. This illustrates how they contribute to the overall logic and functionality. These blocks are essential for managing the order processing flow and ensuring efficient order processing within the simulation.

Table 5.3: *Discrete Event in The ’Hammerfest_warehouse’ Agent.*

Name	Type	Properties , code, and explanation
enter	Enter	Agent type; Order
resourceTaskStart	ResourceTaskStart	Agent type; Vessel
timeMeasureStart	TimeMeasureStart	Agent type; Vessel
queue	Queue	Capacity; Maximum capacity Queuing; FIFO FIFO (first in, first out) means treating the first order first Agent type; Vessel
hold	Hold	Agent type; Vessel
TraveltimeStart	TimeMeasureStart	Agent type; Vessel
Preparing_SP	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Agent type; Vessel It usually takes approximately two to three hours to load a vessel, with the duration determined by uniform distribution, as shown in Figure C.4 in Appendix C.
moveToRemote	MoveTo	Agent; moves to Destination; Agent/unit Agent; agent.client Movement is defined by; Distance/speed Agent type; Vessel The destination is determined from the vessel parameter (client)

seize	Seize	Seize; (alternative) resource sets Resource set; vessels Seize policy; Seize whole set at once Capacity; Maximum queue capacity Action –>on seize unit; ((Vessel) unit).client = agent.customer; Agent type; Order It assigns the platform from which it received the order.
Receive	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Action –>on exit; send('equipment is on board', agent.customer); Agent type; Order It usually takes two to three hours to receive the order, with the duration determined by uniform distribution, as shown in Figure C.4 in Appendix C. At the exit from the delay, it sends a message to the platform (Customer) that the equipment has been delivered.
timeMeasureEnd	TimeMeasureEnd	Dataset capacity; 100 Agent type; Vessel
release_W_Pump_J	Release	Release; All seized resources (of ant pool) Moving resources; Return to home location Wrap-up (e.g. move home); each time 'Wrap-up' usage statistics are; counted as 'busy' Agent type; Order
moveBack	MoveTo	Agent; moves to Destination; Agent/unit Agent; main.hammerfest_warehouse Movement is defined by; Distance/speed Agent type; Vessel The destination is the warehouse.
TraveltimeEnd	TimeMeasureEnd	Dataset capacity; 100 Action –>on enter; TravelTime_Stock = TravelTime_Stock + TraveltimeEnd.dataset.getYMax(); Cost_CO2_Stock = Cost_CO2_Stock + TraveltimeEnd.dataset.getYMax() * CO2_KgPerHour * CO2_CostperHour; CO2_Stock = CO2_Stock + TraveltimeEnd.dataset.getYMax() * CO2_KgPerHour; Agent type; Vessel The code consists of three main parts. The first part calculates the total travel time for all trips. The second part calculates the total CO$_2$ emission cost for all trips. Finally, the last part calculates total CO$_2$ emissions for all trips.
sink	Sink	Agent type; Order
resourceTaskEnd	ResourceTaskEnd	Agent type; Vessel

In the matter of recognizing the 'Order' for the discrete event, a connection has been used to direct the received order message into the 'Enter' block within the discrete event. This connection is implemented using the code depicted in Figure 5.9. This means that when the order is received by the warehouse, it is placed into the 'Enter' block, allowing the order agent to progress through that process logic. This mechanism ensures that the 'Order' flows smoothly through the simulation model, adhering to the principles of discrete event simulation.



Name: connections

☑ Show name ☐ Ignore

Visible: yes

This is a standard agent connections link

Agent type: Agent

● Collection of links

○ Single link

This standard link is always bidirectional

These actions are executed for messages from all applicable connections

Message type: Order

On message received:

```
enter.take(msg);
```

Forward message to:

Statecharts

☑ statechart

__Figure 5.9:__ Properties of the connection inside the 'Hammerfest_warehouse' agent.

To ensure the completion of the discrete event process, a state chart is implemented to control the activation and deactivation of the 'Hold' block, considering the availability of equipment in the onshore warehouse. This state chart has the default state 'HOLD_OFF' of the 'Hold' block where it remains deactivated under the normal condition, as illustrated in Figure 5.10. However, when the stock level of one or more equipment falls below the minimum level in the warehouse, the state chart activates the 'Hold' block, until the restocking. Once the restocking is completed, which takes two to three weeks with a uniform distribution of the duration as shown in Figure C.4 in Appendix C, the 'Hold' block transitions back to the deactivation state. This mechanism ensures efficient management of the 'Hold' block based on the inventory levels of the equipment in the onshore warehouse.

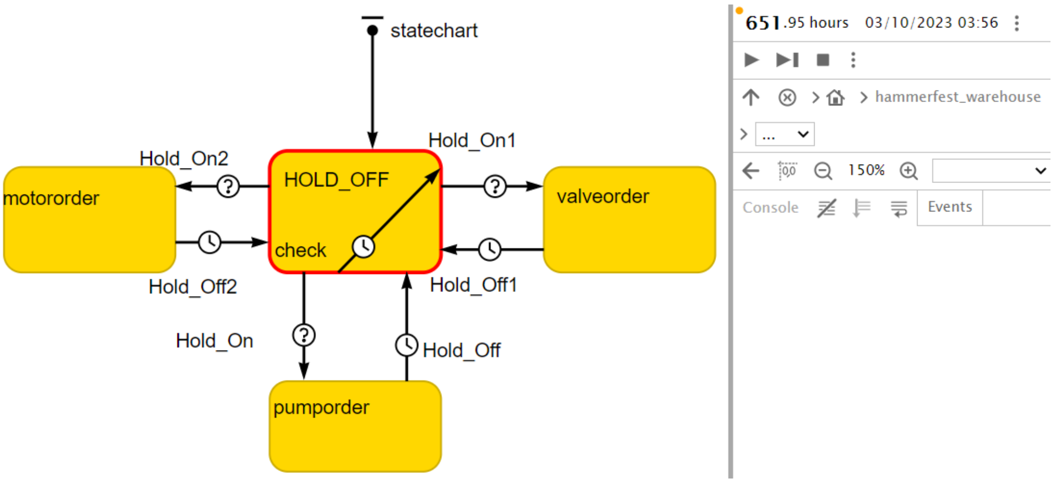


Figure 5.10: *State chart for 'Hold' block inside the 'Hammerfest_warehouse' agent.*

To understand the functionality of this state chart, a comprehensive overview of all states and transitions, along with associated triggers, codes, and actions, are provided in Table C.1 in Appendix C, which is similar to the previous ones.

Figure 5.11 shows several parameters and stocks that can be found on the dashboard of the the'Hammerfest_warehouse' agent. These are the key factors for obtaining the desired results with respect to CO_2 emissions, associated costs, and vessels' travel time. The two specific parameters, namely 'CO2_KgPerHour' and 'CO2_Costper Hour', play a crucial role in determining the amount of CO2 emissions per trip and calculating how much does this emission cost the operating company. The parameter 'CO2_KgPerHour' is defined as 2775.4 kg, obtained from Table 4.4, representing the CO_2 emission rate of the SOV per hour, while 'CO2_ CostperHour' is set at 1.1 NOK as a carbon tax, obtained from Section 4.2 in Chapter 4.

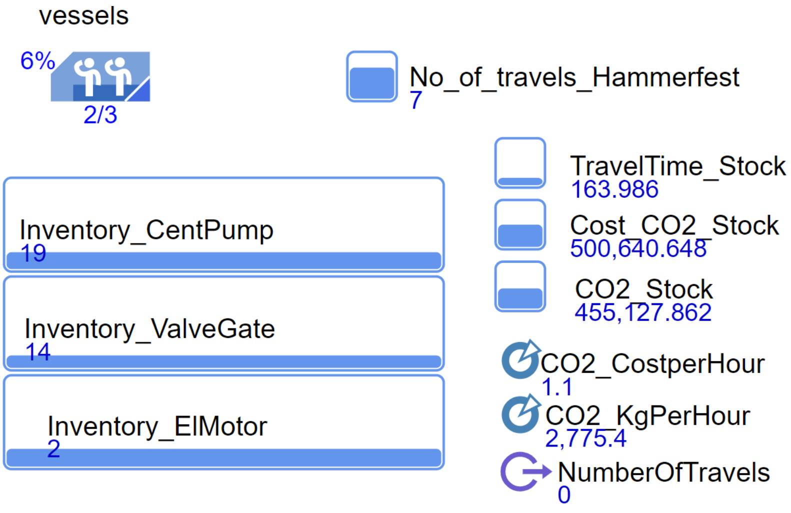


Figure 5.11: *Stocks and parameters inside the 'Hammerfest_warehouse' agent.*

There are also three important stocks, illustrated in Figure 5.11, representing the stock levels of the centrifugal pump, gate valve, and electric motor in the Hammerfest warehouse, which are ’Inventory_CentPump’, ’Inventory_ValveGate’, and ’Inventory_ElMotor’, respectively.

Each stock has an initial value estimated according to the failure rate of that particular piece of equipment.

- For the ’Inventory_CentPump’ stock, the initial value is set to 25 pieces of pumps, which is estimated based on its high failure rate of 3233.73, as specified in OREDA in Appendix B, which indicates the need for a significant inventory to cover the expected number of failures.
- Similarly, for the ’Inventory_ValveGate’ stock, the initial value is estimated to be 15 pieces of gate valves due to its failure rate of 685.32 as set in OREDA in Appendix B. This inventory level is chosen to ensure enough supply of gate valves to address potential failures.
- Lastly, the ’Inventory_ElMotor’ stock has an initial value of two pieces of electric motors. This estimation is based on the relatively low failure rate of 171.25 as provided in OREDA in Appendix B, which indicates that a smaller inventory level is enough to meet the demand for electric motors.

The last two agents in the baseline scenario are ’Order’ and ’Vessel,’ as shown in the Figure 5.5, each having a specific parameter. The ’Order’ agent includes a parameter called ’Customer’ which is used in the model to create a spare parts order from a specific platform. Whereas the ’vessel’ agent has the ’Client’ parameter, which serves the purpose of determining the platform that has ordered the spare parts. This ensures that the model directs the vessel to the correct designated platform for delivery.

5.3 Conceptional and Computational Modeling for Solution Case

This section focuses on the solution case scenario which represents the suggested solution and how it translated into a simulation model. The solution case scenario integrates the concept of shared spare parts among platforms, as prioritized in the Pugh matrix presented in Figure 5.2. This concept involves having an onboard stock for each platform to store the most frequently failing equipment, ensuring its availability when needed.

The sequence diagram in Figure 5.12 serves as a valuable tool for understanding the flow of spare parts supply processes for each of the selected platforms involved in this solution scenario, allowing for a clear understanding of the differences compared to the baseline scenario.This diagram is divided into three conditions, as illustrated in Figure 5.12, according to the number of platforms presented. Although each platform has a different condition from the others however they all share the same scenario.

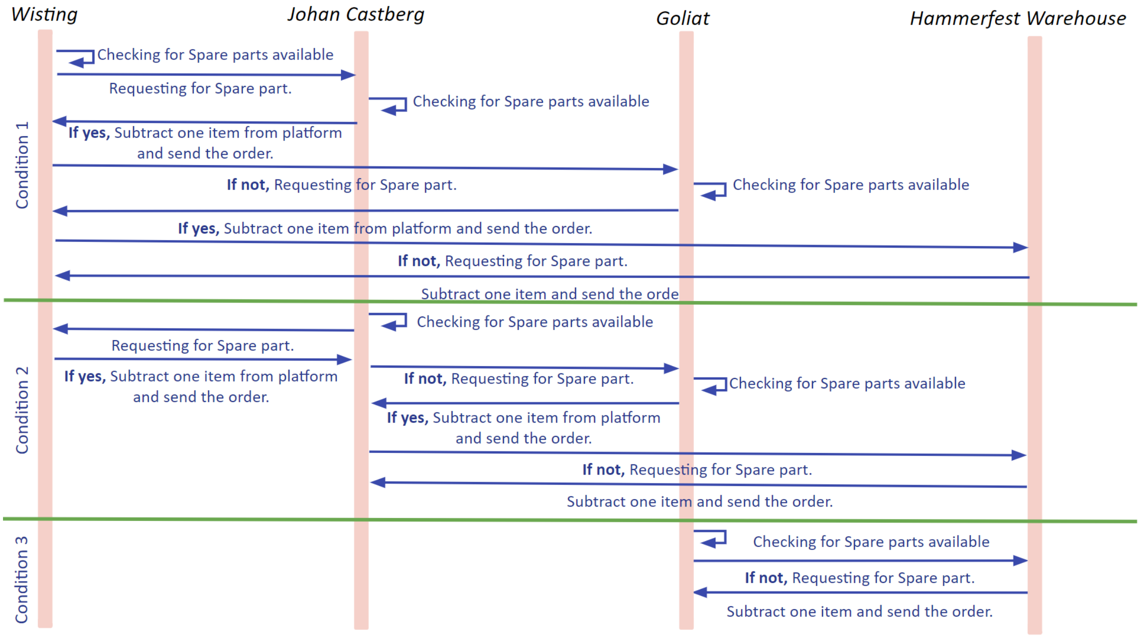


Figure 5.12: *Sequence diagram of the performance for the solution scenario*

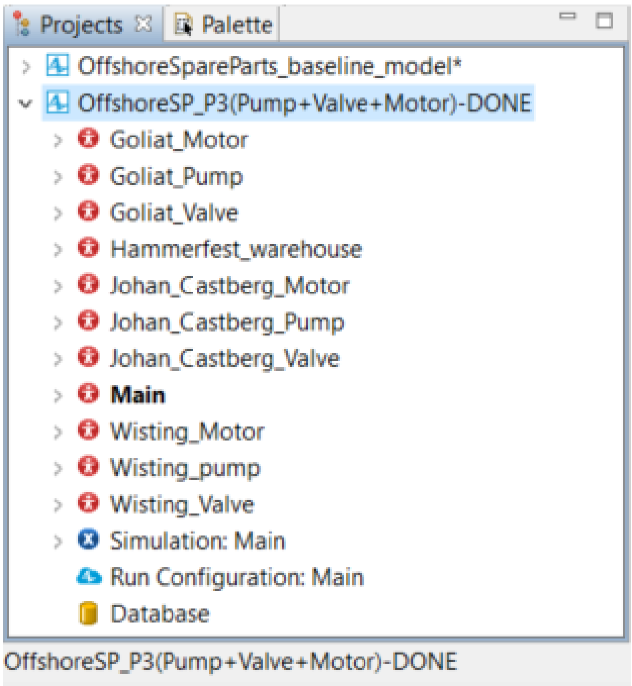
The process in the diagram starts with Wisting, as it is the furthest platform from the onshore warehouse and is the first condition as illustrated in Figure 5.12. The Wisting platform has three options to check for spare parts before ordering from the warehouse, according to the following steps First, Wisting checks its own stock for available spare parts. If the specific equipment is not found, it proceeds to Johan

Castberg, which is the nearest platform to Wisting. If Johan Castberg also does not have the equipment, the check continues to the next nearest platform, Goliat. If none of these platforms have the specific equipment in their onboard stocks, the order is then placed with the onshore warehouse.

Similar steps are followed for the Johan Castberg platform, the second condition, but with a slight difference in the sorting process, where the sorting of spare part requests is based on the distances between platforms and their closeness to the onshore warehouse. Since Wisting is closer to Johan Castberg than Goliat, the spare part gets requested from Wisting first if it is available in its own stock. If Wisting also does not have the equipment, the check proceeds to Goliat. Finally, if none of these platforms have the specific equipment, the order is placed with the onshore warehouse.

In the case of the third condition, Goliat, being the nearest platform to the onshore warehouse, the only option available is to order directly from the warehouse.

The process of translating the theoretical concept into a simulation model involves the utilization of 11 agents, which are shown in Figure 5.13, including the warehouse, each piece of equipment present on each platform, and the main agent that contains all of them. Each of these agents plays a big role in the simulation model for this scenario. Their interactions and functionalities contribute to the overall dynamics and outcomes of the simulation model, allowing for a comprehensive analysis of the spare parts management system in the given context.



OffshoreSpareParts_baseline_model*
OffshoreSP_P3(Pump+Valve+Motor)-DONE
Goliat_Motor
Goliat_Pump
Goliat_Valve
Hammerfest_warehouse
Johan_Castberg_Motor
Johan_Castberg_Pump
Johan_Castberg_Valve
Main
Wisting_Motor
Wisting_pump
Wisting_Valve
Simulation: Main
Run Configuration: Main
Database

OffshoreSP_P3(Pump+Valve+Motor)-DONE

Figure 5.13: *The agents of the solution case.*

There are no big changes in the 'Main' agent in this scenario, as shown in Figure 5.14 compared to the baseline scenario. The map (GIS) remains unchanged as the same platforms have been used in both baseline and solution scenarios for the sake of allowing for smooth comparison and analysis between the two scenarios.

Instead of having the stocks, parameters, and graphs in the 'Hammerfest_ warehouse' agent as in the baseline scenario, they are now integrated into the 'Main' agent of this scenario. Additionally, as the number of agents increased in this scenario, the extra agents are included within the 'Main' agent as illustrated in Figure 5.14, in order to ensure a comprehensive representation of all entities involved in the simulation model.

However, in this scenario, it is worth noting that there is a vessel located on each platform instead of having all three vessels in the Polar base in Hammerfest. Additionally, each platform is equipped with three spare parts stocks that represent the availability of each selected equipment type onboard. Where all of the nine spare parts stocks are compiled in the 'Main' agent, such as 'GoliatStock_ Offshore_CentPump', 'GoliatStock_Offshore_ValveGate', and 'GoliatStock_Offshore_ ElMotor' which reflect respectively the inventory of centrifugal pumps, gate valves, and electric motors on the Goliat platform. Similarly, the other two platforms have their respective stocks for each equipment type.

Based on estimations, the onboard stocks on each platform are refilled every eight months, which means that the stocks are replenished once at the beginning of the simulation model and remain without refilling throughout the simulation period (eight months).

Where each of these stocks has an estimated initial value;

- In the case of the Goliat platform, the initial values of the stocks onboard have been estimated to be five centrifugal pumps, three gate valves, and one electric motor.
- On the Johan Castberg platform, the initial values of the stocks are seven centrifugal pumps, two gate valves, and two electric motors.
- Lastly, the stocks onboard the Wisting platform have initial values of four centrifugal pumps, one gate valve, and one electric motor.

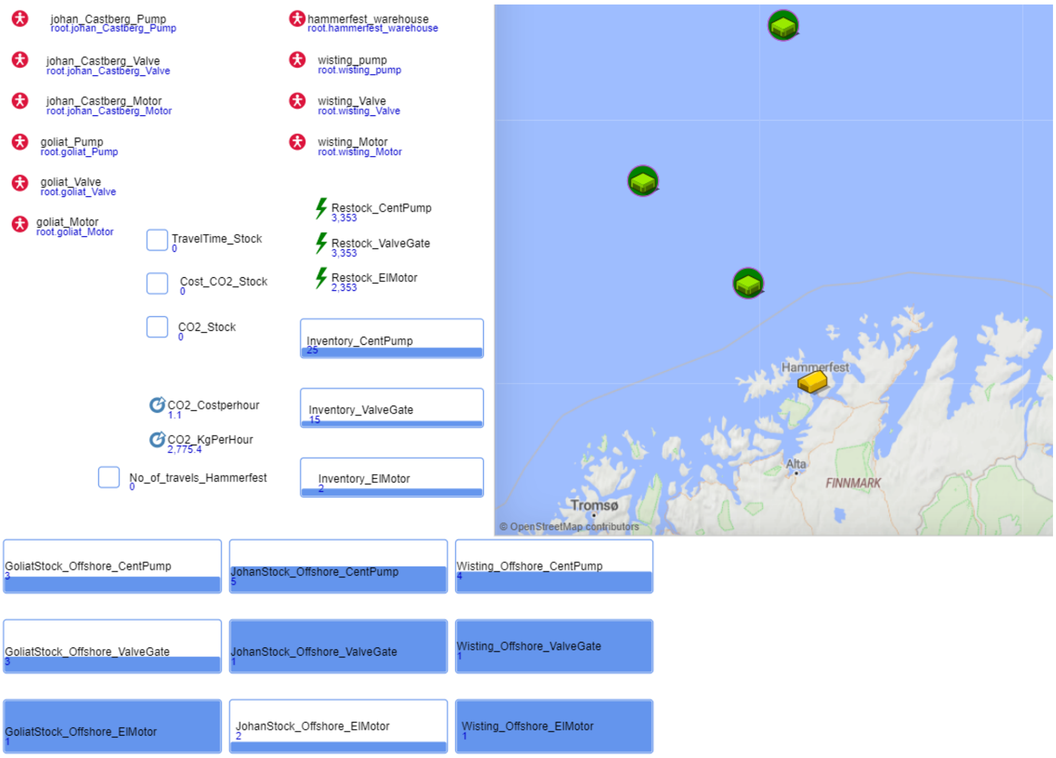
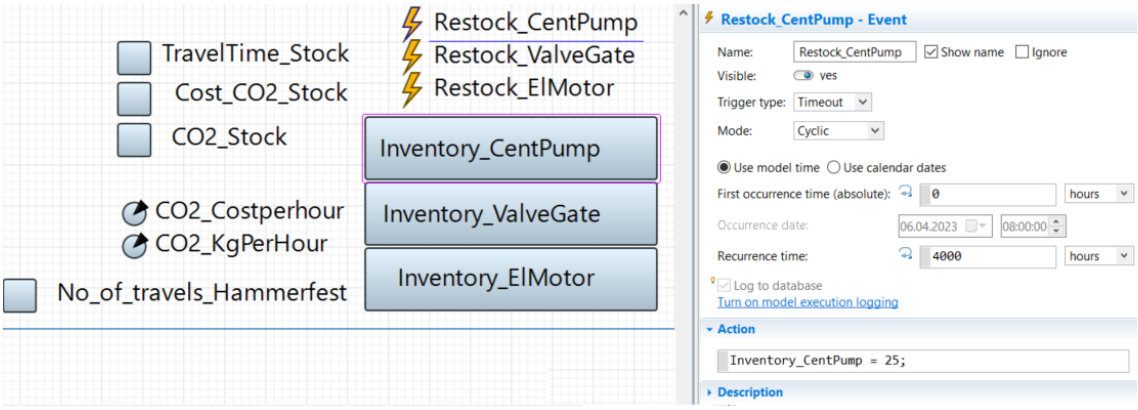


Figure 5.14: *Main agent in the solution scenario.*

On the other hand, the onshore stocks in this scenario follow a refill schedule of every 4000 hours, which is equivalent to approximately every five and a half months. This estimated and fixed refilling period eliminates the need to 'Hold' block on all discrete events for this scenario consequently eliminating the two to three weeks warehouse refill delay duration that existed in the base scenario. The 'Hold' block has been replaced with three events, namely 'Restock_CentPump', 'Restock_ValveGate', and 'Restock_ElMotor' as shown in Figure 5.15. These events are triggered by a time-out mechanism with a cycle mode and a recurrence time of 4000 hours, ensuring that the onshore stocks are replenished at the specified intervals.



Restock_CentPump - Event

Name: Restock_CentPump ☑ Show name ☐ Ignore
Visible: yes
Trigger type: Timeout
Mode: Cyclic
● Use model time ○ Use calendar dates
First occurrence time (absolute): 0 hours
Occurrence date: 06.04.2023 08:00:00
Recurrence time: 4000 hours
☑ Log to database
Turn on model execution logging

Action

```
Inventory_CentPump = 25;
```

Description

Figure 5.15: *Properties for the restocking events.*

Starting with the Wisting platform, which is the furthest one from the onshore warehouse. Three agents are created for this platform in order to represent the three selected pieces of equipment on this platform. The steps and contents within these three agents are duplicated, with the only difference being the failure rate value, which is specific to each equipment type. To gain a comprehensive understanding of the contents and the interconnection between them, the ’Wisting_pump’ agent has been taken as an example.

Figure 5.16 illustrates the inside compositions of the ’Wisting_pump’ agent, which are state chart named ’statechart_Pump_Wisting’, three separate lines of discrete events, resources pool ’vessel_On_Wisting1’, and a graph that helps to control the lead time for the pump based on the method of obtaining the equipment.

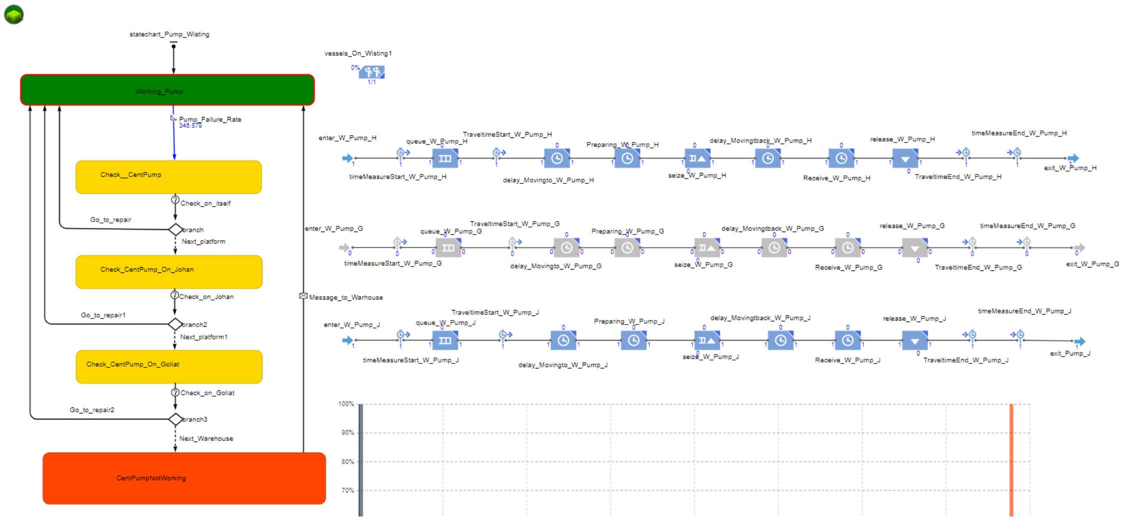


Figure 5.16: *’Wisting_pump’ agent overview.*

The state chart provided in Figure 5.17 consists of several states and transitions that are responsible for transfer from one state to another, and they play a significant role in ordering and whom to order from. The triggering of these transitions is based on the same failure rate similar to the baseline scenario.

For the centrifugal pump on the Wisting platform, the initial state is ’Working_pump’ as the equipment is functioning properly, then it is triggered by the failure rate and proceeds to the ’Check_CentPump’ state, which involves checking the availability of the pump in its own stock. If the pump is unavailable, the process moves to the ’Checking_CentPump_On_Johan’ state, where it checks for the pump on the Johan Castberg platform. If still unavailable, it proceeds to the ’Checking_CentPump_On_Goliat’ state. If none of the platforms have the pump in their onboard stocks, it transitions to the final state, ’CentPumpNotWorking’, where the order is sent to the onshore warehouse, and from there, it returns to the initial working state once again to fulfill the cycle.

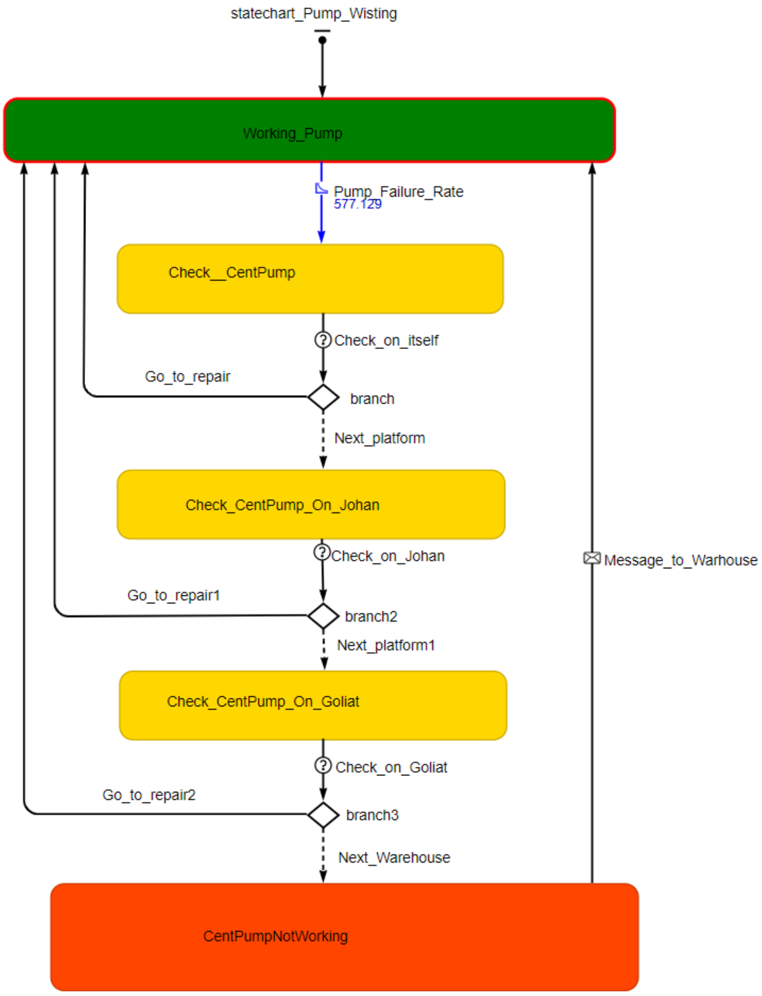


Figure 5.17: *'Wisting_pump' agent (State chart).*

These states and transitions ensure a systematic approach to the centrifugal pump in the Wisting platform which follows the sequence provided in the sequence diagram in Figure 5.12. However for further details about the contents and the logical interconnection between them, Table 5.4 provides a thorough breakdown of all states and transitions of this state chart, including their related triggers, codes, and actions.

Table 5.4: *'Wisting_pump' State Chart.*

Name	Type	Triggered by, code, and explanation
statechart_Pump_Wisting	statechart entry point	–
Working_Pump	State	–
Pump_Failure_Rate	Transition	Triggered by: Rate Rate; 1/309.3 time per hour This will be used to create the orders
Check_CentPump	State	–
Check_on_itself	Transition	Triggered by: Condition Condition; true The transition will keep going no matter what
branch	Branch	–

Go_to_repair	Transition	Triggered by: Condition Condition; main.Wisting_Offshore_CentPump >0 Action; main.Wisting_Offshore_CentPump -= 1; If the pump stock onboard the Wisting platform has a pump as a spare part, subtract one item from them and proceed back to the working state.
Next_platform	Transition	Default (is taken if all other conditions are false)
Check_CentPump_On_Johan	State	–
Check_on_Johan	Transition	Triggered by: Condition Condition; true The transition will keep going no matter what
branch2	Branch	–

Go_to_repair1	Transition	Triggered by: Condition
		Condition; main.JohanStock_Offshore_CentPump >0
		Action; enter_W_Pump_J.take(this);
		main.JohanStock_Offshore_CentPump -= 1;
		send('Pump from Johan is on Wisting', get_Main());
		
		If the pump stock onboard the Johan Castberg platform
		has a pump as a spare part, then the code consists
		of three main parts.
		The first part is to take the discrete event that starts
		with the 'enter_W_Pump_J' block.
		The middle part is to send a message to the platform
		that required spare parts and proceed back to
		the working state.
		The last part is to subtract one item from them.

Next_platform1	Transition	Default (is taken if all other conditions are false)
Check_CentPump_On_Goliat	State	–
Check_on_Goliat	Transition	Triggered by: Condition Condition; true The transition will keep going no matter what
branch3	Branch	–

Go_to_repair2	Transition	Triggered by: Condition
		Condition; main.GoliatStock_Offshore_CentPump >0
		Action; enter_W_Pump_G.take(this);
		main.GoliatStock_Offshore_CentPump -= 1;
		send('Pump from Goliat is on Wisting', get_Main());
		
		If the pump stock onboard the Goliat platform has
		a pump as a spare part, then the code consists of three
		main parts.
		The first part is to take the discrete event that starts
		with the 'enter_W_Pump_G' block.
		The middle part is to send a message to the platform
		that required spare parts and proceed back to
		the working state.
		The last part is to subtract one item from them.

Next_Warehouse	Transition	Default (is taken if all other conditions are false)
CentPumpNotWorking	State	Entry action; enter_W_Pump_H.take(this); This code is to take the discrete event that starts with the 'enter_W_Pump_H ' block. Exit action; main.Inventory_CentPump -= 1; main.No_of_travels_Hammerfest = main.No_of_travels_Hammerfest + 1; This code is to subtract one item from the stock on the onshore warehouse that belongs to. The second part of the code is to count the number of travels to the Hammerfest warehouse.
Message_to_Warehouse	Transition	Triggered by: message Message type; string Message; 'Pump from warehouse is on Wisting' This transition is the receipt of a message called 'Pump from warehouse is on Wisting' that will change the state of the offshore agent from CentPumpNotWorking to normal working condition

Moving on to the discrete events to explain the logic behind the three separate lines of discrete events, which are illustrated in Figure 5.18. In this scenario, there are several paths to obtain the spare parts for the Wisting platform, including the centrifugal pump, gate valve, or electric motor, since they are following the same conditions with different failure rates. These separate lines of discrete events provide alternative paths for getting the necessary spare parts based on the availability and nearness of stocks across the platforms.

By taking the same sequence of sorting priorities as in the state chart, where the Wisting platform checks first its own stock for the required spare parts. Then, if the condition specified in the 'Go_to_Repair1' transition is met, it triggers the last path of the discrete events, enabling the order to flow through and obtain the required spare parts from the Johan Castberg platform.

If the condition in 'Go_to_Repair1' is not fulfilled, the next condition in 'Go_to_Repair2' is checked. If this condition is met, the middle path of the discrete events is activated, allowing the order to flow through and get the required spare parts from the Goliat platform.

However, if none of these conditions are fulfilled, then the order goes ahead to the last state 'CentPumpNotWorking' triggering the first path of the discrete events, where it secures the required spare parts from the Hammerfest warehouse.

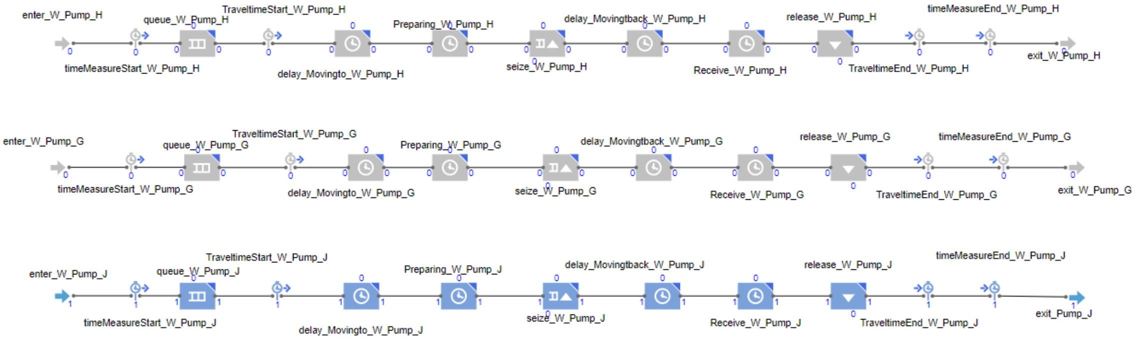


Figure 5.18: *'Wisting_pump' agent (discrete events).*

Three tables were made to understand these three paths containing these different blocks employed in this discrete event, involving their properties, codes, and actions along with explanations of the codes used within these blocks. Table C.2, Table C.3, and Table C.4 are included in Appendix C, to provide explanations for the blocks in the last path, middle path, and first path, respectively. They can be referenced in order to gain a better understanding of the specific blocks within each path and to enhance understanding of how these blocks contribute to the overall logic and functionality.

It is worth noting that the traveling time between the platforms and between the platforms and the Hammerfest warehouse is calculated based on the distances obtained from Chapter 4. These distances are multiplied by the vessel speed of 26 km/h, obtained from Table 4.4. To account for possible delays due to adverse environmental conditions such as high waves or fog, an additional duration of up to 30 minutes is added to each trip. So, the estimated travel time is distributed as a uniform distribution, as illustrated in Figure C.4 in Appendix C. This approach ensures that the simulation model considers realistic travel times while accounting for potential challenges in the marine environment.

Regarding the 'Wisting_Valve' and 'Wisting_Motor' agents on the Wisting platform, they are treated exactly the same way as the centrifugal pump in terms of the state chart and discrete event processes. The main difference lies in their own failure rate. By applying the same logic and structure as the centrifugal pump on Wisting, the simulation model ensures consistent handling of other pieces of equipment failures on the Wisting platform and their corresponding order processing flows.

Moving on to the second furthest platform from the onshore warehouse which is Johan Castberg. Similar to the Wisting platform, each equipment type on Johan Castberg has its own agent. Therefore, another three agents are created 'johan_Castberg_Pump', 'johan_Castberg_Valve', and 'johan_Castberg_Motor' to represent the three selected pieces of equipment on this platform.

However, there is a small difference in the sorting of priorities additionally to the main difference being the failure rate value, which is specific to each equipment type. The steps and contents within these three agents are almost identical to those of the Wisting platform, with adjustments made to account for the differences in priorities and failure rates.

To provide a comprehensive understanding of the differences in priorities, the state chart within the 'Johan_Castberg_Pump' agent, as shown in the Figure 5.19, is taken as an example. This state chart consists of a similar number of states and transitions as the previous platform. These states and transitions ensure the systematic approach to managing the piece of equipment on the Johan Castberg platform, as provided in the second condition in Figure 5.12 in terms of prioritizing whom to order from, taking into account equipment failure rates and stock availability across all platforms. Additionally, three lines of discrete events provided in Figure 5.19 are created in order to determine the path that the order process should follow based on the availability and proximity of stocks on the different platforms.

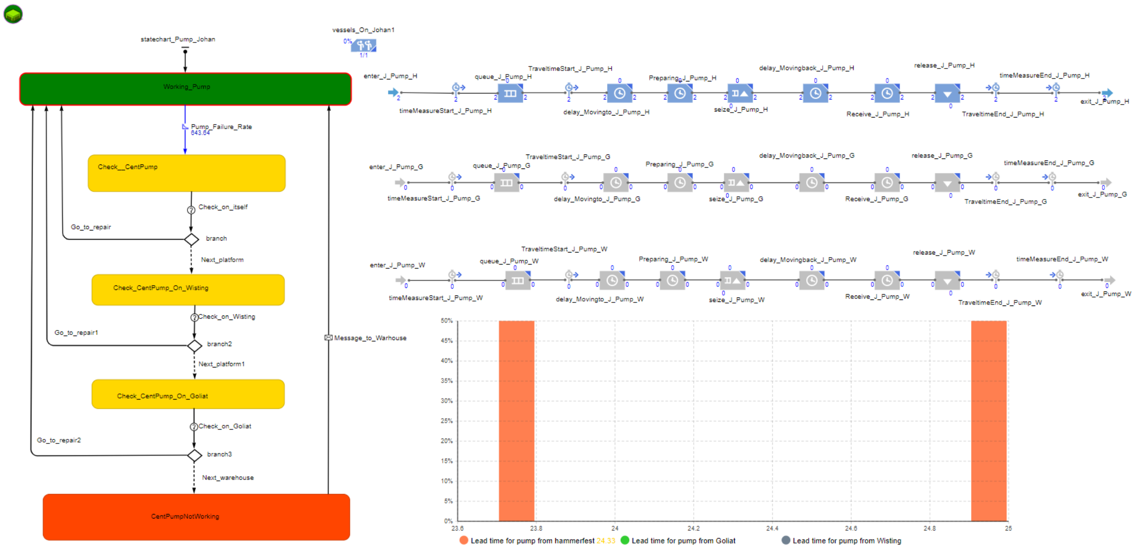


Figure 5.19: *'Johan_Castberg_Pump' agent.*

For the centrifugal pump on the Johan Castberg platform, the initial state is 'Working_pump,' indicating that the equipment is in a normal functioning situation, then when it is triggered by the pump's failure rate, it transitions to the 'Check_CentPump' state, where it checks if the pump is available in its own onboard stock. If the pump is not available, the checking process moves to the 'Check_CentPump_On_Wisting' state, where it checks for the pump on the Wisting platform. If the pump is still not available there, it goes ahead to the 'Checking_CentPump_On_Goliat' state. If none of the platforms have the pump in their onboard stocks, it transitions to the final state, 'CentPumpNotWorking.' In this state, the order is sent to the onshore warehouse and then returned to the initial working state to finish the cycle.

By replicating the structure and logic used for the Wisting platform, including the state chart and discrete event processes, for all three agents of the Johan Castberg platform while taking into account the previously mentioned differences, the simulation model ensures consistent handling of equipment failures and order processing across different platforms.

The last three agents, namely 'goliat_Pump', 'goliat_Valve', and 'goliat_Motor', belong to the Goliat platform, and similar to the Wisting and Johan Castberg platforms, these agents are created to represent the three selected pieces of equipment specific to the Goliat platform. However, there is a difference in the approach to meet the third condition provided in Figure 5.12. It is somewhat very similar to the baseline case because this platform has only one option to order spare parts, which is directly from the warehouse when its own onboard stock is depleted and there is a need for spare parts. The steps and contents of these three agents are identical to each other, except for the unique failure rate values associated with each equipment type.

Using the ’Goliat_Pump’ agent that belongs to the Goliat platform as an example to provide a deeper understanding of how the state chart and discrete event are structured and interconnected to be suitable for the concerned condition for this platform.

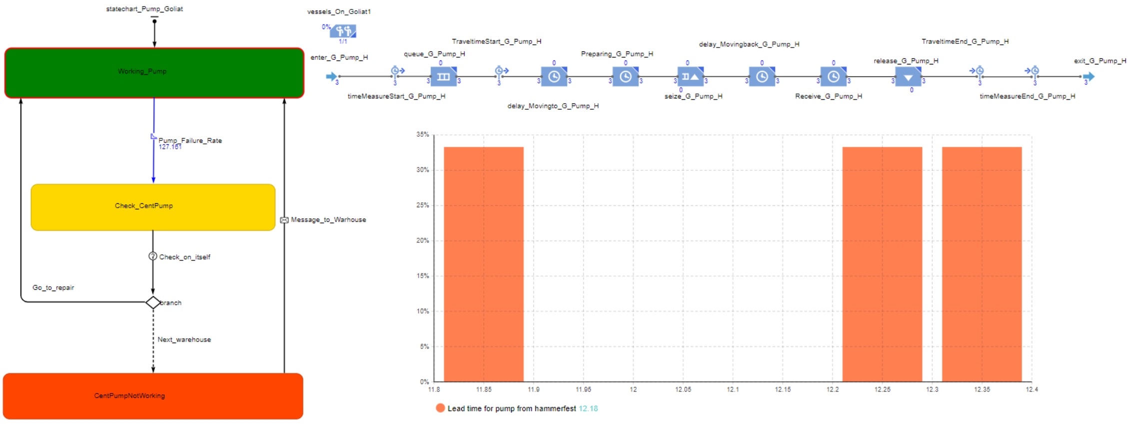


Figure 5.20: *’Goliat_Pump’ agent.*

As usual, the default state of the pump is labeled as ’Working_pump’, as shown in the Figure 5.20, meaning that the equipment is assumed to be working normally. However, when it is triggered by the pump’s failure rate, it transitions to the ’Check_CentPump’ state, where it verifies the availability of the pump in its own onboard stock. Then in case, the pump is not available, it proceeds directly to the ’CentPumpNotWorking’ state, where the order is sent to the onshore warehouse, and then returned to the initial working state again to complete the cycle.

To understand the interconnection between these states and transition in this state chart and how they relate to the discrete event, a table similar to the previous ones is made where it is available asTable C.5 in the Appendix C. This table includes the triggers, codes, and actions associated with this state diagram.

To explore the discrete event and understand how it functions in conjunction with the state chart. By following the same sequence of sorting priorities as in the state chart, the Goliat platform first checks its own stock for the required spare parts, then in case of the condition specified in the ’Go_to_Repair’ transition is not met, it triggers into next state ’CentPumpNotWorking’ where it leads to taking the path of the discrete event, allowing the order to proceed and obtain the necessary spare parts from the Hammerfest warehouse.

Table C.6 in Appendix C explains in depth the path within the discrete event, highlighting the various blocks used to complete it. Table C.6 includes information about the properties, codes, and explanations of these blocks, illustrating how they contribute to the overall logic and functionality that is represented in Figure 5.20.

The ’Goliat_Valve’ and ’Goliat_Motor’ agents that belong to the Goliat platform are treated in the same manner as the centrifugal pump, including the state chart and discrete event processes, with the main difference being the failure rate. So, by implementing the same structure and logic used for the centrifugal pump on the Goliat platform, the simulation model ensures consistency in handling other equipment failures and order processing for Goliat platforms.

The approach used in this simulation model is systematic and consistent, aiming to handle effectively with equipment failures and streamline order processing across multiple platforms. By replicating the technique for each platform, taking into account the specific failure rates of the pieces of equipment, and using both state charts and discrete event processes, the simulation model gives an exhaustive overview of all parties involved in this system. This approach assures efficiency, effectiveness, and accuracy in handling equipment failures for the selected pieces of equipment across all three platforms, and order processing between these platforms and the warehouse. This unified management approach enhances the overall reliability of the simulation model and enables a more robust evaluation of the system’s performance.

5.4 Experiments for Solution Scenario

This section focuses on conducting simulation experiments using the solution scenario model, which involves sharing spare parts between platforms. These experiments aimed to explore in detail the impact of changing the amount of the pieces of equipment in the onboard stocks on the spare parts management system, without changing anything in the structure and logic of the model applied to the solution scenario.

The experiments are performed in three stages with each stage involving different levels of stock, in order to gain valuable insights into the system dynamics and understand how changes in stock level affect the key performance indicators. These experiments may help to determine optimal stock levels that balance operational efficiency, and environmental impact. The results of these experiments are crucial in formulating strategies that ensure efficient and sustainable spare part management in the Barents Sea.

It is worth noting that the simulation model performed with these experiments is using the same consistent time duration as the previous two scenarios. This ensures that the outcomes of the three experiments can be effectively compared and the differences between the outcomes of the experiments and the two previous scenarios analyzed. Each experiment begins with a specific stock level, which is changed for each subsequent experiment. The stock levels have been assumed to be equal for each stock of the equipment type, as illustrated in Table 5.5.

Table 5.5: *Overview of The Number of Each Piece of Equipment on Each Platform .*

	Experiment 1	**Experiment 2**	**Experiment 3**
Number of pump on each platform	10	8	4
Number of valve on each platform	4	3	1
Number of motor on each platform	2	1	1

In the first experiment, the initial values of the equipment stocks on each platform were assumed to be set to their maximum capacity, as shown in Table 5.5 meaning they were fully stocked with spare parts at the beginning of this experiment. For the stocks of the spare parts representing the centrifugal pumps onboard the Wisting, Johan Castberg, and Goliat platforms, an initial value of ten pieces was assumed for each platform. Similarly, for the gate valve stocks, an initial value of four pieces was assumed for each platform. Lastly, for the electric motor stocks, an initial value of two motors was assumed.

As well, the second experiment involved adjusting the estimated initial values of the onboard equipment stocks to be less than the estimated maximum capacity, as shown in Table 5.5. Where the centrifugal pump stocks were assumed to be eight pieces per platform, while in the case of gate valve stocks were set to have an initial value of three pieces. As for the onboard electric motor stocks level were assumed to be one as the initial value.

In contrast to the first experiment, Table 5.5 illustrates that the last experiment had the assumption of setting up the stock level on each platform to its minimum capacity. In the case of the centrifugal pump, each onboard stock had an assumed initial value of four pieces, on the other hand, the onboard stocks of the gate valve and electric motor, had only one piece as an initial value.

5.5 Verification & validation

In this light, this section focuses on the verification and validation processes carried out for the simulation model of managing spare parts in the Barents Sea scenarios and experiments. This process includes the technologies used, the data referred to, and the results of these processes.

5.5.1 Verification & Validation of Simulation Model

The models underwent more than 100 runs and tests to ensure their accurate representation of the intended conceptual model. Several techniques were used to ensure that the simulation model was executed as meant in the sequence diagrams and without errors, such as a GIS map structure has been implemented in the model, allowing for a visual and logical examination of each part of the model, including the logistic processes, equipment failure rates, and the service time in each platform. As well as visually confirming that all system dynamics, state charts, and discrete event components are correctly performed and working properly based on the failure rates, and they are logically interconnected to each other.

5.5.2 Verification & Validation Input Parameters

The models have been run and tested more than once during their development by manipulating different values of input parameters, events, transitions, and stocks within realistic ranges in order to see how each affects the logic and mathematical equations within the model. Additionally, it was visually inspected from the GIS map, state charts, and result plots in order to ensure their accurate representation of the specified conceptual model. This approach evaluated how well the model responded to changes in inputs, as it is critical given the unpredictability and uncertainty inherent in the real-world system.

Table 5.6 below provides a comprehensive overview of the verification and validation tests conducted with the academic expert. These tests aimed to provide valuable insights and confirm that the model's behavior and outputs aligned with his understanding and expectations of the real system's dynamics.

Table 5.6: *Validation and Verification Tests of The Simulation Models.*

Aspects	Test of verification	Test of validation	Comments
The structure of the model (Baseline and solution cases)	Ok.	Ok.	The model has been checked and it matches the conceptual model. The model structure represents properly the real-life scenarios
The logic of the model (Baseline and solution cases)	Ok.	Ok.	Models have been run several times and all rules work as expected.
The behavior of the model (Baseline and solution cases)	Ok.	Ok.	The model behaves as expected under different scenarios as the GIS map shows Comparing the behavior of the model with real-life data
Inputs (Parameters, Events,Stocks)	Ok.	Ok.	Adjusting the parameters, events, and initial values of stocks shows the different outputs The model shows flexible behavior under various input conditions which makes the model more reliable to handle real-world data.
Processes (Functions, Rates)	Ok.	Ok.	The functions and rates are correct under different scenarios. The model mimics real-world dynamics effectively.
Model Impact	Ok.	Ok.	The model influence on cost, CO2 emission, and efficiency This influence leads to making changes and improvements within these parameters

One of the experiences that were faced in the solution scenario is having an error message that appears every time the model was run, describing that it can not occur two equipment failures at the same time within the discrete event, the same applies to the state chart. Where it has been observed that sometimes equipment failure occurs and enters into force before the previous equipment failure gets fixed. This makes sense in a real-world situation because when the first failure occurs and the system is down, it is expected that none of the equipment will experience subsequent failures until the initial failure is resolved. However, the model was not running as expected and still showed the error message. This error was solved by splitting the onboard stocks into each agent and having their own state chart and discrete event within their own agent.

The verification and validation processes have supported the credibility and reliability of the simulation model. This model has been exhaustively verified, indicating its technical integrity by confirming that its structure, logic, and implementation corresponded to the desired goals. Moreover, a comprehensive sensitivity analysis of the model has shown flexible behavior under various input conditions, which gives confidence in its reliability by running the model in different operation conditions.

The main goal is to enhance trust in the model's capability in order to gain reliable analyses for spare part management in offshore remote locations. This can be seen by the precise representation of the model of spare part management dynamics in the Barents Sea region. As a result, this model provides a realistic framework for discovering various scenarios and strategies.

Chapter 6

Results & Discussion

This chapter focuses on presenting and discussing the results derived from the simulation model, which was developed to optimize spare parts management in offshore remote locations within the Barents Sea. The simulation model was run for a duration of 5760 hours, equivalent to eight months, as mentioned earlier. The primary objective is to provide a comprehensive and understandable overview of the outcomes, along with insightful analysis and interpretation, that can aid in the development of sustainable and efficient practices for spare part management in offshore remote locations, not only in the Barents Sea but also in other similar environments.

6.1 Outcomes of The Simulation Baseline Scenario

This section presents and discusses the results obtained from simulating the baseline scenario, which represents the current state of spare part management in the offshore remote locations of the Barents Sea. In this scenario, whenever any equipment of the three selected types fails on any of the three platforms, the required spare parts are ordered from the onshore warehouse using vessels for logistics.

The developed model indicates that the number of equipment failures in the current system is 59 for the total pieces of equipment on the three platforms, meaning that the number of trips to the onshore warehouse is also 59 as illustrated in Figure 6.1. It looks like a huge number, but again it is based on the failure rate used that encompasses all modes and is represented in upper values in order to be on the safe side as the worst-case scenario.

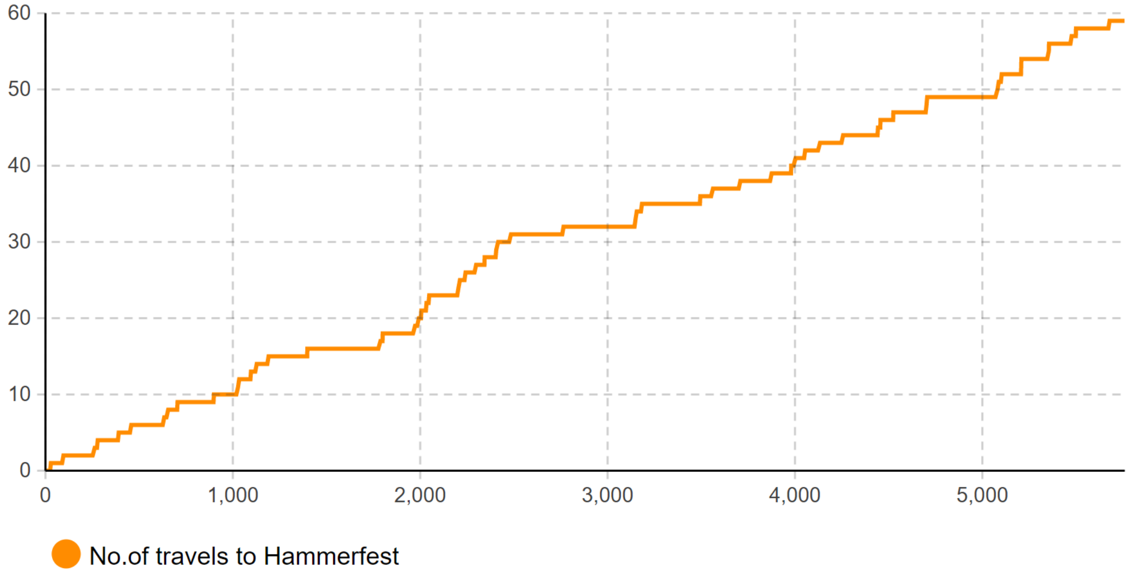


Figure 6.1: *Number of trips to the onshore warehouse of the Baseline scenario*

The simulation model provides insights into the time used for all logistic processes during the simulation model time to cover the 59 necessary trips, related to the number of failures, to different remote locations in the Barents Sea. This analysis takes into account potential delays that may occur due to several factors such as the availability of vessels, preparation and reception times, and the number of orders or demands being under-processed. Figure 6.2 shows the total number of sailing hours spent during the 59 round trips between the various remote locations and the onshore warehouse, which amounts to 1510.445 hours.

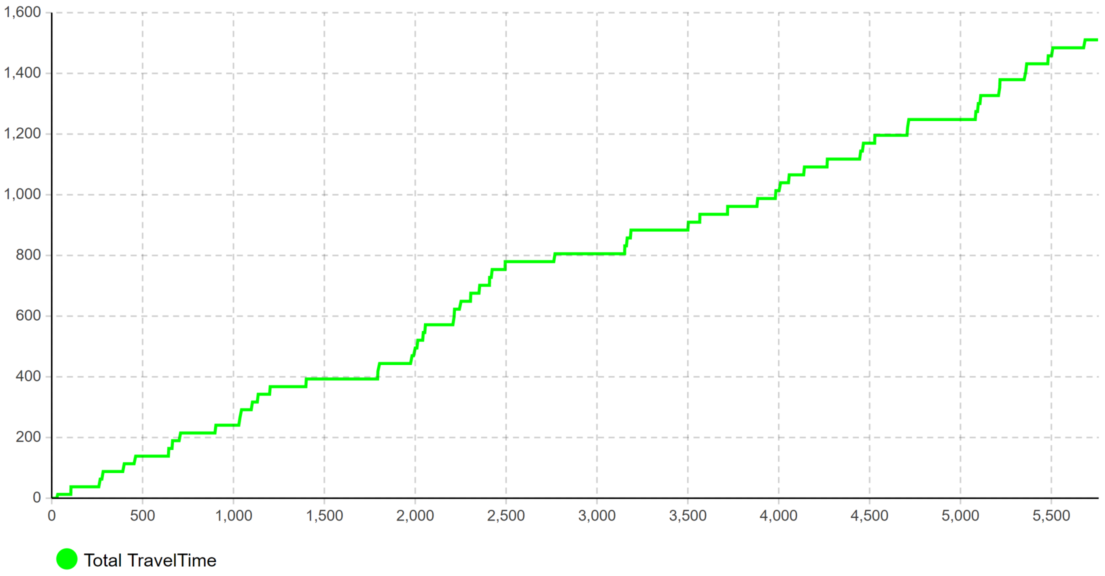


Figure 6.2: *Total travelling time in hours of the Baseline scenario*

In terms of the environmental impact, the 59 round trips with a cumulative duration of 1510.445 hours resulted in significant CO_2 emissions, which impose additional carbon taxes for the companies, in addition to what they already pay for production. The simulation model calculated the amount of CO_2 emitted by the vessels during these trips as 4192089.339 kg, as shown in Figure 6.3. Furthermore, it determined the corresponding amount of money that needs to be paid as taxes for these emissions, totaling NOK 4611298.273 as depicted also in Figure 6.3.

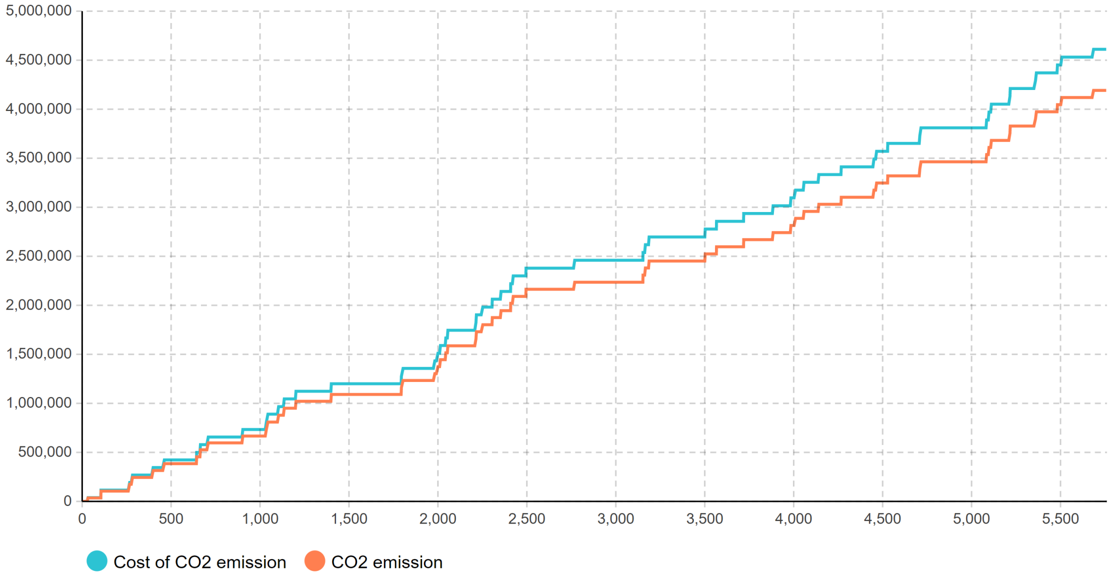
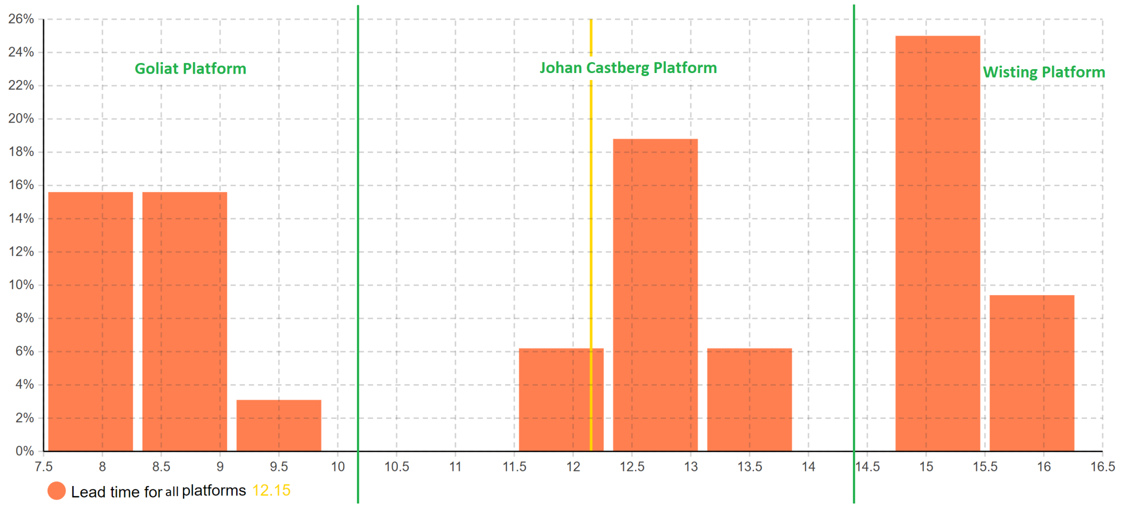


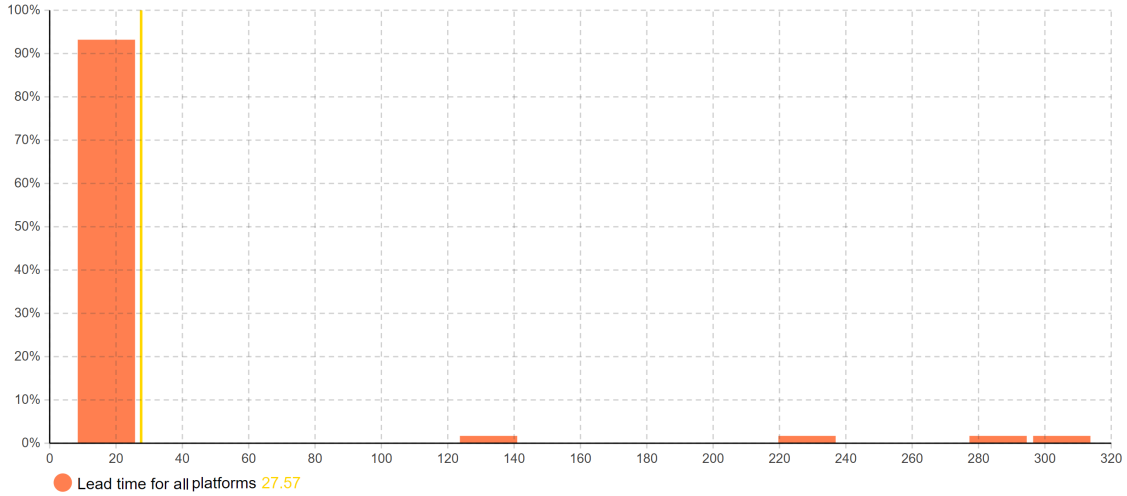
Figure 6.3: *Emissions and associated carbon tax costs of Baseline scenario*

When considering costs, the lead time caused by equipment failures is an important factor for companies, as it refers to the downtime and waiting time until platforms receive the required equipment. The simulation model accurately captures and analyzes lead time, but for better understanding, it is divided into two periods as illustrated in Figure 6.4. The first period, shown in Figure 6.4a, extends from the start of the model until just before the onshore warehouse requires refilling. In this period, Figure 6.4a provides a detailed breakdown of lead times per location, with each platform represented in its respective picks group.

The current system has an average spare parts delivery lead time of approximately 8.5 hours for Goliat, 13 hours for Johan, and 15.9 hours for Wisting. Taking Goliat as an example, to understand the logic behind these numbers. As mentioned earlier, the distance between Goliat and the onshore warehouse in Hammerfest is 85 km, requiring around 3 hours and 27 minutes of travel time by vessel. Additionally, there are preparing and receiving activities that each take two to three hours. Consequently, the total lead time ranges between 7.5 hours and 9.5 hours, as shown in Figure 6.4a. Similar lead time calculations apply to Johan Castberg and Wisting platforms.



(a) Lead Time for The First Period of The Baseline Scenario.



(b) Lead Time for Entire Duration of The Baseline Scenario

Figure 6.4: *Lead time of the Baseline scenario.*

After running the entire model, Figure 6.4b illustrates the change that occurs in the lead time. At a certain point, the vessel was unable to obtain the required spare part due to a waiting period of two to three weeks for the onshore warehouse to be refilled. This had a significant impact on the overall lead time, resulting in a significant increase in hours for all platforms. However, this occurrence was limited to as it happens once during the running model duration, therefore less than 5% of the trips get affected, while approximately 95% of trips kept the normal lead time duration, as on average, the lead time for all platforms was 27.57 hours.

The simulation model offers insights into the behavior of the onshore warehouse, highlighting the reasons behind the long lead time for the three platforms. Figure 6.5 provides a detailed description of the onshore warehouse deduction and refilling processes, providing a comprehensive understanding of warehouse dynamics.

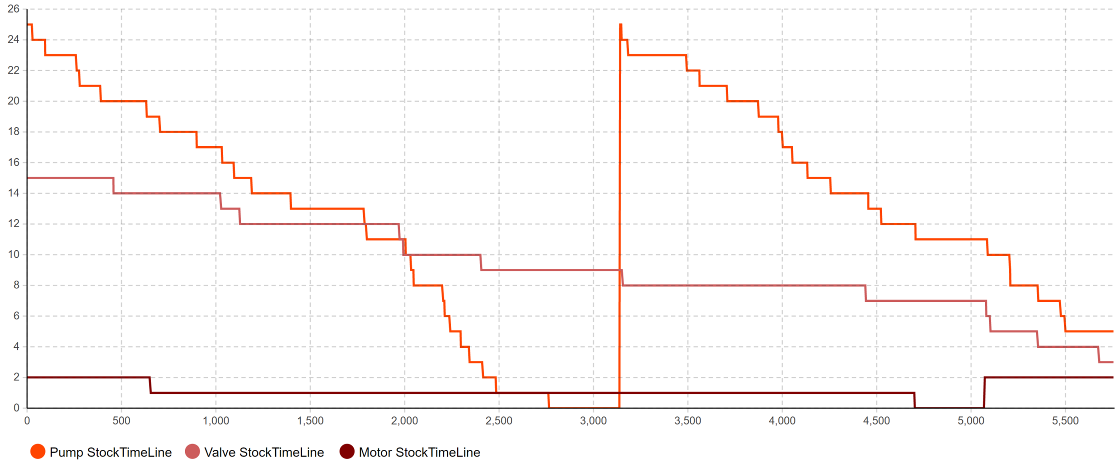


Figure 6.5: *Overview of the onshore warehouse for Baseline scenario.*

The simulation results offer valuable insights into the performance of the current spare part management system in offshore remote locations. These baseline scenario outcomes indicate that while the current spare part management system has effective elements, there are areas where some improvements can be made. In the following section, the outcomes of the solution scenario were explored, which includes changes aimed to improve the overall efficiency of the spare part management system.

6.2 Outcomes of The Simulation Solution Scenario

This section involves the results of simulating the solution scenario which focuses on the concept of sharing spare parts between the offshore remote locations of the Barents Sea, through having spare parts stocks on each. This section illustrates the impact of implementing such a scenario on various aspects of the spare parts management system such as carbon emissions, lead times, traveling time, and warehouse management. Additionally, providing a further understanding of how the proposed modifications can positively impact the whole system's performance.

The solution scenario indicates that there were a total of 34 trips made from these three platforms to the onshore warehouse, as shown in Figure 6.6. This reflects that the pieces of equipment in stocks on each platform, whether used individually or shared among these platforms, were exhausted before they start traveling to the onshore warehouse to get the required equipment.

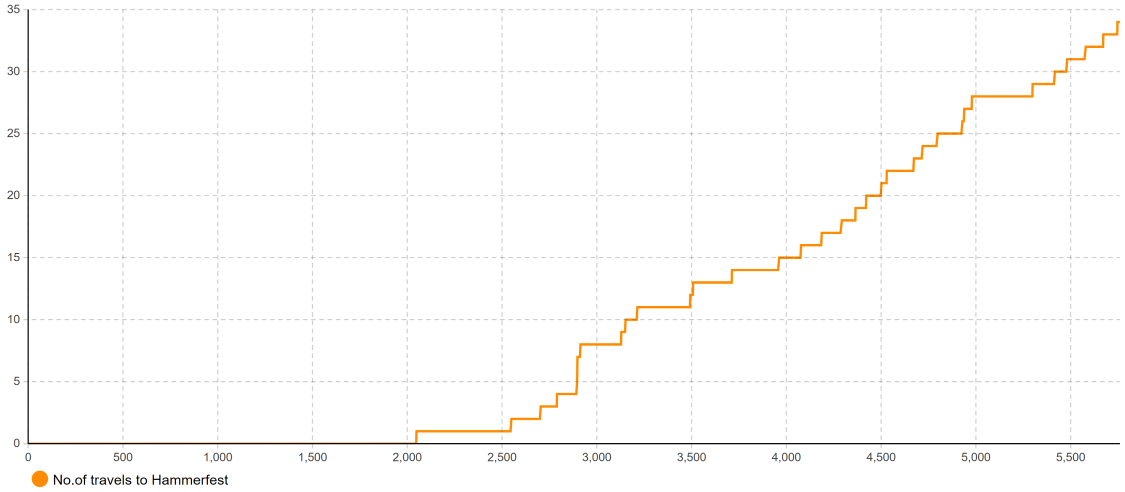


Figure 6.6: *Number of trips to the onshore warehouse of the Solution scenario*

The total time required to complete these 34 round trips and the other trips between the platforms themselves as a part of the solution scenario, is properly calculated throughout the simulation model. This calculation takes into consideration the delay caused by the previously mentioned factors in addition to the delay of up to 30 minutes is considered during each trip due to the harsh environment. As a result, the total time for these trips amounts to 775.689 hours, as illustrated in Figure 6.7.

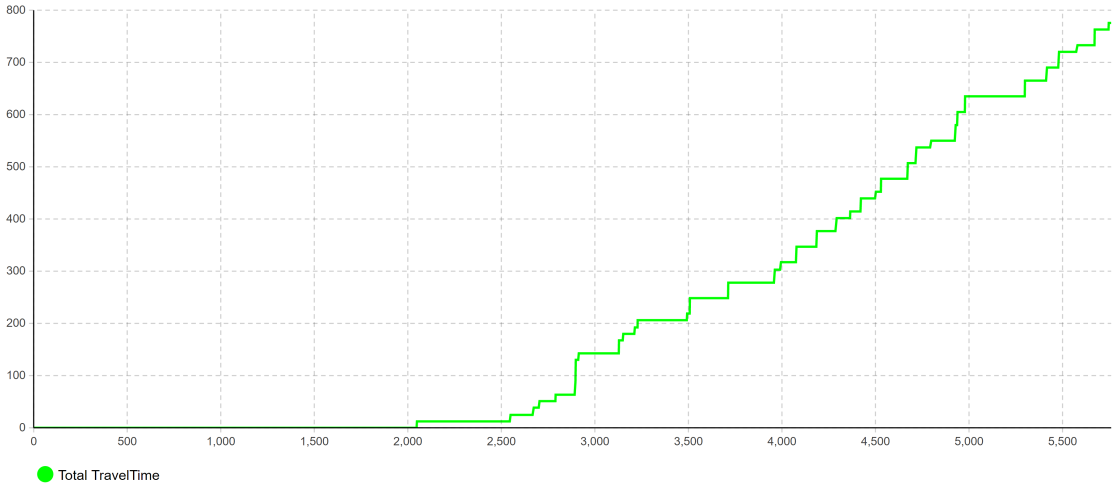


Figure 6.7: *Total traveling time in hours of Solution scenario*

Similar to the baseline scenario, the simulation model provides valuable insights into CO_2 emissions and carbon taxes associated with the solution scenario. Throughout these 34 round trips and the other trips between the platforms themselves, which extended for a total of 775.689 hours, the vessels emitted a total of 2152846.432 kg of carbon dioxide. As a result, the companies are required to pay additional carbon taxes, estimated to be a total amount of NOK 2368131.075, as depicted in Figure 6.8.

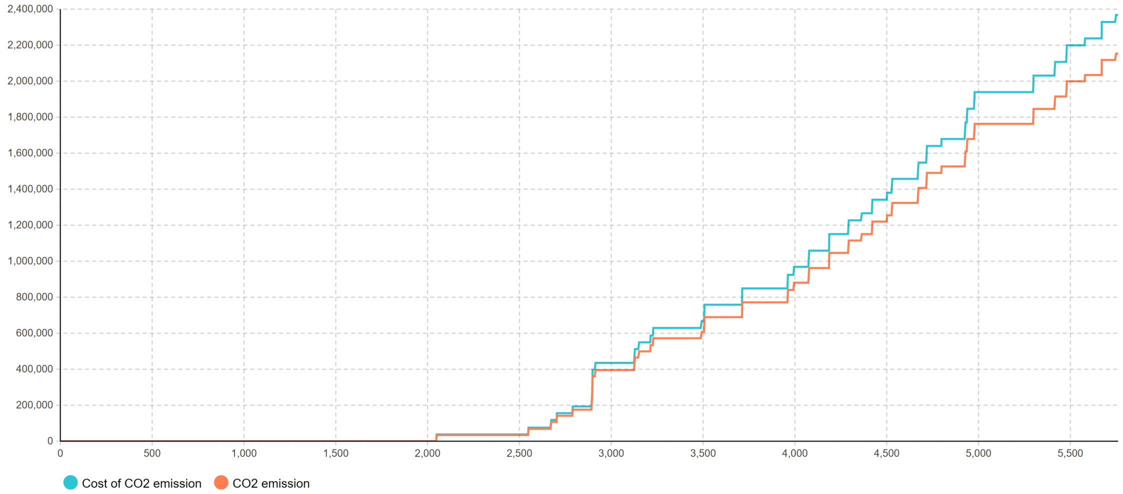


Figure 6.8: *Emissions and associated carbon tax costs of Solution ccenario*

Before discussing the lead time in the solution scenario, it is important to consider that there is a vessel located on each platform, which is responsible for sailing to bring the required spare parts from other platforms or the onshore warehouse, as discussed earlier. This means that the lead time in the solution scenario may still be significant, but at the same time, some of the delays were mitigated compared to the baseline scenario. This was achieved through a fixed refill period of 4000 hours for the onshore warehouse and the reduced number of trips to the onshore warehouse as Figure 6.6 illustrated.

The lead time in the solution scenario was divided based on the platform that needs the spare parts and the source from which the spare parts were obtained. To illustrate this, Figure 6.9 below provides an example of the lead time for the Wisting platform, specifically in the case where a centrifugal pump is required. Figure 6.9 indicates by the grey bar that the average lead time to obtain a centrifugal pump from the Johan Castberg platform is 14 hours, while the average lead time for a round trip to the onshore warehouse is approximately 29 hours, represented by the orange bars in Figure 6.9.

Figure 6.9: *Lead time for centrifugal pump in Wisting platform.*

The behavior of the onshore warehouse was analyzed to understand the impact of the solution scenario on onshore warehouse dynamics and identify areas that can be improved. Figure 6.10 illustrates in detail the processes involved in deducing and refilling spare parts in the onshore warehouse.

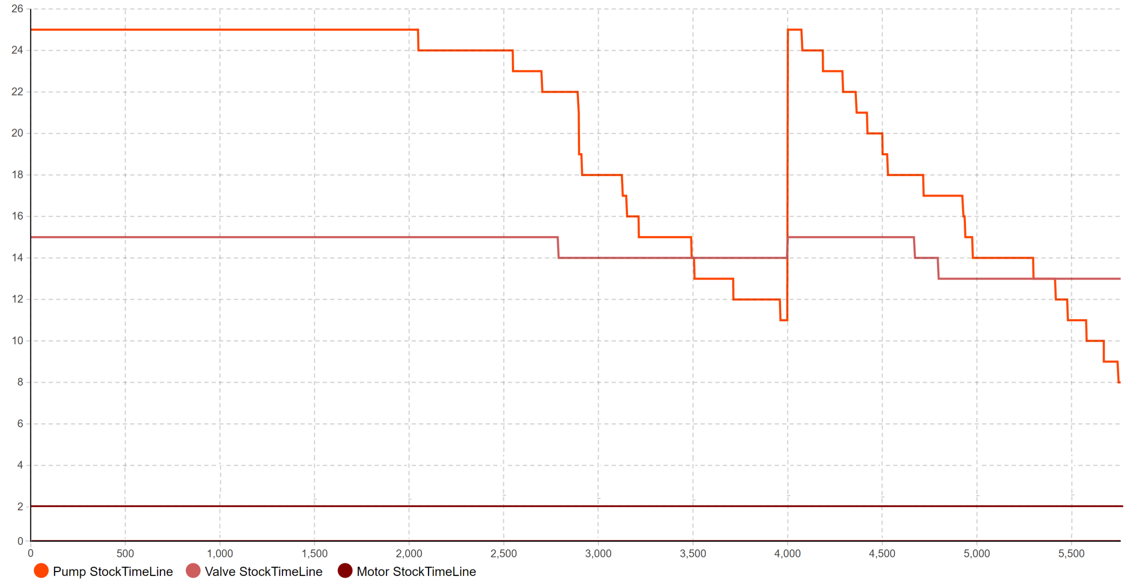


Figure 6.10: *Overview of the onshore warehouse for Solution scenario.*

The results of the solution scenario show that the suggested modifications have an opportunity to significantly enhance the performance of the spare part management system. To better understand the impact of the suggested solutions, the results of the baseline and solution scenarios were compared directly and in detail in the next section.

6.3 Comparing Outcomes of Both Simulation Scenarios

The simulation models presented in this thesis were developed to represent the baseline and solution scenarios for three remote locations within the Barents Sea, each of which is equipped with three equipment types, and there is one onshore warehouse. A comparison assessment is performed in order to discuss the difference in the results, as presented in Table 6.1. This comparison takes into account key factors such as the number of trips to the onshore warehouse, total travel time, CO_2 emissions, and carbon emission tax.

Table 6.1: *Scenarios Comparison.*

	Baseline Scenario	**Solution Scenario**
Total number of trips to onshore warehouse [h]	59	34
Total traveling time [h]	1510.445	775.689
CO_2 **emission [Kg]**	4192089.339	2152846.432
Carbon emission tax [NOK]	4611298.273	2368131.075

According to Table 6.1, the solution scenario resulted in a total of 34 trips to the onshore warehouse, which represents a significant reduction of approximately 42% compared to the baseline scenario. As Figure 6.6 and Figure 6.10 illustrate that the first trip to the onshore warehouse in the solution scenario occurred after more than 2000 hours of running the model, which is equivalent to around two and a half months of self-sufficiency and cooperation between the platforms. These results indicate the effectiveness of the spare parts sharing system in minimizing the need for frequent trips to the onshore warehouse and offer useful insights into operational efficiency.

Consequently, the solution scenario has significantly reduced the total traveling time to 775.689 hours, as depicted in Table 6.1, which corresponds to a remarkable 48.6% reduction compared to the baseline scenario. This reduction in traveling time has a big impact on the overall system downtime, as this saved time can be effectively utilized in operational activities, allowing companies to allocate resources more efficiently and enhance productivity. Thus, this has the potential to generate cost savings and increased profitability for the companies involved. These results provide valuable insights into how sharing spare parts between offshore remote locations would enhance uptime.

As shown in Table 6.1 the solution scenario resulted in approximately 48.6% reduction in CO_2 emissions compared to the baseline scenario. This significant reduction highlights the potential for reducing the environmental impact of the transportation activities associated with spare parts in the solution scenario and ensuring the importance of considering and mitigating CO_2 emissions in spare part management practices.

Additionally, the substantial reduction in CO_2 emissions achieved through the solution scenario has a positive financial impact, as this significant decrease in emissions leads to large savings by reducing the amount of carbon emission tax that needs to be paid. According to the results of the solution scenario model given in Table 6.1, approximately 48.6% of carbon taxes are saved compared to the baseline scenario. By minimizing carbon emissions, companies can not only contribute to environmental conservation but also reduce their financial burden by avoiding high carbon emission taxes.

Finally, a comparison between Figure 6.5 and Figure 6.10 shows the potential for improving onshore warehouse management. As depicted in Figure 6.10, the first drop of the onshore warehouse level occurred after more than 2000 hours of running the solution scenario model. Anyway, it was refilled after 4000 hours as scheduled to its maximum capacity. Consequently, at the end of the running time, the remaining quantities of the equipment were 9 pieces of centrifugal pumps, 13 gate valves, and two intangible electric motors in the onshore warehouse. In contrast, the baseline scenario experienced its first drop within a few hours, and it required a refill for centrifugal pumps at approximately 2800 hours of model runtime. By the end of the simulation, the onshore warehouse in the baseline scenario had five centrifugal pumps remaining after one refill, three gate valves from the initial quantity, and two electric motors after one refill too.

These results highlight the potential for improved inventory management. In the baseline scenario, the onshore warehouse required refilling due to the high demand for the equipment, whereas in the solution scenario, there were instances, where specific equipment such as electric motors on the onshore warehouse, remained intangible throughout the whole simulation model. Additionally, not a large amount of equipment like gate valves has been demanded from the onshore warehouse. These results suggest that there is an opportunity to free up space in the warehouse for other critical equipment that experiences higher failure rates and high demand. This approach can contribute to more efficient inventory management in terms of optimizing warehouse processes and ensuring efficient spare part availability.

6.4 Outcomes of Experiments for Solution Scenario

This section presents and discusses the results of three experiments conducted using the solution scenario, with the main difference being the variation in the quantity of equipment in each stock on the platforms. This approach allowing to explore the overall impact on key performance indicators.

Referring back to Table 5.5, the inputs for the first experiment included ten centrifugal pumps, eight gate valves, and four electric motors on each platform. The second experiment involved four centrifugal pumps, three gate valves, and one electric motor on each platform. Lastly, the inputs for the third experiment comprised two centrifugal pumps, one gate valve, and one electric motor on each platform.

The results of three experiments are presented in Table 6.2, enabling a comparison of their impact on the total traveling time, CO_2 emissions, carbon tax, and the replenishment requirements of the onshore warehouse.

Table 6.2: *Experiments Comparison.*

	Experiment 1	**Experiment 2**	**Experiment 3**
Total number of trips to onshore warehouse [h]	22	22	38
Total traveling time [h]	449.041	477.244	904.604
CO_2 **emission [Kg]**	1246269.525	1324542.497	2510636.909
Carbon emission tax [NOK]	1370896.477	1456996.746	2761700.6

The first experiment gives excellent results, as it significantly reduced the total traveling time and minimized CO_2 emissions and carbon taxes compared to the baseline scenario. Additionally, the onshore warehouse could dispense with replenishment for any of the three equipment types throughout the runtime of the simulation model. However, at the same time, it was observed that not all the quantities of equipment that existed on the offshore stocks were consumed, leading to some platforms having excess stock of that equipment.

The second experiment also produced good results in terms of the main factors as presented in Table 6.2, with all quantities of the three equipment types in the offshore stocks being consumed. This led to some of the equipment in the onshore warehouse also being consumed which resulted in the need for replenishment.

In contrast, the results of the final experiment were higher compared to the previous two experiments. This indicates that all the equipment in the offshore stocks was consumed within a shorter period, resulting in a higher demand for equipment from the onshore warehouse, which makes the number of trips to the warehouse increase by approximately 73% compared to the two previous experiments. Consequently, the onshore warehouse needed to be refilled at least once to cover this amount of demand.

These results indicate that keeping stocks at maximum capacity level can lead to overstocking on offshore platforms, which may be a problem and challenge for smaller platforms with limited storage space. On the other hand, having the minimum level of stock capacity on the offshore platforms minimizes the number of trips to the onshore warehouse compared to the baseline scenario. However, this approach may not align with the goal of achieving zero CO_2 emissions. While a capacity level between them may be better if the platforms can dispense the onshore warehouse till the next replenishment on their own stocks.

However, achieving the optimal level of equipment in each stock and also the onshore warehouse, requires running numerous experiments, because each time a small adjustment is made to the quantities of equipment in the stocks, can have a significant impact on all key performance indicators and the simulation model gives different results based on these adjustments.

6.5 Further work

The outcomes of this study have pointed toward a viable way for improving spare part management in offshore operations within the Barents Sea. However, several pathways remain to be explored to further refine and enhance these outcomes

- Future studies should consider incorporating different maintenance strategies like preventive, predictive, and condition-based maintenance into the simulation model. Understanding their interaction with a shared spare parts strategy can reveal new opportunities for further optimizing spare parts management in offshore operations.
- While this research focused on three specific types of equipment within three criticality classes, future studies could broaden the scope to include more various equipment, components, and spare parts categories. This will help validate the universality of the shared spare parts strategy.

- The simulation model considered factors like logistics traveling time, lead times, carbon emissions, and the cost of carbon taxes. Future research could incorporate more operational variables, such as cost of the downtime or unforeseen equipment failures, to make the model more representative of real-world scenarios.
- Although the simulation model was primarily focused on three offshore locations, future research could expand the simulation to more platforms or different geographic regions with complex logistics and inventory management challenges, such as the Gulf of Mexico or the Persian Gulf. This could also involve exploring different scenarios, such as significant shifts in demand for certain spare parts.

Chapter 7

Conclusion

In this thesis, a simulation model of spare parts management in the Barents Sea across three offshore remote locations, each equipped with three types of equipment, is developed and analyzed. The model takes into account the unique challenges and complexities involved in spare parts management in offshore remote locations, including lead time, logistics, and sustainability considerations, such as minimizing carbon emissions and enhancing the reuse of spare parts among the platforms.

The main objectives of this thesis are to address these challenges by implementing the concept of sharing spare parts between these offshore remote locations to enhance the overall efficiency of spare part management, as well as contributing towards assessing the impact of different capacity levels of offshore stocks on several key factors.

The results of the simulation model demonstrate the effectiveness of the solution scenario in improving spare part management in offshore remote locations in the Barents Sea. Compared to the baseline scenario, the solution scenario significantly reduced the number of trips to the onshore warehouse by approximately 42%. It also resulted in a 48.6% reduction in CO2 emissions from the vessels in use, leading to a saving of about 48.6% in cost by avoiding higher taxes on carbon emissions. The solution scenario optimized lead times, with average lead times ranging from 12 to 29 hours for different platforms and equipment types. Furthermore, inventory management was improved, ensuring the availability of critical equipment while minimizing overstocking. The analysis highlights the importance of sharing spare parts, optimizing logistics, and considering environmental sustainability in offshore operations.

The results obtained from the simulation model suggest that it is possible to substantially reduce lead times, lower carbon emissions, save costs associated with carbon taxes, and improve spare parts reusing among these platforms. These outcomes can dramatically enhance overall operational efficiency in remote locations, potentially saving considerable resources and costs.

In addition, the model developed in this thesis could serve as a template for other offshore remote locations, even beyond the Barents Sea. The applied approach can be carried over to platforms that wish to cooperate in sharing spare parts between them with the ability to reduce CO2 emissions and the cost of CO2 taxes, minimize lead time and optimize the warehouse leading to balancing operational efficiency and sustainability in managing operation.

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Appendix A

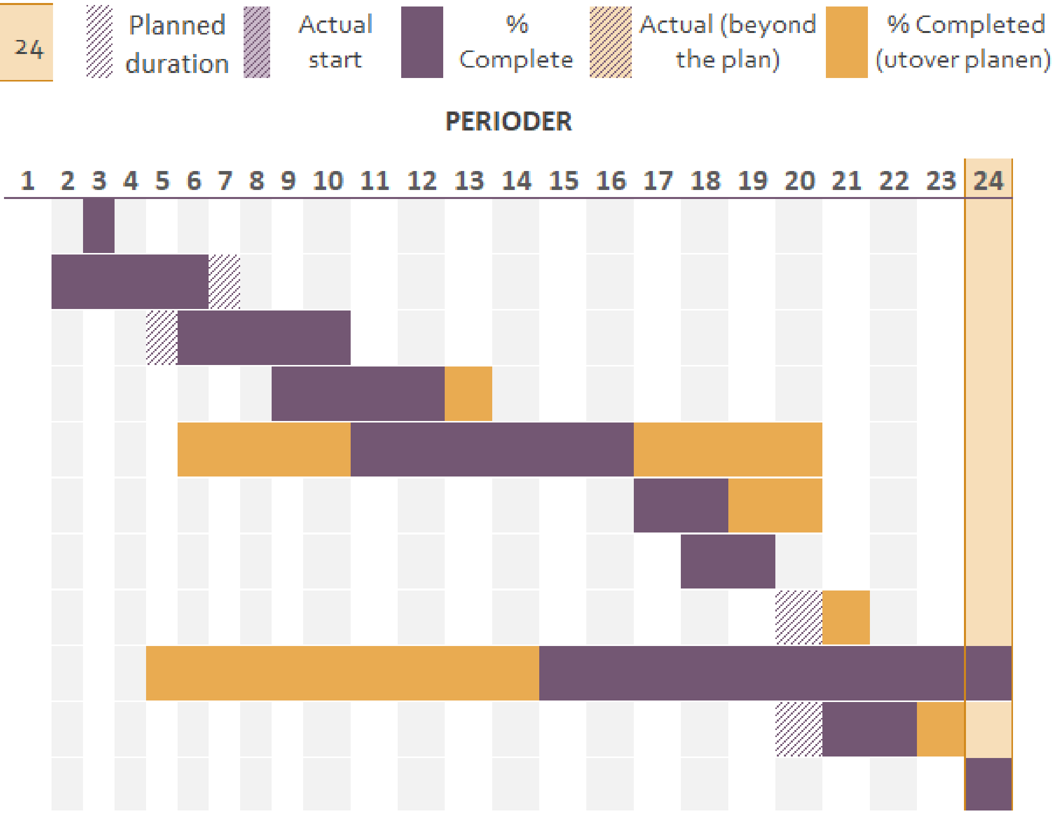
Gant Chart

Project planning

Select a period to be highlighted on the right. A legend describes the following diagram.

Periodeuth eving: 24

Activites	PLANNING START	SCHEDULED DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Kick-off meeting	3	1	3	1	100 %
Data collection	2	6	2	5	100 %
literature acquisition	5	6	6	5	100 %
Draft inn theory	9	4	9	5	100 %
Simulation model	11	6	6	15	100 %
Verification & Validation	17	2	17	4	100 %
Revision	18	2	18	2	100 %
Submit first draft	20	1	21	1	100 %
Thesis writing	15	10	5	20	100 %
Final Revision of the Thesis	20	3	21	3	100 %
Complete the thesis	24	1	24	1	100 %



Appendix B

OREDA

Taxonomy no	Item
1.3.1	Machinery Pumps Centrifugal

Population	Installations	Aggregated time in service (10⁶ hours)		No of demands
		Calendar time *	Operational time †	
350	59	13.9546	5.7455	10340

Failure mode	No of failures	Failure rate (per 10⁶ hours).					Active rep.hrs	Repair (manhours)		
		Lower	Mean	Upper	SD	n/τ		Min	Mean	Max
Critical	**464***	**0.00**	**21.60**	**124.23**	**67.21**	**33.25**	**39.7**	**1.0**	**57.6**	**1025.0**
	464†	**0.12**	**70.52**	**284.09**	**106.81**	**80.76**				
Breakdown	37*	0.00	1.20	1.67	7.82	2.65	16.4	3.0	57.1	766.0
	37†	0.00	3.70	21.16	11.38	6.44				
Erratic output	2*	0.00	0.15	0.79	0.54	0.14	19.8	11.0	39.5	68.0
	2†	0.00	0.46	2.22	0.92	0.35				
External leakage - Process medium	77*	0.00	2.25	5.52	11.84	5.52	30.2	2.0	42.0	444.0
	77†	0.00	7.04	38.07	17.67	13.40				
External leakage - Utility medium	46*	0.00	1.61	2.94	9.28	3.30	16.0	2.0	29.8	90.0
	46†	0.00	4.81	26.68	13.65	8.01				
Fail to start on demand	42*	0.01	2.28	8.52	3.14	3.01	55.8	1.0	63.0	551.0
	42†	0.02	13.74	55.88	21.10	7.31				
Fail to stop on demand	2*	0.00	0.13	0.65	0.57	0.14	3.5	3.0	3.5	4.0
	2†	0.00	0.38	1.55	0.58	0.35				
High output	3*	0.00	0.69	3.58	2.77	0.21	-	1.0	3.3	6.0
	3†	0.00	2.49	13.73	6.44	0.52				
Internal leakage	3*	0.00	0.16	0.87	0.57	0.21	188.0	36.0	90.7	188.0
	3†	0.00	0.56	2.63	1.08	0.52				
Low output	40*	0.00	2.58	3.33	17.49	2.87	38.2	3.0	45.3	508.0
	40†	0.00	4.68	7.79	27.92	6.96				
Noise	4*	0.00	0.25	1.29	0.57	0.29	25.0	16.0	67.3	122.0
	4†	0.03	0.78	2.34	0.80	0.70				
Other	8*	0.00	0.60	3.20	2.68	0.57	275.5	2.0	424.5	734.0
	8†	0.00	1.85	8.07	3.14	1.39				
Overheating	5*	0.11	0.36	0.72	0.19	0.36	183.2	3.0	265.0	1025.0
	5†	0.00	6.83	37.16	17.32	0.87				
Parameter deviation	16*	0.00	0.65	2.84	3.03	1.15	11.6	1.0	21.7	88.0
	16†	0.15	2.58	7.60	2.53	2.78				
Spurious stop	120*	0.00	6.33	33.92	15.65	8.60	39.7	1.0	45.0	714.0
	120†	0.51	22.56	69.52	24.44	20.89				
Structural deficiency	27*	0.00	0.61	0.72	6.77	1.93	23.9	7.0	47.3	211.0
	27†	0.00	1.77	3.32	10.06	4.70				
Vibration	32*	0.00	2.12	10.93	4.76	2.29	81.2	5.0	118.3	896.0
	32†	0.62	6.76	18.55	6.00	5.57				
Degraded	**537***	**0.00**	**32.39**	**163.45**	**70.23**	**38.48**	**22.3**	**0.5**	**32.1**	**798.0**
	537†	**3.74**	**237.30**	**747.95**	**267.91**	**93.46**				
Abnormal instrument reading	9*	0.00	0.85	4.95	2.70	0.64	9.0	2.0	16.0	65.0
	9†	0.00	2.95	12.59	4.86	1.57				
Erratic output	10*	0.00	1.95	10.27	6.99	0.72	20.3	2.0	17.4	65.0
	10†	0.00	4.87	26.99	13.79	1.74				

Comments

(cont

Taxonomy no	Item
1.3.1	Machinery Pumps Centrifugal

Population	Installations	Aggregated time in service (10^6 hours)		No of demands
		Calendar time *	Operational time †	
350	59	13.9546	5.7455	10340

Failure mode	No of failures	Failure rate (per 10^6 hours).					Active rep.hrs	Repair (manhours)		
		Lower	Mean	Upper	SD	n/τ		Min	Mean	Max
External leakage - Process	56*	0.00	3.25	18.02	9.21	4.01	14.1	2.0	31.7	278.0
medium	56†	0.02	10.52	41.84	15.63	9.75				
External leakage - Utility medium	178*	0.00	9.26	45.08	18.79	12.76	30.2	1.0	36.3	219.0
	178†	0.00	57.14	265.19	107.20	30.98				
Fail to stop on demand	3*	0.00	0.30	1.59	1.11	0.21	3.8	6.0	7.7	10.0
	3†	0.00	9.30	43.28	17.53	0.52				
High output	1*	0.00	0.07	0.20	0.07	0.07	2.0	2.0	2.0	2.0
	1†	0.00	0.15	0.48	0.17	0.17				
Internal leakage	11*	0.00	0.87	4.75	2.22	0.79	56.8	2.0	56.0	304.0
	11†	0.00	6.17	34.28	17.67	1.91				
Low output	30*	1.32	2.15	3.15	0.56	2.15	8.4	0.5	14.4	144.0
	30†	4.96	37.34	94.91	29.45	5.22				
Minor in-service problems	3*	0.00	0.29	1.61	0.83	0.21	13.0	18.0	22.0	26.0
	3†	0.00	9.27	43.11	17.46	0.52				
Noise	5*	0.00	0.32	1.72	1.08	0.36	17.7	6.0	35.3	75.0
	5†	0.00	0.95	4.61	1.91	0.87				
Other	46*	0.00	4.29	21.19	8.96	3.30	18.5	1.0	21.8	165.0
	46†	0.00	27.99	132.88	54.47	8.01				
Overheating	9*	0.00	0.83	4.58	2.14	0.64	45.6	7.0	66.0	112.0
	9†	0.00	6.15	34.20	17.71	1.57				
Parameter deviation	70*	0.00	2.60	3.48	17.29	5.02	4.5	1.0	7.3	67.0
	70†	0.00	5.71	19.81	27.67	12.18				
Structural deficiency	61*	0.00	1.73	1.92	13.81	4.37	26.9	1.0	33.9	798.0
	61†	0.00	5.75	20.30	27.74	10.62				
Vibration	45*	0.00	2.89	16.73	9.18	3.22	34.2	1.0	78.1	737.0
	45†	0.00	8.58	37.96	14.93	7.83				
Incipient	**936***	**0.00**	**56.57**	**262.99**	**106.45**	**67.07**	**10.8**	**0.5**	**15.6**	**697.0**
	936†	**95.49**	**834.30**	**2182.80**	**686.83**	**162.91**				
Abnormal instrument reading	445*	0.00	25.76	128.63	54.90	31.89	5.7	0.5	8.1	144.0
	445†	4.46	274.18	862.22	308.37	77.45				
Erratic output	5*	0.00	0.39	2.04	1.41	0.36	4.1	2.0	8.2	16.0
	5†	0.00	1.36	5.38	2.01	0.87				
External leakage - Process	46*	0.00	2.73	14.38	9.89	3.30	15.3	0.5	24.4	206.0
medium	46†	0.00	8.60	44.48	19.52	8.01				
External leakage - Utility medium	108*	0.00	5.29	28.69	13.34	7.74	23.5	1.0	28.0	179.0
	108†	0.57	17.63	53.47	18.40	18.80				
Internal leakage	9*	0.00	0.45	2.09	0.84	0.64	42.6	0.5	41.2	172.0
	9†	0.28	1.42	3.27	0.96	1.57				
Low output	1*	0.00	0.06	0.33	0.15	0.07	2.0	2.0	2.0	2.0
	1†	0.00	0.18	0.55	0.20	0.17				

Comments

(cont.)

Taxonomy no	Item
1.3.1	Machinery Pumps Centrifugal

Population	Installations	Aggregated time in service (10^6 hours)		No of demands
		Calendar time *	Operational time †	
350	59	13.9546	5.7455	10340

Failure mode	No of failures	Failure rate (per 10^6 hours).					Active rep.hrs	Repair (manhours)		
		Lower	Mean	Upper	SD	n/τ		Min	Mean	Max
Minor in-service problems	213^*	0.00	15.38	80.97	36.69	15.26	6.1	0.5	10.4	111.0
	$213^\dagger$	39.27	391.65	1057.33	338.88	37.07				
Noise	8^*	0.00	0.64	3.23	1.39	0.57	7.3	0.5	20.1	46.0
	$8^\dagger$	0.04	2.12	6.58	2.32	1.39				
Other	47^*	0.00	3.14	17.24	8.40	3.37	27.3	1.0	46.0	697.0
	$47^\dagger$	0.00	20.65	103.50	44.28	8.18				
Overheating	4^*	0.00	0.23	0.95	1.08	0.29	30.3	3.0	34.3	64.0
	$4^\dagger$	0.00	0.67	2.83	1.09	0.70				
Parameter deviation	23^*	0.00	1.08	5.59	4.15	1.65	9.3	2.0	14.1	81.0
	$23^\dagger$	0.02	3.82	13.98	5.17	4.00				
Structural deficiency	12^*	0.00	0.79	4.43	2.30	0.86	42.1	1.0	70.0	213.5
	$12^\dagger$	1.32	2.21	3.28	0.60	2.09				
Unknown	4^*	0.00	0.41	0.74	2.34	0.29	45.3	8.0	38.5	70.0
	$4^\dagger$	0.00	1.48	8.16	4.96	0.70				
Vibration	11^*	0.00	0.78	3.33	1.28	0.79	9.9	1.0	26.7	96.0
	$11^\dagger$	0.01	2.48	9.16	3.38	1.91				
Unknown	**12^***	**0.00**	**1.17**	**6.41**	**3.08**	**0.86**	**6.8**	**2.0**	**13.6**	**48.0**
	$12^\dagger$	**0.01**	**4.50**	**17.83**	**6.65**	**2.09**				
External leakage - Utility medium	1^*	0.00	0.21	0.59	1.05	0.07	-	29.0	29.0	29.0
	$1^\dagger$	0.00	0.84	4.67	2.38	0.17				
Other	2^*	0.01	0.15	0.43	0.14	0.14	-	12.0	12.0	12.0
	$2^\dagger$	0.00	0.60	3.14	1.42	0.35				
Unknown	9^*	0.00	0.82	4.48	2.79	0.64	6.8	2.0	12.1	48.0
	$9^\dagger$	0.00	3.20	15.07	6.15	1.57				
All modes	**1949^***	**0.00**	**112.64**	**546.74**	**226.89**	**139.67**	**21.3**	**0.5**	**30.5**	**1025.0**
	$1949^\dagger$	**172.90**	**1277.00**	**3233.73**	**1001.75**	**339.22**				

Comments

On demand probability for consequence class: Critical and failure mode: Fail to start on demand = $1.3 \cdot 10^{-3}$

Taxonomy no		Item		
2.2		Electric Equipment Electric motors		
Population	**Installations**	**Aggregated time in service (10⁶ hours)**		**No of demands**
		Calendar time *	**Operational time †**	
178	16	5.4324	4.3894	6368

Failure mode	No of failures	Failure rate (per 10⁶ hours). Lower	Mean	Upper	SD	n/τ	Active rep.hrs	Repair (manhours) Min	Mean	Max
Critical	**119***	**2.24**	**28.44**	**80.34**	**26.30**	**21.91**	**35.3**	**1.0**	**55.6**	**1140.0**
	119†	**3.36**	**32.75**	**87.95**	**28.11**	**27.11**				
Breakdown	9*	0.16	1.53	4.06	1.29	1.66	12.4	4.0	21.9	45.0
	9†	0.75	1.93	3.54	0.87	2.05				
External leakage - Utility medium	2*	0.00	0.48	2.22	0.89	0.37	34.5	38.0	45.5	53.0
	2†	0.00	0.56	2.19	0.81	0.46				
Fail to start on demand	22*	2.08	3.97	6.36	1.32	4.05	17.2	1.0	27.4	250.0
	22†	0.04	4.77	15.81	5.79	5.01				
Fail to stop on demand	2*	0.00	0.52	2.45	1.00	0.37	11.0	2.0	20.5	39.0
	2†	0.00	0.64	3.02	1.23	0.46				
Low output	13*	0.00	5.89	27.44	11.12	2.39	13.9	1.0	19.2	48.0
	13†	0.00	6.51	31.06	12.76	2.96				
Noise	3*	0.01	0.49	1.51	0.53	0.55	6.3	5.0	26.7	60.0
	3†	0.00	0.58	2.50	0.97	0.68				
Other	5*	0.00	1.31	7.37	3.89	0.92	15.5	3.0	30.6	37.5
	5†	0.00	1.57	8.80	4.64	1.14				
Overheating	2*	0.00	0.44	1.95	0.77	0.37	3.0	2.0	3.0	4.0
	2†	0.00	0.50	1.88	0.69	0.46				
Parameter deviation	4*	0.00	0.66	3.76	2.09	0.74	5.0	2.0	9.5	26.0
	4†	0.00	0.76	4.24	2.22	0.91				
Spurious stop	37*	0.03	13.62	54.22	20.26	6.81	99.1	1.0	145.5	1140.0
	37†	0.03	14.98	60.06	22.52	8.43				
Structural deficiency	11*	0.00	1.13	4.70	1.80	2.02	17.1	4.0	33.2	146.0
	11†	0.19	1.70	4.48	1.42	2.51				
Vibration	9*	0.12	1.32	3.60	1.16	1.66	17.1	4.0	25.4	57.0
	9†	0.14	1.60	4.43	1.44	2.05				
Degraded	**76***	**1.23**	**15.95**	**45.23**	**14.83**	**13.99**	**16.1**	**1.0**	**22.7**	**484.0**
	76†	**1.93**	**18.54**	**49.60**	**15.82**	**17.31**				
Abnormal instrument reading	1*	0.00	0.24	1.31	0.61	0.18	6.0	6.0	6.0	6.0
	1†	0.00	0.28	1.45	0.63	0.23				
Erratic output	4*	0.00	2.15	9.99	4.05	0.74	3.0	3.0	5.8	12.0
	4†	0.00	2.82	13.11	5.30	0.91				
External leakage - Utility medium	7*	0.04	2.13	6.63	2.36	1.29	8.0	1.5	13.6	74.0
	7†	0.10	2.40	7.22	2.43	1.59				
Low output	1*	0.00	0.46	2.45	1.11	0.18	3.5	7.0	7.0	7.0
	1†	0.00	0.53	2.75	1.22	0.23				
Noise	4*	0.00	1.82	9.02	3.83	0.74	3.5	4.0	5.0	6.0
	4†	0.00	1.96	9.83	4.21	0.91				
Other	5*	0.00	2.30	10.59	4.26	0.92	161.0	19.0	174.0	484.0
	5†	0.00	2.49	11.57	4.68	1.14				
Overheating	5*	0.00	0.99	5.07	2.20	0.92	3.0	2.0	3.6	6.0
	5†	0.00	1.15	5.53	2.28	1.14				

Comments

(cont.)

Taxonomy no		**Item**		
2.2		Electric Equipment Electric motors		
Population	**Installations**	**Aggregated time in service (10⁶ hours)**		**No of demands**
		Calendar time *	**Operational time** †	
178	16	5.4324	4.3894	6368

Failure mode	**No of failures**	**Failure rate (per 10⁶ hours).**					**Active rep.hrs**	**Repair (manhours)**		
		Lower	**Mean**	**Upper**	**SD**	***n*/τ**		**Min**	**Mean**	**Max**
Parameter deviation	18*	0.01	2.97	11.94	4.48	3.31	3.9	1.0	6.1	34.0
	18†	0.01	3.57	14.51	5.48	4.10				
Structural deficiency	27*	0.00	2.82	14.56	6.36	4.97	14.3	3.0	27.0	173.0
	27†	0.00	3.51	17.28	7.29	6.15				
Vibration	4*	0.04	0.58	1.67	0.55	0.74	5.5	10.0	11.0	12.0
	4†	0.08	0.72	1.89	0.60	0.91				
Incipient	**80***	**4.39**	**19.93**	**44.69**	**12.88**	**14.73**	**6.9**	**1.0**	**11.4**	**100.0**
	80†	**5.73**	**24.71**	**54.60**	**15.58**	**18.23**				
Abnormal instrument reading	24*	0.93	4.61	10.61	3.11	4.42	6.8	1.0	11.0	100.0
	24†	0.97	5.64	13.51	4.05	5.47				
External leakage - Utility medium	2*	0.00	0.57	2.91	1.26	0.37	5.0	4.0	10.0	16.0
	2†	0.00	0.74	3.85	1.70	0.46				
Minor in-service problems	37*	0.77	7.91	21.52	6.93	6.81	4.7	1.0	6.8	57.0
	37†	0.82	10.02	28.10	9.17	8.43				
Other	6*	0.01	2.27	8.29	3.06	1.10	1.2	1.0	1.4	2.0
	6†	0.01	3.14	11.86	4.37	1.37				
Parameter deviation	3*	0.00	1.04	5.36	2.33	0.55	1.3	1.0	1.3	2.0
	3†	0.00	1.18	6.04	2.61	0.68				
Structural deficiency	4*	0.00	1.08	5.96	3.03	0.74	39.0	77.5	77.5	77.5
	4†	0.00	1.29	7.13	3.61	0.91				
Unknown	3*	0.00	1.52	6.79	2.69	0.55	4.5	1.0	4.7	12.0
	3†	0.00	1.72	7.67	3.03	0.68				
Vibration	1*	0.00	0.46	2.45	1.11	0.18	1.5	1.5	1.5	1.5
	1†	0.00	0.53	2.75	1.22	0.23				
Unknown	**4***	**0.00**	**1.51**	**6.53**	**2.53**	**0.74**	**4.0**	**4.0**	**4.0**	**4.0**
	4†	**0.00**	**1.72**	**7.30**	**2.81**	**0.91**				
Overheating	1*	0.00	0.46	2.45	1.11	0.18	-	-	-	-
	1†	0.00	0.53	2.75	1.22	0.23				
Unknown	3*	0.00	0.87	3.45	1.29	0.55	4.0	4.0	4.0	4.0
	3†	0.00	0.98	3.54	1.31	0.68				
All modes	**279***	**13.12**	**67.45**	**156.55**	**46.12**	**51.36**	**21.4**	**1.0**	**33.3**	**1140.0**
	279†	**20.44**	**79.84**	**171.25**	**47.91**	**63.56**				

Comments

On demand probability for consequence class: Critical and failure mode: Fail to start on demand = $1.7 \cdot 10^{-3}$

Taxonomy no	**Item**
4.3.5	Control and Safety Equipment Valves Gate

Population	**Installations**	**Aggregated time in service (10⁶ hours)**		**No of demands**
		Calendar time *	**Operational time †**	
177	28	6.6856	3.8523	

Failure mode	**No of failures**	**Failure rate (per 10⁶ hours).**					**Active rep.hrs**	**Repair (manhours)**		
		Lower	**Mean**	**Upper**	**SD**	***n/τ***		**Min**	**Mean**	**Max**
Critical	**70***	**0.01**	**7.67**	**31.30**	**11.84**	**10.47**	**6.9**	**1.0**	**9.9**	**66.0**
	70†	**8.46**	**69.57**	**179.79**	**56.22**	**18.17**				
External leakage - Process medium	1*	0.00	0.14	0.42	0.15	0.15	2.0	2.0	2.0	2.0
	1†	0.01	0.24	0.74	0.26	0.26				
Fail to close on demand	34*	0.00	3.03	15.85	7.10	5.09	5.7	1.0	9.7	66.0
	34†	0.03	9.62	37.19	13.74	8.83				
Fail to open on demand	24*	0.00	3.81	16.47	6.39	3.59	8.8	1.0	12.0	60.0
	24†	7.51	66.05	173.11	54.53	6.23				
Other	1*	0.00	0.21	1.16	0.55	0.15	-	-	-	-
	1†	0.00	0.56	2.73	1.13	0.26				
Spurious operation	4*	0.00	0.52	2.29	0.89	0.60	6.3	3.0	6.3	8.0
	4†	0.00	2.17	10.47	4.32	1.04				
Structural deficiency	4*	0.00	0.45	1.72	0.63	0.60	4.3	2.0	4.5	9.0
	4†	0.19	0.95	2.19	0.64	1.04				
Valve leakage in closed position	2*	0.00	0.25	0.83	0.30	0.30	12.5	10.0	12.5	15.0
	2†	0.07	0.48	1.20	0.37	0.52				
Degraded	**76***	**0.00**	**6.52**	**34.27**	**15.48**	**11.37**	**7.5**	**1.0**	**8.1**	**62.0**
	76†	**0.41**	**33.00**	**106.11**	**38.43**	**19.73**				
Abnormal instrument reading	3*	0.00	0.41	2.12	0.92	0.45	4.0	4.0	4.7	6.0
	3†	0.00	1.20	6.51	3.03	0.78				
Delayed operation	4*	0.00	0.61	3.36	1.62	0.60	8.0	12.0	13.5	15.0
	4†	0.02	1.44	4.53	1.62	1.04				
External leakage - Process medium	8*	0.00	2.06	10.10	4.24	1.20	7.3	3.0	8.3	30.0
	8†	4.55	42.37	112.63	35.78	2.08				
External leakage - Utility medium	6*	0.00	0.71	4.08	2.27	0.90	13.8	1.0	15.8	62.0
	6†	0.01	1.79	6.17	2.27	1.56				
Minor in-service problems	1*	0.00	0.21	1.16	0.55	0.15	4.0	4.0	4.0	4.0
	1†	0.00	0.56	2.73	1.13	0.26				
Other	31*	0.00	1.68	5.59	8.24	4.64	4.5	2.0	5.4	23.0
	31†	0.00	4.55	21.68	8.90	8.05				
Spurious operation	2*	0.00	0.25	0.83	0.30	0.30	21.0	7.0	21.0	35.0
	2†	0.07	0.48	1.20	0.37	0.52				
Structural deficiency	1*	0.00	0.14	0.44	0.16	0.15	6.0	6.0	6.0	6.0
	1†	0.01	0.24	0.75	0.26	0.26				
Valve leakage in closed position	20*	0.00	0.93	1.64	5.40	2.99	9.4	2.0	9.4	24.0
	20†	0.00	2.84	13.14	5.30	5.19				
Incipient	**86***	**3.31**	**17.93**	**42.16**	**12.50**	**12.86**	**2.3**	**1.0**	**3.2**	**80.0**
	86†	**130.23**	**288.98**	**498.36**	**114.01**	**22.32**				
Abnormal instrument reading	66*	1.46	14.25	38.28	12.23	9.87	2.3	1.0	3.4	80.0
	66†	112.64	262.36	462.84	108.65	17.13				

Comments

(cont.)

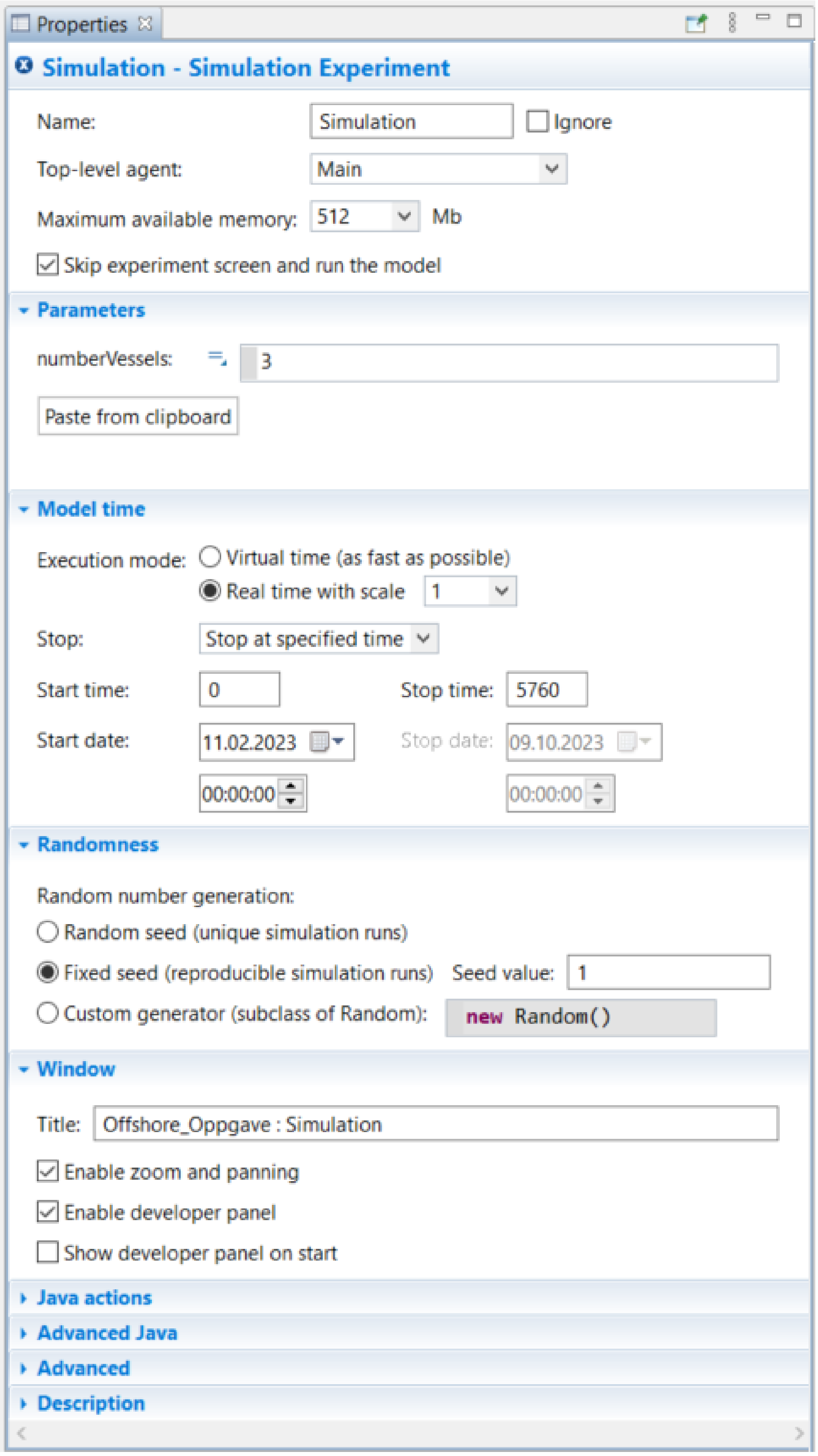
Taxonomy no 4.3.5	**Item** Control and Safety Equipment Valves Gate

Population	**Installations**	**Aggregated time in service (10^6 hours)**		**No of demands**
		Calendar time *	**Operational time †**	
177	28	6.6856	3.8523	

Failure mode	**No of failures**	**Failure rate (per 10^6 hours).**					**Active rep.hrs**	**Repair (manhours)**		
		Lower	**Mean**	**Upper**	**SD**	***n* /τ**		**Min**	**Mean**	**Max**
Delayed operation	2*	0.00	0.35	1.15	0.42	0.30	1.0	1.0	1.0	1.0
	2†	0.06	6.97	23.22	8.51	0.52				
External leakage - Process medium	1*	0.00	0.22	1.20	0.60	0.15	-	3.0	3.0	3.0
	1†	0.00	0.59	2.86	1.20	0.26				
External leakage - Utility medium	7*	0.00	1.59	7.90	3.36	1.05	2.0	1.0	2.6	4.0
	7†	0.26	19.29	61.56	22.21	1.82				
Internal leakage	1*	0.00	0.22	1.20	0.60	0.15	-	4.0	4.0	4.0
	1†	0.00	0.59	2.86	1.20	0.26				
Minor in-service problems	7*	0.44	0.99	1.72	0.40	1.05	2.8	2.0	2.8	3.0
	7†	0.17	1.68	4.55	1.46	1.82				
Other	2*	0.00	0.99	5.45	2.67	0.30	3.0	3.0	3.0	3.0
	2†	0.00	2.20	9.25	3.54	0.52				
Unknown	**8***	**0.01**	**0.86**	**2.73**	**0.99**	**1.20**	**12.2**	**1.0**	**17.8**	**64.0**
	8†	**0.58**	**1.87**	**3.76**	**1.00**	**2.08**				
Unknown	8*	0.01	0.86	2.73	0.99	1.20	12.2	1.0	17.8	64.0
	8†	0.58	1.87	3.76	1.00	2.08				
All modes	**240***	**7.46**	**32.77**	**72.77**	**20.84**	**35.90**	**5.7**	**1.0**	**7.2**	**80.0**
	240†	**185.60**	**401.99**	**685.32**	**154.65**	**62.30**				
Comments										

Appendix C

Modelling



Simulation - Simulation Experiment

Name: Simulation ☐ Ignore

Top-level agent: Main

Maximum available memory: 512 Mb

☑ Skip experiment screen and run the model

Parameters

numberVessels: 3

Model time

Execution mode: ○ Virtual time (as fast as possible)

● Real time with scale 1

Stop: Stop at specified time

Start time: 0 Stop time: 5760

Start date: 11.02.2023 00:00:00 Stop date: 09.10.2023 00:00:00

Randomness

Random number generation:

○ Random seed (unique simulation runs)

● Fixed seed (reproducible simulation runs) Seed value: 1

○ Custom generator (subclass of Random): `new Random()`

Window

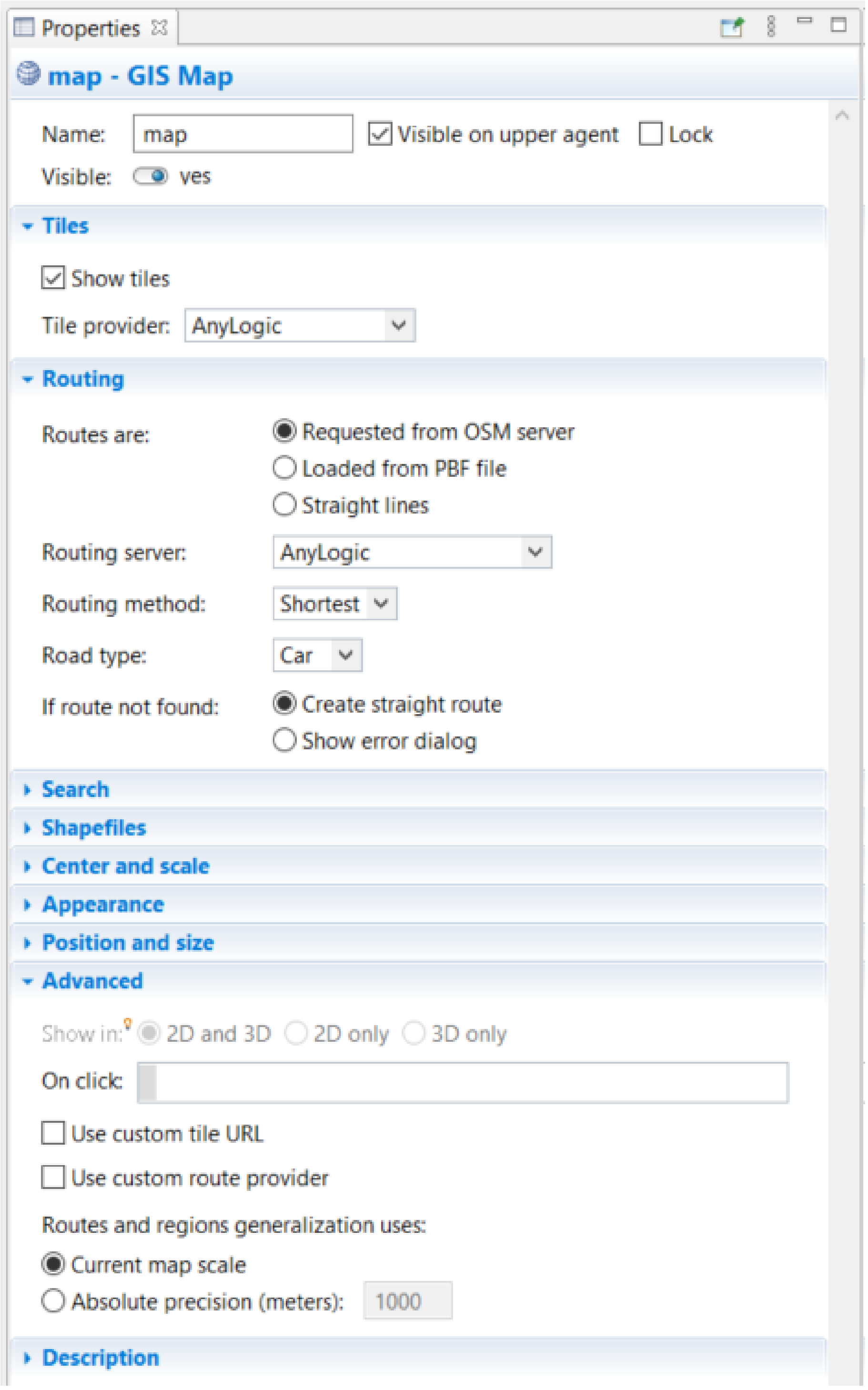
Title: Offshore_Oppgave : Simulation

☑ Enable zoom and panning

☑ Enable developer panel

☐ Show developer panel on start

Figure C.1: *Properties of the agent ’Main’*



map - GIS Map

Name: map ☑ Visible on upper agent ☐ Lock

Visible: yes

Tiles

☑ Show tiles

Tile provider: AnyLogic

Routing

Routes are:
● Requested from OSM server
○ Loaded from PBF file
○ Straight lines

Routing server: AnyLogic

Routing method: Shortest

Road type: Car

If route not found:
● Create straight route
○ Show error dialog

Search

Shapefiles

Center and scale

Appearance

Position and size

Advanced

Show in: ● 2D and 3D ○ 2D only ○ 3D only

On click:

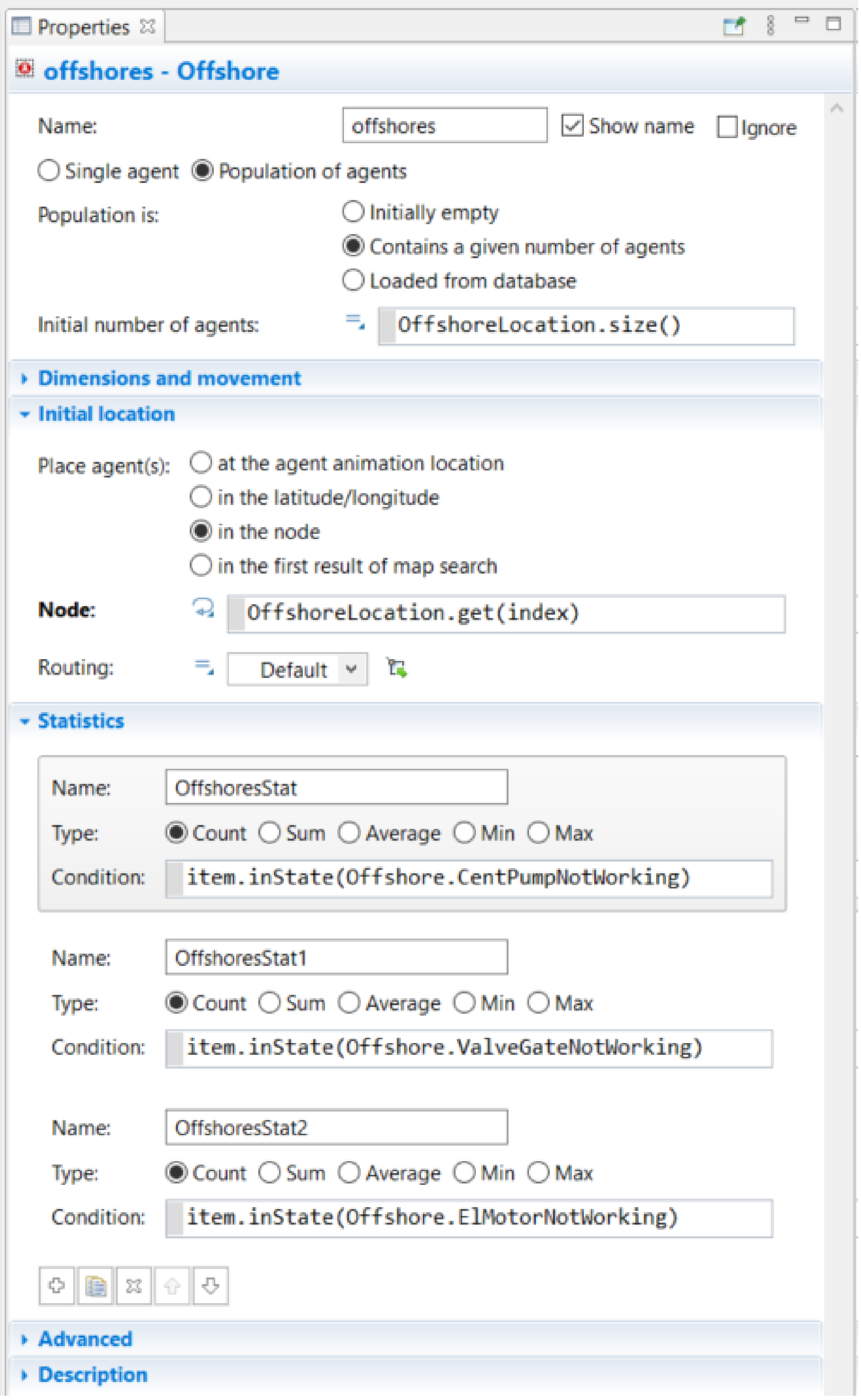
☐ Use custom tile URL

☐ Use custom route provider

Routes and regions generalization uses:
● Current map scale
○ Absolute precision (meters): 1000

Description

Figure C.2: *Properties of the map (GIS).*



Name: offshores ☑ Show name ☐ Ignore

○ Single agent ● Population of agents

Population is:
○ Initially empty
● Contains a given number of agents
○ Loaded from database

Initial number of agents: `OffshoreLocation.size()`

Place agent(s):
○ at the agent animation location
○ in the latitude/longitude
● in the node
○ in the first result of map search

Node: `OffshoreLocation.get(index)`

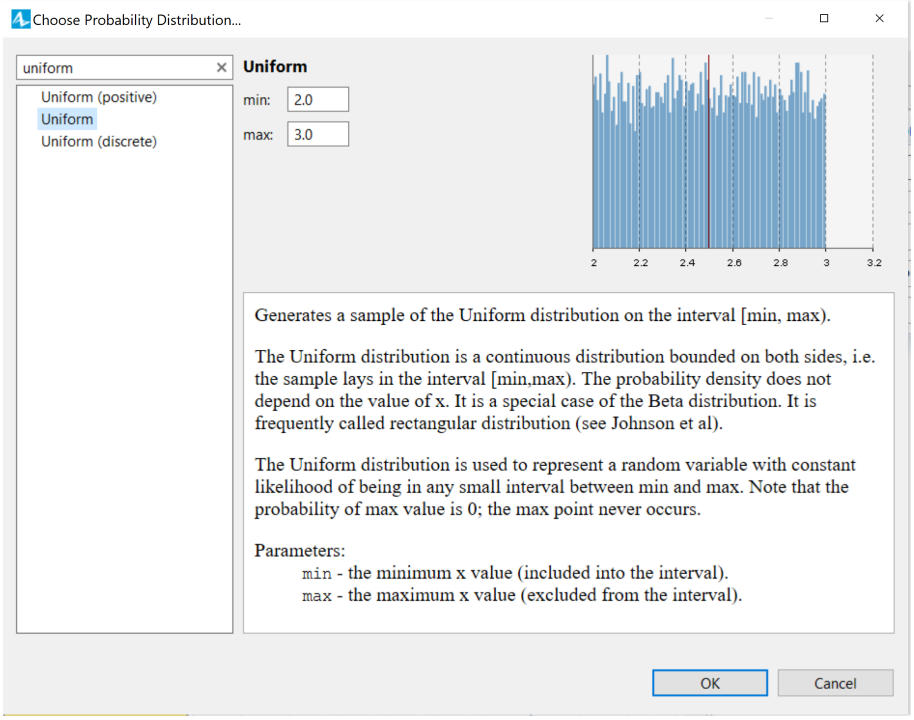
Routing: Default

Name: OffshoresStat
Type: ● Count ○ Sum ○ Average ○ Min ○ Max
Condition: `item.inState(Offshore.CentPumpNotWorking)`

Name: OffshoresStat1
Type: ● Count ○ Sum ○ Average ○ Min ○ Max
Condition: `item.inState(Offshore.ValveGateNotWorking)`

Name: OffshoresStat2
Type: ● Count ○ Sum ○ Average ○ Min ○ Max
Condition: `item.inState(Offshore.ElMotorNotWorking)`

Figure C.3: *Properties of agent 'Offshore'*



uniform

Uniform

min: 2.0

max: 3.0

Generates a sample of the Uniform distribution on the interval [min, max).

The Uniform distribution is a continuous distribution bounded on both sides, i.e. the sample lays in the interval [min,max). The probability density does not depend on the value of x. It is a special case of the Beta distribution. It is frequently called rectangular distribution (see Johnson et al).

The Uniform distribution is used to represent a random variable with constant likelihood of being in any small interval between min and max. Note that the probability of max value is 0; the max point never occurs.

Parameters:
`min` - the minimum x value (included into the interval).
`max` - the maximum x value (excluded from the interval).

Figure C.4: *Probability distribution of the delay.*

Table C.1: ’Hammerfest_warehouse’ State Chart.

Name	Type	Triggered by, code, and explanation
statechart	statechart entry point	–
HOLD_OFF	State	–
check	Transition	Triggered by: timeout Timeout; 1 time per minute This is for checking the stocks every minute
Hold_On	Transition	Triggered by: Condition Condition; Inventory_CentPump <1 Action; hold.setBlocked(true); Once the inventory level of the centrifugal pump ’Inventory_CentPump’ gets below the value of 1, the ’Hold’ block is activated
pumporder	State	–
Hold_Off	Transition	Triggered by: Timeout Timeout; uniform(2, 3) Weeks Action; Inventory_CentPump = 25; It takes two to three weeks to restock inventory to maximum capacity
Hold_On1	Transition	Triggered by: Condition Condition; Inventory_ValveGate <1 Action; hold.setBlocked(true); Once the inventory level of the gate valve ’Inventory_ValveGate’ gets below the value of 1, the ’Hold’ block is activated
valveorder	State	–
Hold_Off1	Transition	Triggered by: Timeout Timeout; uniform(2, 3) Weeks Action; Inventory_ValveGate = 15; It takes two to three weeks to restock inventory to maximum capacity
Hold_On2	Transition	Triggered by: Condition Condition; Inventory_ElMotor <1 Action; hold.setBlocked(true); Once the inventory level of the electric motor ’Inventory_ElMotor’ gets below the value of 1, the ’Hold’ block is activated
motororder	State	–
Hold_Off2	Transition	Triggered by: Timeout Timeout; uniform(2, 3) Weeks Action; Inventory_ElMotor = 2; It takes two to three weeks to restock inventory to maximum capacity

Table C.2: *Discrete Events in 'Wisting_pump' Agent For Obtaining Spare Parts From Johan Castberg Platform.*

Name	Type	Properties , code, and explanation
enter_W_Pump_J	Enter	Agent type; Agent
timeMeasureStart_W_Pump_J	TimeMeasureStart	Agent type; Agent
queue_W_Pump_J	Queue	Agent type; Agent
TraveltimeStart_W_Pump_J	TimeMeasureStart	Agent type; Agent
delay_Movingto_W_Pump_J	Delay	Type; Specified time Delay time; uniform(254, 284) minutes Capacity; Maximum capacity Agent type; Agent It takes approximately 254 to 284 minutes to sail between the Wisting platform and the Johan Castberg platform taking into account adverse environmental weather, with the duration determined by the uniform distribution, as shown in Figure C.4.
Preparing_W_Pump_J	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Agent type; Vessel It usually takes approximately two to three hours to load a vessel, with the duration determined by uniform distribution, as shown in Figure C.4.
seize_W_Pump_J	Seize	Seize; units of the same pool Resource set; vessels_On_Wisting1 Seize policy; Seize whole set at once Capacity; Maximum queue capacity
delay_Movingtback_W_Pump_J	Delay	Type; Specified time Delay time; uniform(254, 284) minutes Capacity; Maximum capacity Agent type; Agent It takes approximately 254 to 284 minutes to sail back from Johan Castberg platform to the Wisting platform and the taking into account adverse environmental weather, with the duration determined by the uniform distribution, as shown in Figure C.4.
Receive_W_Pump_J	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Action –>on exit; send('Pump from johan is on wisting', agent); Agent type; Agent It usually takes two to three hours to receive the order, with the duration determined by uniform distribution, as shown in Figure C.4. At the exit from the delay, it sends a message to the platform (Customer) that the equipment has been delivered.
release_W_Pump_J	Release	Release; All seized resources (of ant pool) Moving resources; Return to home location Wrap-up (e.g. move home); each time 'Wrap-up' usage statistics are; counted as 'busy' Agent type; Agent

TraveltimeEnd_W_Pump_J	TimeMeasureEnd	TimeMeasureStart blocks; TraveltimeStart_W_Pump_J
		Dataset capacity; 100
		Action –>on enter;
		main.TravelTime_Stock = main.TravelTime_Stock + TraveltimeEnd_W_Pump_J.dataset.getYMax();
		main.CO2_Stock = main.CO2_Stock + TraveltimeEnd_W_Pump_J.dataset.getYMax() * main.CO2_KgPerHour;
		main.Cost_CO2_Stock = main.Cost_CO2_Stock + TraveltimeEnd_W_Pump_J.dataset.getYMax() * main.CO2_KgPerHour * main.CO2_Costperhour;
		Agent type; Agent
		
		The code consists of three main parts.
		The first part calculates the total travel time for all trips.
		The second part calculates the total cost of CO_2 emissions for trips.
		Finally, the last part calculates total CO_2 emissions for all trips.

timeMeasureEnd_W_Pump_J	TimeMeasureEnd	TimeMeasureStart blocks; timeMeasureStart_W_Pump_J Dataset capacity; 100 Agent type; Agent
exit_Pump_J	Exit	Agent type; Agent

Table C.3: *Discrete Events in ’Wisting_pump’ Agent For Obtaining Spare Parts From Goliat Platform.*

Name	Type	Properties , code, and explanation
enter_W_Pump_G	Enter	Agent type; Agent
timeMeasureStart_W_Pump_G	TimeMeasureStart	Agent type; Agent
queue_W_Pump_G	Queue	Agent type; Agent
TraveltimeStart_W_Pump_G	TimeMeasureStart	Agent type; Agent
delay_Movingto_W_Pump_G	Delay	Type; Specified time Delay time; uniform(415, 445) minutes Capacity; Maximum capacity Agent type; Agent It takes approximately 415 to 445 minutes to sail between the Wisting platform and the Goliat platform taking into account adverse environmental weather, with the duration determined by the uniform distribution, as shown in Figure C.4.
Preparing_W_Pump_G	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Agent type; Vessel It usually takes approximately two to three hours to load a vessel, with the duration determined by uniform distribution, as shown in Figure.
seize_W_Pump_G	Seize	Seize; units of the same pool Resource set; vessels_On_Wisting1 Seize policy; Seize whole set at once Capacity; Maximum queue capacity
delay_Movingtback_W_Pump_J	Delay	Type; Specified time Delay time; uniform(415, 445) minutes Capacity; Maximum capacity Agent type; Agent It takes approximately 415 to 445 minutes to sail back from Goliat platform to the Wisting platform and the taking into account adverse environmental weather, with the duration determined by the uniform distribution, as shown in Figure C.4.
Receive_W_Pump_G	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Action –>on exit; send(’Pump from Goliat is on Wisting’, agent); Agent type; Agent It usually takes two to three hours to receive the order, with the duration determined by uniform distribution, as shown in Figure C.4. At the exit from the delay, it sends a message to the platform (Customer) that the equipment has been delivered.
release_W_Pump_G	Release	Release; All seized resources (of ant pool) Moving resources; Return to home location Wrap-up (e.g. move home); each time ’Wrap-up’ usage statistics are; counted as ’busy’ Agent type; Agent

TraveltimeEnd_W_Pump_G	TimeMeasureEnd	TimeMeasureStart blocks; TraveltimeStart_W_Pump_G
		Dataset capacity; 100
		Action –>on enter;
		main.TravelTime_Stock = main.TravelTime_Stock + TraveltimeEnd_W_Pump_G.dataset.getYMax();
		main.CO2_Stock = main.CO2_Stock + TraveltimeEnd_W_Pump_G.dataset.getYMax() * main.CO2_KgPerHour;
		main.Cost_CO2_Stock = main.Cost_CO2_Stock + TraveltimeEnd_W_Pump_G.dataset.getYMax() * main.CO2_KgPerHour * main.CO2_Costperhour;
		Agent type; Agent
		
		The code consists of three main parts.
		The first part calculates the total travel time for all trips.
		The second part calculates the total cost of CO_2 emissions for all trips.
		Finally, the last part calculates total CO_2 emissions for all the trips.

timeMeasureEnd_W_Pump_G	TimeMeasureEnd	TimeMeasureStart blocks; timeMeasureStart_W_Pump_G Dataset capacity; 100 Agent type; Agent
exit_W_Pump_G	Exit	Agent type; Agent

Table C.4: *Discrete Events in 'Wisting_pump' Agent For Obtaining Spare Parts From Hammerfest Warehouse.*

Name	Type	Properties , code, and explanation
enter_W_Pump_H	Enter	Agent type; Agent
timeMeasureStart_W_Pump_H	TimeMeasureStart	Agent type; Agent
queue_W_Pump_H	Queue	Agent type; Agent
TraveltimeStart_W_Pump_H	TimeMeasureStart	Agent type; Agent
delay_Movingto_W_Pump_H	Delay	Type; Specified time Delay time; uniform(715, 745) minutes Capacity; Maximum capacity Agent type; Agent It takes approximately 715to 745minutes to sail between the Wisting platform and the Hammerfest warehouse taking into account adverse environmental weather, with the duration determined by the uniform distribution, as shown in Figure C.4.
Preparing_W_Pump_H	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Agent type; Vessel It usually takes approximately two to three hours to load a vessel, with the duration determined by uniform distribution, as shown in Figure C.4.
seize_W_Pump_H	Seize	Seize; units of the same pool Resource set; vessels_On_Wisting1 Seize policy; Seize whole set at once Capacity; Maximum queue capacity
delay_Movingtback_W_Pump_H	Delay	Type; Specified time Delay time; uniform(715, 745) minutes Capacity; Maximum capacity Agent type; Agent It takes approximately 715to 745 minutes to sail back from Goliat platform to the Hammerfest warehouse and the taking into account adverse environmental weather, with the duration determined by the uniform distribution, as shown in the figure.
Receive_W_Pump_H	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Action –>on exit; send('Pump from warehouse is on wisting', agent); Agent type; Agent It usually takes two to three hours to receive the order, with the duration determined by uniform distribution, as shown in Figure C.4. At the exit from the delay, it sends a message to the platform (Customer) that the equipment has been delivered.
release_W_Pump_H	Release	Release; All seized resources (of ant pool) Moving resources; Return to home location Wrap-up (e.g. move home); each time 'Wrap-up' usage statistics are; counted as 'busy' Agent type; Agent

TraveltimeEnd_W_Pump_H	TimeMeasureEnd	TimeMeasureStart blocks; TraveltimeEnd_W_Pump_H
		Dataset capacity; 100
		Action –>on enter;
		main.TravelTime_Stock = main.TravelTime_Stock + TraveltimeEnd_W_Pump_H.dataset.getYMax();
		main.CO2_Stock = main.CO2_Stock + TraveltimeEnd_W_Pump_H.dataset.getYMax() * main.CO2_KgPerHour;
		main.Cost_CO2_Stock = main.Cost_CO2_Stock + TraveltimeEnd_W_Pump_H.dataset.getYMax() * main.CO2_KgPerHour * main.CO2_Costperhour;
		Agent type; Agent
		
		The code consists of three main parts.
		The first part calculates the total travel time for all trips.
		The second part calculates the total cost of CO_2 emissions for all trips.
		Finally, the last part calculates total CO_2 emissions for all trips.

timeMeasureEnd_W_Pump_H	TimeMeasureEnd	TimeMeasureStart blocks; timeMeasureStart_W_Pump_H Dataset capacity; 100 Agent type; Agent
exit_W_Pump_H	Exit	Agent type; Agent

Table C.5: *'Goliat_Pump' State Chart.*

Name	**Type**	**Triggered by, code, and explanation**
statechart_Pump_Goliat	statechart entry point	–
Working_Pump	State	–
Pump_Failure_Rate	Transition	Triggered by: Rate Rate; 1/309.3 time per hour This will be used to create the orders
Check__CentPump	State	–
Check_on_itself	Transition	Triggered by: Condition Condition; true The transition will keep going no matter what
branch	Branch	–
Go_to_repair	Transition	Triggered by: Condition Condition; main.GoliatStock_Offshore_CentPump>0 Action; main.GoliatStock_Offshore_CentPump -= 1; If the pump stock onboard the Goliat platform has a pump as a spare part, subtract one item from them and proceed back to the working state.
Next_Warehouse	Transition	Default (is taken if all other conditions are false)
CentPumpNotWorking	State	Entry action; enter_G_Pump_H.take(this); This code is to take the discrete event that starts with the 'enter_G_Pump_H' block. Exit action; main.Inventory_CentPump -= 1; main.No_of_travels_Hammerfest = main.No_of_travels_Hammerfest + 1; This code is to subtract one item from the stock on the onshore warehouse that belongs to. The second part of the code is to count the number of travels to the Hammerfest warehouse.
Message_to_Warhouse	Transition	Triggered by: message Message type; string Message; 'Pump from warehouse is on Goliat' This transition is the receipt of a message called 'Pump from warehouse is on Goliat' that will change the state of the 'Goliat_Pump'agent from CentPumpNotWorking to normal working condition

Table C.6: *'Goliat_Pump' Discrete event.*

Name	**Type**	**Properties , code, and explanation**
enter_G_Pump_H	Enter	Agent type; Agent
timeMeasureStart_G_Pump_H	TimeMeasureStart	Agent type; Agent
queue_G_Pump_H	Queue	Agent type; Agent
TraveltimeStart_G_Pump_H	TimeMeasureStart	Agent type; Agent
delay_Movingto_G_Pump_H	Delay	Type; Specified time Delay time; uniform(196, 226) minutes Capacity; Maximum capacity Agent type; Agent It takes approximately 196 to 226 minutes to sail between the Goliat platform and the Hammerfest warehouse taking into account adverse environmental weather, with the duration determined by the uniform distribution, as shown in the figure.
Preparing_G_Pump_H	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Agent type; Vessel It usually takes approximately two to three hours to load a vessel, with the duration determined by uniform distribution, as shown in Figure.
seize_G_Pump_H	Seize	Seize; units of the same pool Resource set; vessels_On_Goliat1 Seize policy; Seize whole set at once Capacity; Maximum queue capacity
delay_Movingback_G_Pump_H	Delay	Type; Specified time Delay time; uniform(196, 226) minutes Capacity; Maximum capacity Agent type; Agent It takes approximately 196 to 226 minutes to sail back from Goliat platform to the Hammerfest warehouse and the taking into account adverse environmental weather, with the duration determined by the uniform distribution, as shown in the figure.
Receive_G_Pump_H	Delay	Type; Specified time Delay time; uniform(2, 3) hours Capacity; Maximum capacity Action –>on exit; send("Pump from warehouse is on Goliat", agent); Agent type; Agent It usually takes two to three hours to receive the order, with the duration determined by uniform distribution, as shown in FIGURE. At the exit from the delay, it sends a message to the platform (Customer) that the equipment has been delivered.
release_G_Pump_H	Release	Release; All seized resources (of ant pool) Moving resources; Return to home location Wrap-up (e.g. move home); each time "Wrap-up" usage statistics are; counted as "busy" Agent type; Agent

TraveltimeEnd_G_Pump_H	TimeMeasureEnd	TimeMeasureStart blocks; TraveltimeEnd_G_Pump_H
		Dataset capacity; 100
		Action –>on enter;
		main.TravelTime_Stock = main.TravelTime_Stock + TraveltimeEnd_G_Pump_H.dataset.getYMax();
		main.CO2_Stock = main.CO2_Stock + TraveltimeEnd_G_Pump_H.dataset.getYMax() * main.CO2_KgPerHour;
		main.Cost_CO2_Stock = main.Cost_CO2_Stock + TraveltimeEnd_G_Pump_H.dataset.getYMax() * main.CO2_KgPerHour * main.CO2_Costperhour;
		Agent type; Agent
		
		The code consists of three main parts.
		The first part calculates the total travel time for all trips.
		The second part calculates the total cost of CO_2 emissions for all trips.
		Finally, the last part calculates total CO_2 emissions for all trips.

timeMeasureEnd_G_Pump_H	TimeMeasureEnd	TimeMeasureStart blocks; timeMeasureStart_G_Pump_H Dataset capacity; 100 Agent type; Agent
exit_G_Pump_H	Exit	Agent type; Agent