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Maritime Maintenance Spare Part Inventory Management

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Summary

Transportation has had a significant role in human lives through all the history. People accessed far lands by transportation to connect with others and to access further resources. With respect to the amount and the importance of waterways, the significance of maritime transportation can be understood.

Vessels are one of the most important players in maritime transportation. To have a reliable vessel, it is important to plan for its operation and maintenance. Having a successful maintenance planning needs to prepare for different maintenance tasks. Maintenance tasks can be planned or can be done upon failures. Whatever maintenance tasks should be done on a vessel, there is a need for spare parts. This issue shows the importance of having a comprehensive view on spare parts and their management in maritime maintenance planning.

Spare parts should be available for maintenance tasks. Therefore, they can be delivered to a vessel, or they can be stored on board of a vessel. This shows the significancy of inventory management of spare parts specially on board of vessels when it can be costly to store spare parts on board vessels.

The problem of maritime maintenance spare part inventory management has been mentioned in this thesis. Moreover, this thesis has a focus on preventive maintenance which is considered as planned tasks. Therefore, a mathematical model has introduced to address the problem which has been defined by the collaboration between Molde University College and Star Information Systems as a provider of Enterprise Asset Management Systems (EAM) globally to its customers.

The results show the potential of the model to have an inventory management of the spare part when there is a planning horizon for the maintenance tasks. Inventory management that has been addressed in this thesis considers both on board of vessels and at warehouses as two common places in which an inventory can be considered.

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1.0 Introduction

There are lots of possibilities to transport on waterways both on national and international routes which makes maritime transportation as one of the most significant modes of transportation (UNCTAD 2023). This type of transportation has been considered as an important mode through the history (Rodrigue 2020). In addition, maritime transportation has a great ability to be explored from different perspective in areas of research. These are some important issues which show the significancy of maritime transportation in our today's lives.

Reliability and safety concerns should be respected on vessels when considering the possibility of having maritime transportation. To respect this issue, successful maintenance tasks should be considered for vessels to help them work properly which can avoid failures in the systems. Moreover, a good maintenance should consider detailed planning and a comprehensive view.

Maintenance planning can be divided into two main categories, preventive and corrective maintenances (Zhao and Yang 2018). Preventive maintenances are ones when there is an operating phase of a system, and its goal is to keep an item working in a specific condition. On the other hand, corrective maintenances can be considered when there is a failure in a system (Wang 2002).

However, preventive maintenance is an important part of maintenance planning, it cannot remove failure, so corrective maintenance has also a great importance in maintenance planning (Zhang, Huang, and Yuan 2021).

When a maintenance task comes to an order, there are some necessities for it to be done. One of the most important parts of maintenance tasks is the availability of spare parts. Spare parts can be stored on board of vessels, at warehouses, or can be delivered to a vessel from a supplier.

When there is a possibility to store spare parts for future use in maintenance tasks, inventory management of spare parts should be addressed. The importance of spare part inventory management comes together with the availability of them, and the availability of a vessel as a result which can increase effectivity and performance (Barabadi, Barabady, and Markeset 2014).

The demand for spare parts is related to other factors like maintenance issues and can be different over time (Wagner, Jönke, and Eisingerich 2012). A way to be secure from this change is to have some spare parts in stock (Şahin, Eldemir, and Turkyilmaz 2021). Moreover, the number of items in inventory can be huge due to different demands (Altay Guvenir, and Erel 1998). It can be possible to minimize the number of spare parts, however, this issue should not make a vessel to lose its availability (Basten and van Houtum 2014). Also, lack of sufficient spare parts can increase the risk of failure in a vessel which is an important issue to be considered (Eruguz, Tan, and Houtum 2018). On the other hand, an excess number of spare parts can result in higher holding costs (Lin et al. 2017).

The inventory management of the spare part in maritime transportation has been considered in this thesis. The thesis introduced a mathematical model to find an optimal solution for the problem. The problem has been defined based on the collaboration between Molde University College and Star Information company on issues that customers of the company are facing. Moreover, the thesis has emphasized on preventive maintenance as an important type of maintenance in maritime spare part inventory management.

1.1 Thesis Objective

The objective of this thesis is to expand on the following research questions and to elaborate them in the most proper way.

- How can the spare part inventory management affect maritime maintenance planning in the maritime industry?
- How can spare part inventory management have an optimal approach for the problems related to maintenance tasks?

1.2 Thesis Structure

The following thesis has been structured into six different chapters. Also, there is an appendix at the end of the thesis that can be used to get more information about the study.

The first chapter is an introduction that explains the importance of the thesis and the way to go toward by defining the research questions and finding a solution for them.

The second chapter is a literature review on the spare part inventory management which helped the authors to find an approach for addressing the research problem.

The third chapter explains the problem of this thesis which has been made based on the discussion between the authors and Star Information Company.

The fourth chapter talks about the methodology, and it presents a mathematical model to solve the explained problem.

The fifth chapter explains different instances to test the presented mathematical model which have been introduced by the authors of the thesis. Also, the results from the mathematical modeling have been discussed, and the thesis's findings has been elaborated and explained in this chapter.

The sixth chapter introduces conclusions of the thesis. Also, the limitations of the research have been explained, and possible areas for future research to expand the results of this research has been suggested in this chapter.

2.0 Literature Review

Maritime maintenance and spare part inventory management is the focus of this thesis. In this section related literature to this topic has been reviewed. Literatures show the importance of maritime maintenance in decision makings. Moreover, preventive, and corrective maintenance have been mentioned in the literatures as two types of maintenance tasks. Also, the spare part management was addressed in the literatures as an important issue in maintenance planning.

This thesis has significant attention on finding a connection between maintenance tasks in maritime industry and inventory management of spare parts. This issue is the other important aspect of the literature review. Therefore, the literature review has designed to make the connection by reviewing optimization approaches. Finally, this section introduced a gap in literatures which this thesis worked on them.

2.1 Importance of Maritime Maintenance

Maintenance can increase the efficiency of a vessel and the reliability of its services. Moreover, decisions related to maritime maintenance have a significant effect on other players in a vessel's operation.

Maintenance is a significant part of a vessel's life cycle cost which brings great attention to its efficiency. Also, maintenance's cost includes different other costs from spare parts to personnel costs (Schuh et al. 2015). Moreover, there is a direct relationship between the age of a vessel and maintenance cost (Kimera and Nangolo 2019) which emphasizes on the maintenance importance. Turan et al. (2009) introduced a model to consider the costs through a vessel's life cycle. They presented the maintenance cost as a significant part of the life cycle that includes be about a third of the whole life cycle cost. They showed the significancy of optimization on maintenance cost and its effect on the other parts of a vessel's operation.

There are two major groups of maintenance tasks for a vessel on the literatures, corrective and preventive. Corrective maintenances are implemented when there is an unexpected failure in the system. On the other hand, preventive maintenance tasks are done based on a schedule planning. This thesis worked on preventive maintenances and the related spare part inventory management.

2.2 Preventive Maintenance

One of the most important types of maintenance in maritime industry is preventive which is done on a schedule. The goal of having this type of maintenance is to prevent any disruption due an expected failure. There are different challenges related to preventive maintenance such as availability of professional personnel to do the maintenance tasks, the number of needed spare parts on a vessel, storage of spare parts, and spare part inventory management on storage locations both on seas and on lands.

Pillay et al. (2001) defined of preventive maintenance considering the analysis of the delayed time of the operation. They defined delayed time as the time from the first sign of a failure to the time of when a failure happened. Also, they discussed the reduction of the time between two inspections which shows the significant role of preventive maintenance tasks in operational phase.

Preventive maintenance can be optimized based on their intervals and related spare parts which can help decision makers to consider economic aspects (Lanza, Niggeschmidt, and Werner 2009).

Sustainability consideration can be another way of thinking in preventive maintenance and spare parts analysis. Franciosi, Lambiase, and Miranda (2017) tried to consider sustainability in maintenance and spare part selection through their modeling of preventive maintenance with different considerations. Reducing emissions to the environment can be one of the most important aims of preventive maintenance. When the vessel works well, there can be fewer greenhouse gas (GHG) emissions to the environment. Liu et al. (2022) introduced a model to optimize maintenance tasks based on environmental aspects of a vessel operation. Engine performance in different situations like windy weather was an important issue on their study which can shows the emission of GHG to the environment.

2.3 Spare Part Management

Spare parts have an important role in maritime maintenance. Reliability and availability of spare parts are crucial for a vessel. With respect to available assets for a maritime transportation company, spare parts can be stored on warehouses or on board of vessels. Moreover, spare parts can be restocked to each location by suppliers directly in case of need. Spare part management can help vessels to work reliably and safely. The cost of maintenance tasks can be decreased by a proper spare part management. Moreover, the chance of failure due to lack of spare parts can be decreased by the spare part management. Rinaldi et al.

(2023) worked on spare part management and showed a relationship between the total cost and maximum number of spare parts storages by their proposed procedure. This research shows the importance of spare part management in asset management.

Delivery of spare parts is a crucial step in spare part management. A Proper delivery plan can increase the reliability of vessel, and can decrease the cost of delivery. Wagner, Jönke, and Eisingerich (2012) considered logistical issues to present a strategic framework for spare part management which can be used in different businesses and problems which. This research shows the possibility of planning for spare part management based on logistical issues. In other research, Vukić et al. (2021) introduced an optimal way to deliver spare parts to vessels. They defined the problem of spare parts delivery into different scenarios when a different type of transportation has been considered. Also, they defined a routing solution for vessels to be considered with the spare part delivery. Their study shows the importance of the availability of spare parts for shipping companies. Also, it shows the connection between different parts of a supply chain to make spare parts available and accessible.

Spare parts are needed in different numbers and kinds which can be forecasted based on available information. Wang and Syntetos (2011) presented an approach to forecast the spare parts demand based on different approaches which shows the importance of demand information on the performance of spare part inventory management. Forecasting demand can be challenging when there is a need for considering different issues. Van der Auweraer and Boute (2019) considered maintenance plan and failure behavior of the system to forecast the demand for spare parts which shows the importance of information for the forecasting.

The number of spare parts in the maritime industry can be huge which brings complexity to the spare part management. This issue can be addressed by grouping the spare parts and making the problem smaller in terms of complexity. Sheikh-Zadeh, Farhangi, and Rossetti (2020) proposed a model for spare parts management by grouping them and showed the importance of grouping for the inventory management of spare parts. Cakmak and Guney (2023) worked on spare part classification which can decrease the time of inventory management.

However, increasing holding cost by excess spare parts storage is not an ideal situation, having a stock-out possibility is not preferable too. A stock-out situation can lead to high penalty costs (Turrini and Meissner 2019). There is an option of ordering spare parts at the right time to make a balance between these two situations. Zheng et al. (2023) considered ordering and maintenance optimization together to consider this possibility. Anglou, Ponis, and Spanos (2021) presented an approach for maritime transportation companies to have better management on their orders. They showed the effect of ordering strategy on maintenance cost, and failure in the system. Different factors have been considered in their presented approach to investigate on their effects such as choosing suppliers which is significant in cost estimation of their solution. This research shows significant effect of choosing suppliers which. This issue is considerable while there is a need for cost reduction and having a level of quality for spare parts. Also, it has an important effect on the inventory management of spare parts.

Storage of spare parts both on board of vessels and in warehouses are costly. This issue should be considered specially when there is a need for availability of spare part for maintenance tasks in defined periods. Nenni and Schiraldi (2013) presented an optimized approach for minimizing the inventory cost of spare parts by respecting storage cost and the level of service. This research shows the significancy of inventory management as an important part of spare part management.

New technologies such as additive manufacturing can play an important role in spare part management. Additive manufacturing in maritime industry can help to have better control over the spare part management. Also, it can increase the reliability and availability in spare part management. Kostidi, Nikitakos, and Progoulakis (2021) presented an approach to produce spare parts by additive manufacturing. Their research considers reductions in space of storage and overall cost. This study shows the possibility of considering new technologies in spare part management which can improve the availability and reliability of them for different purposes.

Spare parts can be repaired for future use, and this issue can be considered in the spare part management. Repairing is a time and cost consuming task. Therefore, it can be planed based on different criteria. Sleptchenko, Heijden, and Harten (2005) presented an approach to plan repairing tasks of spare parts based on prioritizing which can reduce the time and cost for repairing tasks and show the importance of this issue in spare part management.

Sustainability concerns are important issues in spare part management which can be respected by mangers in different levels. Driessen et al. (2014) showed the importance of spare part management in a supply chain which can increase the efficiency of the processes. In another research, Pater and Mitici (2021) showed their maintenance planning model has cost reduction of maintenance while dealing with a limited stock level of spare parts.

Spare parts should be chosen to respect their availability and reliability which brings different challenges for manager such as logistical considerations. Huiskonen (2001) presented an approach to respect logistical concerns in spare part management such as demand, spare parts' level of criticality. This study shows an important role of logistical consideration in spare parts management.

2.4 Maintenance Optimization

Maintenance is an important part of a vessel's lifetime. Moreover, the significancy of it on spare parts management in maritime industry should be investigated. Maintenance tasks can be optimized to improve their efficiency. Maintenance optimization can consider logistical challenges such as time to perform maintenance tasks, and operational delay time due to failure of performing in these tasks.

One of the aspects of maintenance optimization is maintenance planning. Kian, Bektas, and Ouelhadj (2018) presented an approach to schedule maintenance tasks based on a mathematical model. Place and time to perform maintenance tasks was a focus of their research. The accuracy of failure prediction was also a point of their attention in their sturdy. This research shows a significant role of maintenance scheduling in optimization of cost and time when there is a need for them in spare part management.

Since maintenance and spare part management has a close relationship, it is a good approach to consider them together when trying to analyze the inventory of spare parts. Wang (2011) tried to present a mathematical optimization model which considers maintenance and spare parts connection to show the importance of their relation. Combining maintenance and spare part management has been addressed in different research. Abderrahmane et al. (2022) considered maintenance and spare part management simultaneously in a finite time horizon and found the optimal number of maintenances. In another research, Eruguz, Tan, and Houtum (2018) presented an approach to consider spare part management and maintenance tasks. Their approach includes minimizing of the total cost, by considering delivery, replacement, and storage of a single spare part. They made a conclusion based on the number of spare parts on board of vessels, and investigation on effectiveness of the process. This study shows an importance of considering spare part management on maintenance tasks in efficiency of the operational phase of a system.

Considering maintenance with spare part management can provide reliability to the system (Fan et al. 2023). However, this issue can be challenging for managers because of the complexity of the problem, it can make the solution more practical and possible to be used for different cases.

Maintenance optimization can deal with uncertainties that can affect the cost, resources, and time. In maritime maintenance, there is a possibility to have uncertainties of different kinds.

Uncertainties can have significant effects on maritime maintenance optimization. Manea, Zăgan, and Manea (2021) presented an approach based on stochastic considerations and different uncertainties such as limitation in cost and labor resources. This study shows the possibility of including uncertainties in maritime maintenance optimization for spare part management when their effects can be considerable.

Maintenance optimization together with inventory management of spare parts brings the importance of maintenance planning. Basten and Ryan (2019) tried to figure out the effect of delayed maintenance based on time, and the inventory management of spare parts while considering costs.

2.5 Spare Part Inventory Optimization

Spare part inventory optimization has been mentioned in different areas of research with different purposes. One of the most important objectives of the optimization is to find an optimal stock level of spare parts. Since spare parts can be used for maintenance issues, the number of them has close relation with the maintenance (Hu et al. 2018).

Spare parts inventories of the maritime industry can be connected to each other by different sources from vessels to warehouses which can increase the availability of them. Zhu and Zhou (2023) showed the possibility of having multiple inventories with different levels of spare parts which can be useful in different industries.

Louit et al. (2011) considered three main optimization criteria in inventory management as minimizing cost, maximizing availability, and achieving considered reliability. Also, they made assumptions for demand rates for their models of optimization. Zhang et al. (2022b) made their inventory optimization model based on the objectives of having the minimum inventory level of spare parts and minimum total cost which consists of different costs such as cost of transportation, cost of inventory holding, and time-related cost.

Transportation costs can be important when considering inventory optimization. Levner et al. (2011) considered the inventory optimization of the spare parts with the transportation cost of the spare parts to show the significancy of that.

Spare part inventory management on a vessel can be optimized with the other important player in asset management such as maintenance. Eruguz, Tan, and van Houtum (2017) considered an optimized integrated approach for maintenance and spare part inventory. They minimized the cost of delivery of spare parts, replacement of spare parts, and inventory holding. In another research, Jiang, Chen, and Zhou (2015) considered maintenance and inventory management together as a part of their optimization approach while facing with deterioration of the spare parts. They considered maximum inventory level and replacement of spare parts in preventive intervals as decision variables. Also, Zhang et al. (2022a) considered maintenance and spare part inventory optimization together, and they showed the importance of inspection on the maintenance which can have a significant effect on the optimization approach.

The number of spare parts is quite significant on a vessel which brings complexity to optimization approaches for their inventory level. Finding a way to categorize them can help us to focus more on the most important ones. Ben Hmida, Regan, and Lee (2013) categorized the most critical spare parts and related maintenance which can help to reduce the cost of downtime in case of a failure. Muniz et al. (2020) found a way of minimizing the inventory level and maximizing the criticality of spare parts to show the importance of inventory management of spare parts.

Demand can be affected by different variables from maintenance tasks to failure in the system (Aktepe, Yanık, and Ersöz 2021). Maintenance has a significant effect on the demand for spare parts. Zhu, Jaarsveld, and Dekker (2020) tried to forecast the demand for the spare part due to planned maintenance and estimate the cost due to traditional methods which show the importance of considering maintenance planning in spare part demand analysis.

2.6 Thesis Focus Based on Reviewed Literature

After doing literature review for the thesis, some gaps and similarities found with respect to the defined problem. Similarities helped the authors to find an approach to fill the considered gaps.

Understanding the possibility of having inventory management of spare parts which are used for maintenance tasks is one of the most important similarities of this thesis with the literatures. Also, there are different factors in literatures as the objective of the inventory management which has been considered in the optimized approach introduced by this thesis. Moreover, spare part selection on the literatures gave the authors of this thesis an idea to focus their study on specific spare parts which is also useful in maritime industry, and can be implemented in different problems.

This thesis emphasis on gaps in literatures with respect to the defined problem. Moreover, it was made based on the spare part inventory management problem in maritime industry which has mentioned few times in the literatures with limited investigations, and the thesis has a novelty in this area to directly address the problem with a comprehensive view. In addition, the thesis introduced a mathematical model with an optimize approach to find the solution for spare part inventory management in maritime maintenance which is another innovation of the thesis. Furthermore, this thesis presented an approach which can be used in different problems related to inventory management of spare parts in maritime maintenance, and the model has an ability to extend based on variety of the problems.

3.0 Problem Description

Star Information Systems has some liner shipping company as its customers who has defined routes for their ships and schedules to travel between different ports. On each port visit, each vessel can pick up and/or deliver goods and people. Also, each vessel can receive different services at a port. In other words, the routes are fixed, and the periods has been defined on schedules in advance. Figure 1 illustrates an example of a liner service for a shipping company. In this example there are 13 ports to visit, the duration of sailing the whole route is fixed and 42 days. Moreover, the route, and the port visits are fixed and can be asked in advance. Also, the distance and duration between different ports are predefined.

Figure 1. An example of a liner shipping service (CAM CGM, North Europe French West Indies 2023)

For each vessel the maintenance tasks are planned. Also, they can be asked in times of failures. A good strategy to be prepared for maintenance tasks is to make sure there are enough spare parts for maintenance tasks. Moreover, it is important to know where, and how much of each spare part is stored which can be accessible in time.

This problem has focus on inventory management of spare parts. The spare parts can be stored eighter on board of vessels, or at the customer's warehouses.

Finding the solution is a complex task considering the number of spare parts and their criticality level. Also, having an optimal number of each spare parts for maintenance purposes has a great impact on customers' costs.

The goal is finding the optimal number of spare parts on board of vessels and at the customers' warehouses. Moreover, the problem has a focus on planned (preventive) maintenance, and the inventory management of spare parts related to the considered maintenance.

The other issue is that there is a need to optimize spare parts on a vessel which should also consider the safety issue when some critical spare parts (e.g., communication equipment, power supply, propulsion/engine) are needed. In other words, it is important to have a minimum number of each spare part on a vessel, however, there is a maximum level of them while storage of spare parts on a vessel are costly, and there is a storage limit on each vessel which is important to be respected. Moreover, each vessel has a plan to stop at different ports which may or may not have access to the customers' warehouses.

The problem has been defined based on a situation when there is a spare part needed for different maintenance tasks. Also, the number of spare parts can be different in each maintenance task. Moreover, there are different vessels which require the considered spare part for their needs.

The maintenance tasks which have been considered in this problem have different due dates to be done. Also, the due dates of different maintenance tasks can have overlapped with each other for different vessels. It has been considered planned maintenance to be done on its due date to avoid the possibility of having a corrective maintenance in the future.

As mentioned earlier, the spare parts can be stored on board of vessels and in warehouses. Also, they can be ordered and delivered directly to each vessel from a supplier if there is a need for that. Moreover, storage on board of a vessel and warehouses has been differentiated in this problem by different storage costs, and upper and lower limits for storage.

The maintenance tasks can be done on a vessel while it is at sea, or when it is at a port. Moreover, the needed number of spare parts can be used directly from a vessel storage, a warehouse storage, directly from the supplier, or any combination of these three places. This problem has considered all the possible sources of delivery of a spare part for a maintenance task.

The other important aspect of this problem is the initial level of inventory of spare parts on each vessel and warehouse which has been defined, and it is an important consideration to find the number of stored spare parts due to the related maintenance.

The problem has considered known values for inventory costs either on board of vessels or at the warehouses. Also, the restocking cost to vessels eighter from warehouses or supplier has been known. Moreover, this problem has considered different values for the cost of maintenance tasks either by vessels' crew and their facilities or by personnel of a port and their facilities. In addition, the cost of performing maintenance can be different on different ports and different vessels.

In this problem the cost of a maintenance task depends on the time of its execution. It is not ideal to have a maintenance task too early or too late. When a maintenance task is done correctly on a vessel, it guarantees the operation of the related part for a period, and having a same maintenance task in this period is not efficient. On the other hand, having a maintenance task too late after finishing this period may cause a failure in the system which is also not an ideal situation for a vessel. Therefore, in this problem the maintenance tasks have defined in relationship with their time of executions on a vessel.

The most important decision in this problem is the number of stored spare parts on board of vessels and in warehouses. Moreover, the number of restocking spare parts from warehouses to a vessel, from supplier to a vessel, and from supplier to warehouses has been considered as another important decision in this problem.

Table 1 shows the available information and decisions to be made for the described problem which has been used to find a solution.

Table 1. Major Parameters and Variables

Available Information	**Decisions**
Planning time Horizon	Inventory Level on Each Vessel
List of Ports, Vessels, and Maintenances	Inventory Level at Each Warehouse
Location of Vessels	Restocking Source Location
Number of Spare Parts needed per Maintenance	Number of Restocking Spare Parts
Initial Inventory Level	Source of Using Spare Parts
Inventory Cost	Number of Using Spare Parts
Restocking Cost	Location of Using Spare Parts
Maintenance Cost	Location of Having Maintenance
Upper and Lower Storage Limits	Time of Performing Maintenance

Understanding the flow of spare parts is an important part of the problem. This flow has been depicted in Figure 2 which explains where the spare parts can be stored and delivered.

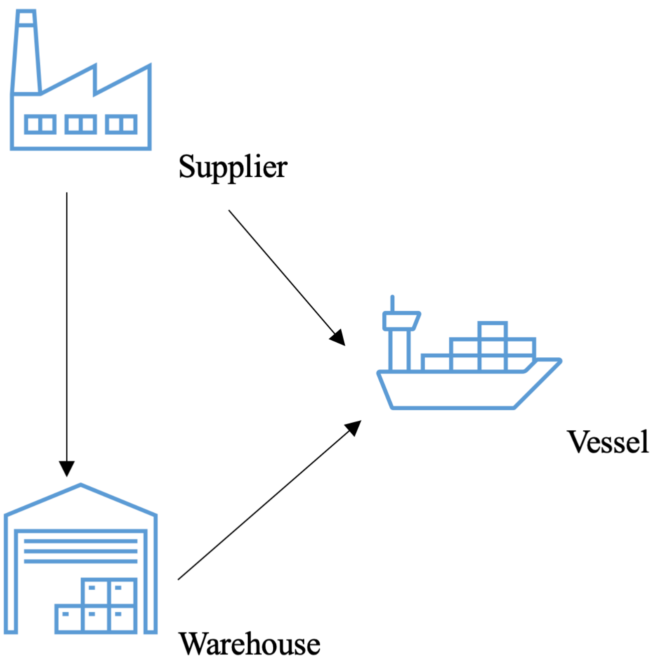

Figure 2. Spare Parts Flow

The flow of spare parts gives a view on different aspects of the problem. It shows the connection between information and decisions to be made for the problem which shows its significancy in the defined problem.

4.0 Data and Methods

Maritime spare part inventory management has been considered with mathematical modeling and an optimization approach for the described problem in this thesis. The data has been generated based on problem explanation by Star Information Systems and the considered issues by the authors of this thesis.

In this chapter, first, the notation of the mathematical modeling has been described. Then, the mathematical model has been elaborated.

4.1 Notation

Based on the explained problem for this thesis, the following notation has been considered to explain the model. Moreover, the role of each notation has been classified into different categories to explain the relationships between different characters. Also, the planning horizon has been divided into equal periods.

4.1.1 Sets

The following sets have been considered for the mathematical modeling.

$T = \{1,2,...,H\}$, set of equal time periods unit which makes the whole planning horizon.

P, set of ports which a vessel can visit to receive or deliver service, passengers, and goods.

V, set of vessels that can travel between different destinations.

M_v, set of maintenance tasks which is done on the vessel v, $v \in V$.

4.1.2 Parameters

Based on considered sets for the mathematical model, the following parameters have been considered for the model.

H, the number of time periods units that has been considered in the model to make the maintenance planning horizon.

I_{0v}^{V}, an initial inventory level of the considered spare part on board of each vessel, $v \in V$.

I_{0p}^{W}, an initial inventory level of the considered spare part at a warehouse at a port, $p \in P$.

L_{tpv}, location of each vessel in each time periods, and based on the defined location of ports, each vessel can either visit a port or sailing on a sea. $t \in T$, $p \in P$, $v \in V$.

N_{vm}, number of spare parts which has been needed to be used for a considered maintenance for on a considered vessel, $v \in V$, $m \in M_v$.

C_v^{IV}, inventory cost for having a considered spare part on board of a vessel, $v \in V$.

C_p^{IW}, inventory cost for having a considered spare part at a warehouse at a port, $p \in P$.

C_p^{RV}, restocking cost of a spare part from a supplier directly to a vessel when the vessel visits a port, $p \in P$.

C_p^{RW}, restocking cost of a spare part from a supplier to a warehouse at a port, $p \in P$.

C_p^{RWV}, restocking cost of a spare part from a warehouse at a port to a vessel visiting the port, $p \in P$.

C_v^{MV}, maintenance cost for tasks done by a vessel's crew and their facilities, $v \in V$.

C_p^{MP}, maintenance cost for tasks done by port's personnel and their facilities, $p \in P$.

C_t^{MT}, maintenance cost based on a chosen time period to be done, $t \in T$.

I_v^{maxV}, the maximum number of spare parts which can be stored on board of a vessel, $v \in V$.

I_p^{maxW}, the maximum number of spare parts which can be stored at a warehouse at a port, $p \in P$.

I_v^{minV}, the minimum number of spare parts which should be stored on board of a vessel, $v \in V$.

I_p^{minW}, the minimum number of spare parts which should be stored at a warehouse at a port, $p \in P$.

4.1.3 Variables

Based on the defined problem on this thesis, the following variables have been considered to elaborate the mathematical model.

I_{tv}^{V}, the inventory level of a vessel in a period, $t \in T$, $v \in V$.

I_{tp}^{W}, the inventory level of a warehouse in a period, $t \in T$, $p \in P$.

X_{tpv}^{RV}, number of a spare parts to be restocked at a period from a supplier directly to a vessel when the vessel visits a port, $t \in T$, $p \in P$, $v \in V$.

Y_{tpv}^{RV}, the binary variable of a spare part to be restocked at a period of time from a supplier directly to a vessel when the vessel visits a port, $t \in T$, $p \in P$, $v \in V$. 1 if it is restocked, 0 otherwise.

X_{tp}^{RW}, number of a spare parts to be restocked at a time period from a supplier to a warehouse at a port, $t \in T$, $p \in P$.

Y_{tp}^{RW}, the binary variable of a possibility of a spare part to be restocked at a period from a supplier to a warehouse at a port, $t \in T, p \in P$. 1 if it is restocked, 0 otherwise.

X_{tpv}^{RWV}, number of a spare parts to be restocked at a period from a warehouse at a port to a vessel visiting the port, $t \in T, p \in P, v \in V$.

Y_{tpv}^{RWV}, the binary variable of a spare part to be restocked in a period from a warehouse at a port to a vessel visiting the port, $t \in T, p \in P, v \in V$. 1 if it is restocked, 0 otherwise.

X_{vmt}^{MV}, number of spare parts coming from storage on board of a vessel to be used for a maintenance task at a period, $v \in V, m \in M_v, t \in T$.

Y_{vmt}^{MV}, binary variable of having a maintenance task on a vessel with the vessel's crew and their facilities at a period, $v \in V, m \in M_v, t \in T$. 1 if done by vessel's crew and facilities, 0 otherwise.

X_{vpmt}^{MW}, number of a spare parts coming from storage at a warehouse at a port of to be used for a maintenance task at a period, $v \in V, p \in P, m \in M_v, t \in T$.

Y_{vpmt}^{MP}, the binary variable of having a maintenance task on a vessel by port's personnel and facilities when a vessel visits a port at a time period, $v \in V, p \in P, m \in M_v, t \in T$. 1 if it is done by port's personnel and facilities from a warehouse, 0 otherwise.

4.2 Mathematical Model

Based on what has been defined earlier in this thesis, the following mathematical model has been defined to explain the problem and to find an optimal solution for it. Also, the mathematical model has been written based on the notation which has been earlier described.

$$\begin{aligned} min \sum_{t \in T} \sum_{v \in V} I_{tv}^{V} C_{v}^{IV} &+ \sum_{t \in T} \sum_{p \in P} I_{tp}^{w} C_{p}^{Iw} + \sum_{t \in T} \sum_{p \in P} \sum_{v \in V} X_{tpv}^{RV} C_{p}^{RV} \\ &+ \sum_{t \in T} \sum_{p \in P} X_{tp}^{RW} C_{p}^{RW} + \sum_{t \in T} \sum_{p \in P} \sum_{v \in V} X_{tpv}^{RWV} C_{p}^{RWV} \\ &+ \sum_{v \in V} \sum_{m \in Mv} \sum_{t \in T} Y_{vmt}^{MV} C_{v}^{MV} \\ &+ \sum_{v \in V} \sum_{p \in P} \sum_{m \in Mv} \sum_{t \in T} Y_{vpmt}^{MP} C_{p}^{MP} \\ &+ \sum_{v \in V} \sum_{m \in Mv} \sum_{t \in T} Y_{vmt}^{MV} C_{t}^{MT} \\ &+ \sum_{v \in V} \sum_{p \in P} \sum_{m \in Mv} \sum_{t \in T} Y_{vpmt}^{MP} C_{t}^{MT} \end{aligned} \tag{1}$$

This mathematical expression describes the objective function of the mathematical model based on defined variables, and parameters.
First, this function considers inventory costs on board of each vessel and each warehouse. Second, it covers restocking costs from a supplier to each vessel, from a supplier to each warehouse, and from each warehouse to each vessel. Third, it takes into account the maintenance cost for each vessel based on the crew's main location. Finally, it considers the maintenance cost based on the period to choose for the maintenance to be done.

Subject to

$$I_{tv}^{V} \leq I_{v}^{maxV} \qquad t \in T, v \in V \qquad (2)$$

This constraint helps to make sure the number of spare parts on board of a vessel never exceeds the considered upper limit for this spare part.

$$I_{tp}^{W} \leq I_{p}^{maxW} \qquad t \in T, p \in P \qquad (3)$$

In this model, it has been considered the number of spare parts at each warehouse at a port never exceeds the capacity of the spare part in the inventory of the warehouse.

$$I_{tv}^{V} \geq I_{v}^{minV} \qquad t \in T, v \in V \qquad (4)$$

The number of spare parts on board of a vessel should never drop below the lower limit for this part at the vessel which has been considered by this constraint.

$$I_{tp}^{W} \geq I_{p}^{minW} \qquad t \in T, p \in P \qquad (5)$$

A spare part has a lower inventory level at each warehouse at a port which should be never touched, and this constraint respects this issue.

$$I_{tp}^{W} = I_{tp}^{W} + X_{tp}^{RW} - \sum_{v \in V} X_{tpv}^{RWV} - \sum_{v \in V} \sum_{m \in Mv} X_{vpmt}^{MW} \qquad t \in T, p \in P \qquad (6)$$

The inventory level of a spare part at each warehouse at a port at each period has been considered to be related to the previous time period. Also, each warehouse can receive spare parts from a supplier in each period. Moreover, spare parts can be sent from a warehouse to a vessel for a maintenance task, and to restock the inventory on board of the vessel. All these considerations have been respected by this constraint.

$$X_{tp}^{RW} \leq I_p^{maxW} Y_{tp}^{RW} \qquad t \in T, p \in P \qquad (7)$$

This constraint helps to have the number of spare parts which sends to each warehouse at a port from a supplier never exceeds the upper inventory level limit of the considered spare part at the warehouse.

$$X_{vpmt}^{MW} \leq Y_{vpmt}^{MW} \; I_p^{maxW} \qquad t \in T, v \in V, p \in P, m \in Mv \qquad (8)$$

Spare parts can be picked up from a warehouse for a maintenance task, however, the number of them should not exceed the capacity of a spare part which a warehouse has been assigned to. These issues have been defined and considered by this constraint.

$$Y_{vpmt}^{MW} \leq L_{tpv} \qquad t \in T, v \in V, p \in P, m \in Mv \qquad (9)$$

It has been considered in this thesis a spare part can only be picked from a warehouse for a maintenance task on a vessel when the vessel visits a port that has access to the considered warehouse.

$$I_{tv}^{V} = I_{tv}^{V} + \sum_{p \in P} X_{tpv}^{RV} + \sum_{p \in P} X_{tpv}^{RWV} - \sum_{m \in Mv} X_{vmt}^{MV} \qquad t \in T, v \in V \qquad (10)$$

This constraint shows the level of inventory of each vessel at the end of each period which has a direct relationship with the previous inventory level. Also, each vessel can receive spare parts directly from a supplier or a warehouse when it visits a port that has access to them. Moreover, spare parts can be picked up from a storage area on board of a vessel to be used for a maintenance task.

$$Y_{tpv}^{RV} \leq L_{tpv} \qquad t \in T, p \in P, v \in V \qquad (11)$$

A vessel can only receive spare parts from a supplier when it visits a port that has access to the supplier.

$$Y_{tpv}^{RWV} \leq L_{tpv} \qquad t \in T, p \in P, v \in V \qquad (12)$$

There is a possibility of receiving spare parts for a vessel from a warehouse when it visits a port that has access to the warehouse.

$$X_{tpv}^{RV} \leq I_v^{maxV} Y_{tpv}^{RV} \qquad t \in T, p \in P, v \in V \quad (13)$$

When spare parts send to a vessel from a supplier, there is an upper limit of storage on each vessel for the spare part which should be respected.

$$X_{tpv}^{RWV} \leq I_v^{maxV} Y_{tpv}^{RWV} \qquad t \in T, p \in P, v \in V \quad (14)$$

Spare parts can be restocked from a warehouse to a vessel when the vessel visits a port. The restocking value should not exceed the considered capacity for the spare part on board of the vessel.

$$X_{vmt}^{MV} \leq Y_{vmt}^{MV} I_v^{maxV} \qquad t \in T, v \in V, m \in Mv \quad (15)$$

It is possible to get the spare parts from storage areas on board of a vessel to be used for a maintenance task. The number to be picked should never be higher than the upper capacity limit of the spare part for each vessel.

$$\sum_{t \in T} Y_{vmt}^{MV} + \sum_{t \in T} \sum_{p \in P} Y_{vpmt}^{MP} = 1 \qquad v \in V, m \in Mv \quad (16)$$

A maintenance task can be done by a vessel's crew and their facilities, or by a port's personnel and their facilities when the vessel visits the port. It has been considered not to be efficient if both the vessel and the port's crews and facilities be considered for the same maintenance task on the same vessel and in the same period.

$$\sum_{p \in P} X_{vpmt}^{MW} + X_{vmt}^{MV} \geq N_{vm} \sum_{p \in P} Y_{vpmt}^{MP} + N_{vm} Y_{vmt}^{MV} \qquad v \in V, m \in Mv, t \in T \quad (17)$$

Each vessel has its own maintenance tasks which have been planned to be done. Also, each task has its own number of needs for a spare part. This number should be respected because a maintenance task can be interrupted if there is no sufficient number of spare parts are available. The needed number of spare parts can be picked from the storage area for the maintenance tasks either from a vessel, warehouses or a combination of both.

5.0 Results and Discussion

In this chapter some instances for the introduced mathematical modeling have been defined. Also, the results from the optimized approach have been explained, and it has discussed around the results to elaborate more on the findings.

5.1 Computational Study

The mathematical model has an innovative approach of addressing the problem of maritime spare part inventory management. However, the EAM system provided by Star Information Systems has capabilities to store multiple types of data, the customers of the company have not fully engaged with the system with their data. Therefore, it has been decided to get the aspects of the problem from the available data at the EAM system and make some artificial instances to test the presented model.

This thesis considers two different groups of instances based on considered planning horizons for the problem.

The first group of instances has a planning horizon for maintenance tasks for a year, and the second one has a planning horizon for three years. Moreover, the planning horizon in the first group of instances has been divided equally into 365 daily periods, and the planning horizon in the second group of instances has been divided into 156 equal weekly periods. The location of each vessel has been defined based on periods in each group of instances, and the location of the ports.

A base instance has been defined based on artificial data in each planning horizon, and results from the based instance compared with results from each instance in each group to investigate the effect of different parameters' values on the presented mathematical model.

In each instance, there are some moving vessels that can visit different ports in a planning horizon. Also, a vessel can visit a port multiple time. Moreover, vessels can have different maintenance with different numbers of spare parts to be used. In addition, each maintenance has its own due date to be perform.

Warehouses have access to their nearest port, and spare parts can be delivered to vessels from warehouses while they visit the port, or directly from a supplier. Therefore, the only possibility to deliver spare parts to vessels while they are visiting ports with no access to warehouses is to send them directly from a supplier.

It has been considered a single supplier for sending spare parts to each port, and the cost of sending spare parts from a supplier to a port can be different at each port to the other ones.

The supplier can be located in different locations, however, all ports have their own access to a supplier.
The cost of performing maintenance has been differentiated for each vessel and each port based on what has been discussed earlier.
Transportation cost of spare parts has been considered to be different for each vessel and each port which included into restocking costs.

5.1.1 Base Instance

The base instance has been defined for each considered planning horizons. The value of different parameters has been considered in the following lines. The model has the possibility to consider any different values.

- There are 10 moving vessels in the problem.
- There are 20 ports to be visited by vessels.
- Each vessel can visit a port multiple time through the considered planning horizon.
- 2 out of 20 ports has access to warehouses.
- Each vessel has 3 different planned maintenance for the one-year planning horizon, and 6 for the three-year planning horizon.
- Each maintenance task uses 1 spare part to be done.
- There is no spare part in initial inventory for vessels and warehouses.
- The upper band values for the storage of the spare part on board of each vessel have been considered as 5.
- Each warehouse has a capacity up to 10 for the number of spare parts to be stored.
- There is no ask for an availability of spare part as a lower band limit in stock and on board.
- There is no minimum limit for warehouses to have a number of spare parts at their storage.
- The inventory cost for a single spare part on each vessel has been considered as 1 United States Dollars (USD) per day for the one-year planning horizon and 7 USD for the three-year planning horizon.
- The inventory cost for a single spare part at each warehouse is 0.1 USD per day through the one-year planning horizon and 0.7 USD per week for the three-years planning horizon.

- The restocking cost from a supplier to a vessel has been considered 200 USD for a single spare part which also includes transportation.
- The restocking cost from a supplier to a warehouse is 100 USD per spare part which includes transportation as well.
- The restocking cost from a warehouse to a vessel when the vessel visits a port is considered as 10 USD for each spare part.
- In the case of having maintenance on a vessel using vessel crew and facility, there has been a 200 USD per task consideration.
- Having maintenance on a vessel while visiting a port and using port personnel has a cost of 100 USD per task.
- The maintenance tasks have been valued based on the time and considered as first descending and then ascending in all of them on each vessel. The lowest value is 10 USD per task if the task has been done at its best time (not too early, not too late). Also, the highest possible value for maintenance tasks based on the time to be done has been considered as a big number that the solver should deal with it.

Parameters' values that have been used for the base instance in one-year and three-years planning horizons have been summarized in Table 2.

Table 2. Parameters' values for Base Instance

Planning Horizon	**Number of Vessels**	**Number of Port**	**Number of Warehouse**
365 days, 156 weeks	10	20	2
Number of Maintenance Per Vessel	**Number of Spare Part Per Maintenance**	**Initial Invetroy Vessel**	**Initial Inventory Warehouse**
3, 6	1	0	0
Minimum Inventory Vessel	**Maximum Inventory Vessel**	**Minimum Inventory Warehouse**	**Maximum Inventory Warehouse**
0	5	0	10
Restocking cost Supplier to Vessel	**Restocking cost Supplier to Warehouse**	**Restocking cost warehouse to Vessel**	**Maintenance Cost by time**
200 USD	100 USD	10 USD	Not constant
Vesel Inventory Cost (day or week)	**Warehouse Inventory Cost (day or week)**	**Maintenance Cost by Vessel (per task)**	**Maintenance Cost by Port (per task)**
1 USD, 7 USD	0.1 USD, 0.7 USD	200 USD	100 USD

The other instances have been defined in two groups based on their planning horizons, and they have been introduced in the following sections.

5.1.2 One-Year Planning Horizon Instances

As mentioned earlier this group of instances have been defined in a one-year planning horizon which has been defined into 365 equally daily periods. Instances are similar to the base instance, except specific parameter's values which has been decided to change for investigation of their effect on the presented mathematical model. The goal of having different instances is to understand the effects of the following changes in the parameters' value:

- Number of ports which have access to costumers' warehouses
- Number of moving vessels
- Number of maintenance tasks to be done on each vessel
- Number of needed spare parts for each maintenance task
- Initial inventory level at vessels
- Initial inventory level at warehouses
- Ratio of inventory to ordering cost
- Ratio of maintenance cost by vessel's crew and facilities to maintenance cost by port's personnel and facilities
- Minimum inventory level in vessels

Based on the considered values to change, nine different instances have been defined for the one-year planning horizon.

The major parameters values for the first group of instances have been summarized in Table 3. Moreover, the maintenance costs are for each maintenance tasks, and they are in USD. Also, "No." stands for number in this table.

Table 3. Major Parameters' Values in Different Instances for One-Year Planning Horizon

Instance	No. of Warehouse	No. of Vessel	No. of Maintenance Per Vessel	No. of Spare Part per Maintenance	Vessel Initial Inventory	Warehouse Initial Inventory	Ordering Cost to Vessel	Ordering Cost to Warehouse	Maintenance cost by Vessel Crew	Maintenance Cost by Port Personel	Vessel Minimum Inventory
Base	2	10	3	1	0	0	200	100	200	100	0
1	3	10	3	1	0	0	200	100	200	100	0
2	2	9	3	1	0	0	200	100	200	100	0
3	2	10	2	1	0	0	200	100	200	100	0
4	2	10	3	2	0	0	200	100	200	100	0
5	2	10	3	1	1	0	200	100	200	100	0
6	2	10	3	1	0	1	200	100	200	100	0
7	2	10	3	1	0	0	400	200	200	100	0
8	2	10	3	1	0	0	200	100	300	100	0
9	2	10	3	1	0	0	200	100	200	100	1

5.1.3 Three-Years Planning Horizon Instances

This group of instances has been defined based on the second planning horizon as three years which was equally divided into 156 weeks. This group of instances followed the same strategy as the first group of instances to be defined. Therefore, most of the parameters are the same as the base instance. There are only few changes in each instance, and the reason for this decision is to investigate on the effect of each parameter on the presented model.
The number of generated instances in the second group and the changes in each follow the same goal as the first group of instances.
Table 4 summarized the major parameters' values in the second group of instances.

Table 4. Major Parameters' Values in Different Instances for Three-Years Planning Horizon

Instance	No. of Warehouse	No. of Vessel	No. of Maintenance Per Vessel	No. of Spare Part per Maintenance	Vessel Initial Inventory	Warehouse Initial Inventory	Ordering Cost to Vessel	Ordering Cost to Warehouse	Maintenance cost by Vessel Crew	Maintenance Cost by Port Personel	Vessel Minimum Inventory
Base	2	10	6	1	0	0	200	100	200	100	0
1	3	10	6	1	0	0	200	100	200	100	0
2	2	9	6	1	0	0	200	100	200	100	0
3	2	10	4	1	0	0	200	100	200	100	0
4	2	10	6	2	0	0	200	100	200	100	0
5	2	10	6	1	1	0	200	100	200	100	0
6	2	10	6	1	0	1	200	100	200	100	0
7	2	10	6	1	0	0	400	200	200	100	0
8	2	10	6	1	0	0	200	100	300	100	0
9	2	10	6	1	0	0	200	100	200	100	1

5.2 Computational Time

The mathematical modeling of optimization has been coded by the AMPL language of programming (see Appendix A) and has been solved by CPLEX 20.1.0. solver. Moreover, the instances were run by a computer with an operating system of macOS Ventura, with 16 GB RAM, and a processor of Apple M2.

Based on the computation of the instances, there is a unique computational time for each of them. The computational time has been calculated by "_total_solve_time" (Fourer, Gay, and Kernighan 2003) code in AMPL.

The computational time for all instances varies between 1.7 to 15.6 seconds.

5.3 Structure of the Solution

In this section the results from the computation of mathematical modeling by the solver has been compared between different instances and the base instance. The comparison is for each time planning horizon.

5.3.1 Delivery of Spare Parts by Order

As mentioned earlier, there are two warehouses in base instances which have access to a port and can send spare parts to each vessel visits the considered ports.

The number of times to order from a supplier directly to vessels, and from a supplier to warehouses have changed in different instances. Also, there is a change in the total number of spare parts received from different places to vessels in different instances. Table 5 shows changes of the number of times to order spare parts, and the total number of spare parts received from different sources to vessels in the one-year planning horizon.

Table 5. Spare Part Flow to Vessels by Sources, and Number of Times to Order (One-Year Planning Horizon)

Instance	Orders From a Supplier to Vessels (times)	Orders From a Supplier to Warehouses (times)	Total Number of Spare Parts From a Supplier to Vessels	Total Number of Spare Parts From a Supplier to Warehouses
Base	1	11	2	28
1	2	13	2	28
2	1	10	2	25
3	1	10	1	19
4	3	11	4	56
5	2	10	2	28
6	1	10	1	27
7	0	11	0	30
8	2	11	2	28
9	1	11	2	28

For the three-years planning horizon, the same approach has been chosen. Table 6 presents the difference in the number of times to order spare parts for vessels, and the total number of spare parts received from different sources in the three-year planning horizon.

Table 6. Spare Part Flow to Vessels by Sources, and Number of Times to Order (Three-Years Planning Horizon)

Instance	Orders From a Supplier to Vessels (times)	Orders From a Supplier to Warehouses (times)	Total Number of Spare Parts From a Supplier to Vessels	Total Number of Spare Parts From a Supplier to Warehouses
Base	1	12	1	59
1	0	12	0	60
2	1	11	1	53
3	1	12	1	39
4	3	19	8	112
5	1	12	1	49
6	1	11	1	57
7	1	12	1	59
8	1	12	1	59
9	1	12	2	58

The delivery of spare parts from a warehouse to a vessel has been done because of two different reasons. The reasons are delivery for a maintenance task on a port, or a delivery for restocking the storage of a vessel. The restocking part of a delivery can be considered for a future use of spare part for maintenance tasks, or for respecting the minimum level limit of the spare parts at each vessel.

Table 7 shows the delivery of spare parts from a warehouse to a vessel for restocking the vessels by number of times to deliver, and by total number of restocking spare parts. Table 7 has been made based on instances in the one-year planning horizon.

Table 7. Restocking Vessels from Warehouses by Number of Times, and Total Number of Spare Parts (One-Year Planning Horizon)

Instance	Restock Vessels (times)	Restock Vessels (total number)
Base	3	7
1	3	7
2	3	7
3	3	5
4	3	14
5	2	4
6	4	8
7	3	9
8	3	7
9	3	7

The same consideration has been done on the three-year planning horizon for restocking vessels by the warehouses. Table 8 shows the restocking value of spare parts from warehouses to vessels based on the number of times to deliver, and the total number of restocking spare parts in the three-year planning horizon.

Table 8. Restocking Vessels from Warehouses by Number of Times, and Total Number of Spare Parts (Three-Year Planning Horizon)

Instance	Restock Vessels (times)	Restock Vessels (total number)
Base	1	5
1	0	0
2	1	5
3	1	3
4	1	4
5	1	4
6	1	5
7	1	5
8	1	5
9	1	4

Direct Delivery of spare parts from a supplier to a vessel considers two different reasons which are doing the maintenance at a same time, or storage on board of a vessel for future uses. Both values of delivery from a supplier to vessels have been presented in table 5 and table 6 on second and forth columns.

5.3.2 Maintenance Location

Crew are one of the most important parts of a vessel maintenance. They can help a vessel to work reliable and to be available. Therefore, understanding the effect of different parameter on a vessel's crew can help managers to make decisions based on who is and who is supposed work on a vessel.

In this section the effect of changing different parameters on the number of maintenances done by a vessel's crew and facilities has been taken into account. As mentioned earlier the total number of maintenance tasks in the one-year planning horizon is 27 for instance 2 and instance 3, and 30 for other instances.

Table 9 shows the total number of maintenance tasks done by vessels' crew in the one-year planning horizon.

Table 9. Number of Maintenance Tasks Done by Vessels' Crew and Facilities (One-Year) Planning Horizon

Instance	Number of Maintenances Tasks
Base	9
1	9
2	9
3	6
4	9
5	16
6	9
7	9
8	9
9	9

In the three-years planning horizon the total number of planned maintenance tasks has been changed for vessels which are 54 for instance 2, 40 for instance 3, and 60 for all other instances. Table 10 presents the total number of maintenance tasks done by vessels' crew and facilities in the three-years planning horizon.

Table 10. Number of Maintenance Tasks Done by Vessels' Crew and Facilities (Three-Years) Planning Horizon

Instance	Number of Maintenances Tasks
Base	6
1	0
2	6
3	4
4	6
5	15
6	6
7	6
8	6
9	6

5.3.3 Spare Part's Inventory Level

This section shows effects of changing parameters on inventory level at vessels and warehouses. The focus of this section is on inventory level on board of vessels because the optimization approach tries to keep the inventory of spare parts in warehouses to the minimum level. Therefore, the orders from a supplier to a warehouse did not store in the warehouses, and sent to vessels as soon as possible mostly on the date of their ports' visits which has an access to the considered warehouse.

To have a better investigation on the effects of differing parameters on inventory level of spare parts on board of vessels, the total number of days with stock level more than the minimum values, has been taken into account in the one-year planning horizon. All instances have a minimum limit of spare parts as none except instance 9 which has one, and this limit should be respected all the time. Table 10 shows the total number of days on all vessels for each instance in the one-year planning horizon which there is a number of spare part on stored on board of them that is higher than mandatory minimum level to be respected. The total number of days is a value for all vessels which means a summation of total days on all vessels.

The total days for all the vessels in all instances are 3650 days except for instance 2 which is 3285 days in the one-year planning horizon.

Table 11. Total Number of Days with Inventory more than minimum Vessels' Inventory Level (One-Year Planning Horizon)

Instance	Total Number of Days
0	170
1	160
2	170
3	145
4	174
5	1095
6	178
7	170
8	170
9	170

Investigation of the inventory level on board of vessels for the three-years planning horizon also can give us some information about the effects of each parameter. Table 12 shows the total number of weeks for all vessels which they have an inventory of spare parts more than the considered minimum limit.

The total number of weeks for all vessels in the three-years planning horizon is 1560 weeks for all the instances except 1404 for instance 2.

Table 12. Total Number of Weeks with Inventory more than minimum Vessels' Inventory Level (Three-Year Planning Horizon)

Instance	Total Number of weeks
0	1
1	0
2	1
3	1
4	1
5	172
6	1
7	1
8	1
9	1

5.4 Discussion

In this section the results from computation study have been considered to make a discussion around them. Moreover, this section considered the structure of the solution to elaborate the results.

5.4.1 Delivery of Spare Parts by Order

By focusing on the number of times to deliver a spare part from a supplier to a vessel, and based on Table 5, the greatest number of times for this type of order is for the instance with the highest number of needed spare parts in the one-year planning horizon. On the other hand, the least number of times to use this type of order is for the instance with the highest order cost. In other word, by doubling the ordering cost, the model decided to not order directly from a supplier to vessels. This shows the importance of ordering cost specially for expensive spare parts with high value of ordering cost.

Based on Table 6, in the three-year planning horizon, the highest time to order directly from a supplier to a vessel is for the instance with highest need for spare parts. On the other hand, the least number of times for this type of order is for the instance with have more warehouses which means by adding one more warehouse access, the model decided to not order directly from a supplier to a vessel.

Based on Table 5, delivery of spare parts from a supplier to a warehouse has the highest value for the instance 1 in the one-year planning horizon. This means the model decided to order more from a supplier to warehouses when there was an increase in the number of warehouses.

Decreasing the need for spare parts, decreases the need for ordering from a supplier to a warehouse in the one-year planning horizon in instances 2 and 3. Also, increasing the initial inventory both on vessels and warehouses, decreased the need for this type of orders.
Based on Table 6, and in the three-year planning horizon, increasing the need for spare part, increased the number of times to order from a supplier to warehouse. On the other hand, this order has decreased when there was an initial inventory level at warehouses. It should be mentioned that based on Table 10, most of the maintenance tasks has been decided to be done by the ports' personnel and facilities. This made the solution to be less effected by having an initial inventory level of spare parts in instance 5 for the three-years planning horizon when considering times of ordering spare parts from a supplier to warehouses.
Based on Table 7 and in the one-year planning horizon, the greatest number of times to restock vessels from warehouses is for the instance 6 where there is an initial level of inventory at warehouses. On the other hand, the least number of restocking vessels from warehouses is the time when there is an initial level of inventory on board of vessels. This shows the reaction of the model to the change of initial inventory value based on defined instances.
As mentioned earlier, the most maintenance tasks have been done by ports' personnel and facilities in the three-years planning horizon. Based on Table 8, by adding a warehouse to the problem in instance 1, the model decided to not consider the restocking to vessels from warehouses. Warehouses sent spare parts to vessels to do the maintenance tasks at the same time.

5.4.2 Maintenance Location

Based on Table 9 the greatest total number of maintenance tasks done by vessel's crew and facilities has been considered for the time when there is an initial inventory of the spare parts on board of vessels in the one-year planning horizon. On the other hand, when there is less need for maintenance tasks in instance 3, the number of this type of maintenance is the least among all the instances.
In the three-years planning horizon and based on Table 10, the greatest number of maintenance tasks by the vessels' crew and facilities follows the same path and reason as the one-year planning horizon. On the other hand, the least number of this type of maintenance is for the instance with highest number of warehouses which gives the possibility to model for having different options to find an optimal solution.

Decreasing the number of vessels in both time horizons has no effect on the number of maintenance tasks by the vessels' crew and facilities, because there were no planned maintenance on this type for the eliminated vessel.

5.4.3 Spare Part's Inventory Level

Based on Table 11 and 12, the greatest total number of days / weeks for vessels to have inventory of spare parts more than minimum level is for the instance with an initial inventory level for vessels in both time horizons. This shows the unnecessary situation of having an initial inventory level on board of vessel when there is no need for them in a short time.

Based on Table 11, the least total number of days for having an inventory more than minimum inventory level on board of vessels in the one-year planning horizon is for the instance 3 with the least number of needed numbers of maintenance tasks. The least number of weeks to have this consideration based on Table 12 for the three-years planning horizon is for the instance with the highest number of warehouses which gives the model the possibility to consider different option for solving the problem in an optimal way.

6.0 Conclusion

Transportation is an essential part of our lives. Our daily plans are affected directly and indirectly by transportation which exists in different forms. Among transportation modes, maritime transportation plays an important role which expands different areas of research around it. One of these research areas is maritime maintenance and related issues which has been mentioned in this thesis.

With an understanding of the importance of spare part management in maritime transportation, it has been decided to work on inventory management of spare parts in maritime transportation in this thesis. Also, it has been focused on preventive maintenance planning which brings the possibility to go through the problem deeper.

Maritime maintenance and spare part inventory management is a massive area of knowledge and many research can be expanded around each part of it. Each way of looking at the problem should be in relation to the other parts. As more knowledge has been gotten about the problem from the Star Information Systems company, maritime maintenance and spare part inventory management has been connected by this thesis in a way that can address the customers of Star Information Systems' concerns and define an approach to find a solution for the problem. As a result, a mathematical model has been introduced for the explained problem, and the model has been tested by different instances.

A considerable challenge in the maritime transportation industry is the lack of reliable data which would be better to be respected more by transportation companies. This thesis defined artificial instances to test the model to be as close as possible to a real problem.

The model and the presented results show the potential of using an optimization approach for spare part inventory management in maritime maintenance. Also, the model has an ability to extend upon request and to have focus on other aspects of the problem.

The presented model can be considered as a general model which can address not only the Star Information Systems, but also any other inventory management of spare parts in maritime maintenance. Moreover, the model shows the importance of inventory management in storage areas of a company like on board a vessel, and warehouses.

The explained approach and model can give a comprehensive view to transportation companies on which data can be collected for research purposes to have inventory management on their spare parts.

The instances have been defined for different planning time horizons which are common in maritime maintenance planning. This shows the ability of the model to work with different cases and different planning time horizons. Moreover, the instances consider different cases of maintenance planning with different need for spare parts which is an important issue for maritime companies that works with variety of situations and have different assets to be controlled and managed.

6.1 Limitations of The Study and Future Research

Based on what has been discussed, there are some limitations to this study that can be considered on future research. It should be mentioned that some of the limitations are from the origin of the maritime maintenance planning and spare part inventory management which needs more collaboration with maritime transportation companies.

This study has focused on preventive maintenance which is an important part of maritime maintenance planning. There are other types of maintenance like corrective maintenance in maritime studies which can be considered for future research. Also, working with corrective maintenance needs better managerial decisions in maritime transportation companies to have a good data collection.

The artificial instances have been defined based on discussions between the authors of the thesis and Star Information Systems. However, the instances have been considered in a way to represent general, realistic, and comprehensive cases, it can be a good idea to test the model with real data. This issue can be respected also by a data collection from transportation companies, and their collaboration.

This thesis considers a single item of spare part for inventory management. As mentioned earlier, the number of spare parts which are needed for maintenance tasks is huge, and there might be some tasks that need different spare parts in different numbers. A good path for future research is to extend the model to multiple items spare part inventory management which can be helpful for different maritime companies.

As environmental concerns increase among people, there is a need to extend the knowledge in the maritime industry in way of respecting this issue. This can be a good way of thinking for future research by including fuel consumption and the environmental impact of spare part inventory management in the presented model.

This thesis did not consider the effect of choosing suppliers for the inventory management of spare parts in maritime maintenance planning. The reason for this decision was the lack of needed data from maritime transportation companies. Also, adding spare part's purchasing cost fluctuation can extend the model for the future research in this area.

As technology arises by exploring different areas of knowledge, it is necessary to adopt new technologies and to use them in the best way of respecting the environment and society. A fast-growing technology is additive manufacturing. This approach can be also a good way of extending the research in the future to make a connection between additive manufacturing and spare part inventory management.

Circularity of a business can be also a good way to expand the presented mode for the future research which can be done by working on the reverse logistics of unused or damaged spare parts.

7.0 References

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8.0 Appendix A

In this chapter, additional information about the thesis and the considered approach has been presented. As a programming language for this thesis, AMPL has been considered. The codes can be found in this section. Also, it has been tried to explain the lines of the code in a way of presenting the authors' ideas for the model.

```
###The idea behind this modeling was to follow a spare part and different maintenance tasks in different locations, different vessels, and with different times to choose to do the task

#Basic Sets
param H>=0; # planning time horizon

set T:={1..H} ;
# time periods

set P;
# set of ports

set V;
# set of vessel

set M{V};
# set of maintenance tasks

#Essential Parameters
param IV_init{v in V}>=0;
#initial inventory level at each vessel

param IW_init{p in P}>=0;
#initial inventory level at each warehouse
```

```
param v_loc { t in T, p in P,v in V};
#vessels' locations in each #time period

param M_spare{v in V, m in M[v]}>=0;
#number of spare parts needed #per maintenance tasks on vessels
```

###costs parameters

```
param inv_cost_V{v in V}>=0;
#inventory cost on board of each vessel

param inv_cost_P {p in P}>=0;
#inventory cost at each warehouse

param rs_cost_SV{p in P}>=0;
#restock cost by a supplier to each vessel

param rs_cost_SW{p in P}>=0;
#restock cost by a supplier to warehouses at the port

param rs_cost_WV{p in P}>=0;
#restock cost by warehouses to vessels

param M_cost_V{v in V}>=0;
#maintenance tasks' costs on each vessel

param M_cost_P{p in P}>=0;
#maintenance cost tasks' costs on each port

param M_cost_T{v in V, m in M[v], t in T};
#maintenance tasks' costs in different periods of time
```

```
###upper and lower stock bounds parameters
param max_W {p in P}>=0;
#storage capacity in each warehouse

param max_V{v in V}>=0;
#storage capacity on board of each vessel

param min_W{p in P}>=0;
#minimum restock level for each warehouse

param min_V{v in V}>=0;
#minimum restock level for each vessel

###inventory variables
var IV {t in T, v in V}>=0;
#inventory level at each vessel, and each period

var IW {t in T, p in P}>=0;
#inventory level at each warehouse, and each period

###restock variables
var XSV{t in T,p in P, v in V}>=0;
#number of spare parts to be restocked from a supplier to each vessel in each period

var XSW{t in T, p in P}>=0;
#number of spare parts to be restocked from a supplier to each warehouse in each period

var XWV{t in T, p in P, v in V}>=0;
#number of spare parts to be restocked from each warehouse to each vessel in each period
```

```
var YSV{t in T,p in P, v in V} binary;
#if spare parts have been restocked from a supplier to a vessel

var YSW{t in T, p in P} binary;
#if spare parts have been restocked from a supplier to a warehouse

var YWV{t in T, p in P, v in V} binary;
#if spare parts have been restocked to from a warehouse to a vessel

###maintenance variables
var XM_V{v in V,m in M[v],t in T}>=0;
#spare parts consumption from a vessel due to maintenance tasks

var XM_W{v in V, p in P, m in M[v],t in T}>=0;
#spare parts consumption from a warehouse due to maintenance tasks

var YM_V{v in V, m in M[v],t in T} binary;
#if a maintenance task is done on a vessel by the vessel's crew and facilities

var YM_P{v in V, p in P, m in M[v],t in T} binary;
#if a maintenance task is done on a vessel by the port's personnel and facilities

###objective
minimize total_cost:
sum{t in T, v in V}IV[t,v]*inv_cost_V[v]+sum{t in T,p in P}IW[t,p]*inv_cost_P[p]+
sum{t in T, p in P,v in V}XSV[t,p,v]*rs_cost_SV[p]+
sum{t in T, p in P}XSW[t,p]*rs_cost_SW[p]+
sum{t in T, p in P, v in V}XWV[t,p,v]*rs_cost_WV[p]+
sum{v in V, m in M[v],t in T}YM_V[v,m,t]*M_cost_V[v]+
sum{v in V,p in P, m in M[v],t in T}YM_P[v,p,m,t]*M_cost_P[p]+
```

```
sum{v in V, m in M[v],t in T} YM_V[v,m,t]*M_cost_T[v,m,t]+
sum{v in V,p in P, m in M[v],t in T}YM_P[v,p,m,t]*M_cost_T[v,m,t];
```

###Constraintes

```
subject to capacity_V {t in T, v in V}: IV[t,v]<= max_V[v];
```
#capacity to store spare parts on board of each vessel

```
subject to capacity_W {t in T, p in P}: IW[t,p]<= max_W[p];
```
#capacity to store spare parts at each warehouse

```
subject to restock_min_V{t in T, v in V}:IV[t,v]>=min_V[v];
```
#minimum inventory level of spare parts on board of each vessel

```
subject to restock_min_W{t in T, p in P}:IW[t,p]>=min_W[p];
```
#minimumiinventory level of spare parts at each warehouse

```
subject to inventory_W1 {p in P}:IW[1,p]=IW_init[p]+XSW[1,p]-sum{v in V}XWV[1,p,v]-sum{v in V, m in M[v]}XM_W[v,p,m,1];
```
#inventory level at each warehouse in the first period based on the flow of spare part

```
subject to inventory_W {t in 2..H, p in P}:IW[t,p]=IW[t-1,p]+XSW[t,p]-sum{v in V}XWV[t,p,v]-sum{v in V,m in M[v]}XM_W[v,p,m,t];
```
#inventory level at each warehouse at other periods based on the flow of spare part

```
subject to restock_warehouse {t in T, p in P}:XSW[t,p]<=max_W[p]*YSW[t,p];
```
#spare parts can be delivered from a supplier to a warehouse by respecting the capacity

```
subject to maintenance_from_warehouse {t in T,v in V,p in P, m in M[v]}:XM_W[v,p,m,t]<=YM_P[v,p,m,t]*max_W[p];
```
#spare parts can be given from a warehouse for a maintenance task when respecting the capacity

```
subject to maintenance_from_warehouse_1 {t in T,v in V,p in P, m in M[v]}:YM_P[v,p,m,t]<=v_loc[t,p,v];
```
#maintenance tasks can be done by a port's personnel and facilities only if a vessel visits the port

```
subject to inventory_V1 {v in V}:IV[1,v]= IV_init[v]+sum{p in P}XSV[1,p,v]+sum{p in P}XWV[1,p,v]- sum{m in M[v]}XM_V[v,m,1];
```
#inventory level on board of each vessel at first period based on the flow of spare part

```
subject to inventory_V {t in 2..H, v in V}: IV[t,v]=IV[t-1,v]+sum{p in P}XSV[t,p,v]+sum{p in P}XWV[t,p,v]-sum{m in M[v]}XM_V[v,m,t];
```
#inventory level on board of each vessel at other periods based on the flow of spare part

```
subject to restock_vessel_1{t in T,p in P, v in V}:YSV[t,p,v]<=v_loc[t,p,v];
```
#spare parts can be delivered to a vessel from a supplier only if the vessel visits a port with access to the supplier

```
subject to restock_vessel_1_1{t in T,p in P, v in V}:YWV[t,p,v]<=v_loc[t,p,v];
```
#spare parts can be delivered to a vessel from a warehouse only if the vessel visits a port with access to the warehouse

```
subject to restock_vessel_2{t in T,p in P, v in V}:XSV[t,p,v]<=max_V[v]*YSV[t,p,v];
```

#spare parts can be delivered to a vessel from a supplier by respecting the capacity on board of the vessel

```
subject to restock_vessel_3{t in T,p in P, v in V}:XWV[t,p,v]<=max_V[v]*YWV[t,p,v];
```

#spare parts can be delivered to a vessel from a warehouse by respecting the capacity on board of the vessel

```
subject to maintenance_from_vessel{t in T,v in V, m in M[v]}:XM_V[v,m,t]<=YM_V[v,m,t]*max_V[v];
```

#spare parts can be given from the storage area on board of a vessel for a maintenance task by respecting the capacity of the storage

```
subject to only_one_maintenance_location{ v in V,m in M[v]}:sum{t in T}YM_V[v,m,t]+sum{t in T, p in P}YM_P[v,p,m,t]=1;
```

#each maintenance task can be done by a vessel's crew and facilities or by a port's personnel and facilities

```
subject to consumption_balance{v in V, m in M[v], t in T}:sum{p in P}XM_W[v,p,m,t]+XM_V[v,m,t]>=M_spare[v,m]*(sum{p in P}YM_P[v,p,m,t])+M_spare[v,m]*YM_V[v,m,t];
```

#consumption of spare parts should respect the need for them by each maintenance task