DELFT UNIVERSITY OF TECHNOLOGY

COMMISSIONED BY MERCURIUS SHIPPING GROUP

MASTER THESIS

# Inventory Optimization for Mercurius Shipping Group's Container-Crane Vessels

*Author:*
W. TER LAARE

*Company Supervisor:*
Dr.ir. J.C.M. VAN DORSSER
*University Supervisor:*
Prof.dr. E.M. VAN DE VOORDE
Ir. J.W. FROUWS

*A thesis submitted in fulfillment of the requirements for the degree of Master of Science*

*in*

Marine Technology
*Specialisation:* Shipping Management

December 28, 2017

*Thesis for the degree of MSc in Marine Technology in the specialization of Shipping Management*

---

# Inventory Optimization for Mercurius Shipping Group's Container-Crane Vessels

---

*by*

**W. TER LAARE**

*Performed at:*

MERCURIUS SHIPPING GROUP

*This Thesis SDPO.18.004.m is classified as confidential in accordance with the general conditions for projects performed by the TUDelft*

*To be defended publicly on January 31st, 2018*

*Company Supervisor:*
Responsible supervisor: Dr.ir. J.C.M. van Dorsser
E-mail: c.van.dorsser@mercurius-group.nl

*Thesis Exam Committee:*
Chair/Responsible Professor: Prof.dr. E.M. van de Voorde
Staff Member: Ir. J.W. Frouws
Staff Member:
Company Member: Dr.ir. J.C.M. van Dorsser

*Author:*
Studynumber: 4142276
E-mail: wesselterlaare@hotmail.com

# *Preface*

In front of you, the thesis: "Inventory Optimization for Mercurius Shipping Group's Container-Crane Vessels. The basis of which is an assessment of the effect of keeping an optimized spare-part inventory on the reliability of the container-crane vessel MKS Mercurius. It has been written to fulfill the graduation requirements of the MSc Marine Technology at Delft University of Technology (TU Delft), within the specialization of Shipping Management. The research was conducted from April 2017 till January 2018.

The project was undertaken at the request of Mercurius Shipping Group, where the associated graduation internship was undertaken. The research was formulated in consultation with Mercurius Shipping Group's Business Development & Strategy Advisor, Dr.Ir. J.C.M. van Dorsser. The research was a challenging experience, but conducting extensive research lead to a substantiated answer to the research problem. Fortunately, both the company supervisor dr.ir. J.C.M. van Dorsser and my university supervisors, prof.dr. E.M. van de Voorde and ir. J.W. Frouws, were always available and willing to answer my queries.

I would like to thank my supervisors for their excellent guidance and support during this process. Their extensive knowledge and valuable feedback were essential in securing a good quality research.

Special gratitude goes out to P. den Haan, technical manager of Mercurius Shipping Group, his knowledge on the technical aspects of inland shipping and especially on components related to the crane was indispensable to the outcome of the research. Furthermore, special gratitude goes out to M. Kleijn, owner barge operator MCT Lucassen, his insights and knowledge of inland shipping operations was essential in the modelling part of this project.

Besides this, I want to thank my family for their support and patience over the years.

I hope you enjoy your reading.

W. ter Laare

December 28, 2017

DELFT UNIVERSITY OF TECHNOLOGY

# *Summary*

Marine Technology

*Specialisation:* Shipping Management

Master of Science

**Inventory Optimization for Mercurius Shipping Group's Container-Crane Vessels**

by W. ter Laare

Mercurius Shipping Group (MSG) invested in two container-crane vessels which are able to load and unload cargo in remote areas, ports without crane capacity and deliver directly to companies located on inland rivers. Due to the fact that the crane mounted on these vessels is an unique feature for inland shipping, there are no comparable vessels operating in the area and no immediate replacement is available in case of failure. As a result, failure of these vessels, in particular failure of the crane, results in large revenue losses and other high financial consequences related to alternative pick-up and delivery solutions for containers at client locations. This makes reliability, or increased uptime, an important attribute for these vessels to maintain/improve their position in the market and to be able to keep client trust.

The main aim of this study is to increase the reliability of Mercurius Shipping Group's container-crane vessel MKS Mercurius by proposing an optimized spare-part inventory. Subsequently, by doing so, reducing the total costs of operating and maintaining the vessel and ensuring profit maximization for MSG. To this end, the main research question is formulated as: *"For which crane components/parts will keeping a spare-part inventory result in a cost-effective improvement of the reliability for the container-crane vessel MKS Mercurius?"*. The research question is answered through the development of cost models to quantify the reduction in financial risk of failures, by having spare-parts directly available, and to determine the costs of keeping a spare-part inventory. As a result a list of spare-parts is proposed based on a comparison between the reduced failure impact/costs (benefit), with a spare-part in inventory, and the corresponding annual inventory costs. The effect of availability of the second container-crane vessel (MKS Transferium) on the financial impact of failure (of the MKS Mercurius), and the resulting selection of spare-parts is furthermore evaluated.

The quantified benefits of keeping a spare-part inventory showed that direct availability of spare-parts mainly has an effect on: failure durations; repair costs; operational consequences; and financial consequences, including downtime related cost. By eliminating lead time, on average, failure durations can be reduced by 7 – 10 days depending on the component. Availability of a spare-part results in a reduction in repair costs, which is related to the elimination of urgency for the repair in case a component fails, this results in reduced costs for delivery and (likely) a more competitive price for the acquisition of the part. Depending on the component a reduction in repair cost can be achieved between €1,000 – €15,000. Operational consequences showed that in case of failure of the crane alternative transportation must be arranged for previously loaded containers in the vessels holds, and for previously

delivered containers on shore at client locations. This may require vessel hires and/or container terminal services. Furthermore operational consequences included: a reduction in executed crane movements, increased planning and rescheduling difficulties, and inability to execute 'special' lifting activities which requires both vessels. For the corresponding financial consequences (i.e. downtime related costs) this therefore showed a division in: opportunity costs (revenue loss), container removal costs, additional planning related costs, and business recovery costs. Direct availability of spare-parts can reduce these failure costs up to €70,000 depending on the component and severity of consequences to the operability of the crane. This leads to a total reduction of failure impact (defined as benefit of keeping a spare-part in inventory) between €1,000 – €85,000. The costs of keeping inventory, i.e. annual inventory costs for each component, showed a division in: interest costs, risk costs, and warehousing costs. The annual inventory costs vary between €300 – €11,000 depending on the type of component. Combining this with failure probabilities of the components, which vary between 4% – 20%, this results in annual net benefits (benefit – costs) between - €6,500 – + €10,000.

Furthermore the operational and resulting financial consequences after failure showed that availability of a second container-crane vessel, in case of failure of the MKS Mercurius, resulted in a substantial decrease in failure costs (or financial impact). Which is explained by the fact that this second container-crane vessel is able to take-on MKS Mercurius' lifting activities in case of failure. Therefore, with availability of a second container-crane vessel, without any inventory, a reduction in failure costs can be achieved between €2,000 – €40,000 depending on the type of component. As a result, for the inventory selection and optimization a distinction is made in two scenarios, which results in an optimized spare-part inventory for: (1) MKS Mercurius, taking into account availability of MKS Transferium in case of failure, and (2) MKS Mercurius as MSG's single container-crane vessel.

The results of the model(s) showed that a cost-effective improvement to vessel reliability, due to a decrease in vessel downtime, can be achieved with direct availability of spare-parts kept in inventory. For the inventory of the MKS Mercurius with availability of a second container-crane vessel, in case of failure, this results in an optimal level of inventory of 35% and includes 13 components. This inventory requires an investment of €50,000, includes €8,500 annual inventory costs, and leads to a reduction of expected annual failure costs of €22,000, which means the annual net benefit is equal to €13,500. As a result the investment has a return of 26% and is expected to be recouped within a period of approximately 4 years. A larger inventory would lead to a further reduction in annual failure costs, by due to increasing inventory costs the annual benefit will be reduced (and eventually eliminated). This means that for larger levels of inventory the investment may eventually not be recouped in the vessels remaining life. Meaning it does not result in a cost-effective improvement to vessel availability/reliability and is therefore considered a sub-optimal inventory. With the MKS Mercurius as single container-crane vessel, minimizing downtime and reducing the probability of failure with severe financial consequences, is of increased importance to the vessels financial result. For this reason a more extensive inventory is recommended, including 28 components. This inventory slightly exceeds the optimal (minimizing expected annual costs) level of inventory (55%, 23 components), in order to reduce the probability of outliers regarding annual failure costs and increase reliability. This inventory requires an initial investment of €137,000, includes €24,000 annual inventory costs, and leads to a reduction of expected annual failure costs of €79,000, which means the annual net benefit is equal to €55,000. As a result the investment has a return of 43% and is expected to be recouped in less than 3 years.

Essentially, the amount of components to store in inventory and the corresponding initial investment is a managerial decision for MSG. This requires a consideration for either a cost-minimizing inventory, or a larger inventory for which probability of outliers regarding annual failure costs decreases. In the current situation, with both container-crane vessels operating in the same area, the recommended inventory consists of 13 components which will lead to expected annual savings of €13,000. However, when MSG decides to sell or relocate one of the container-crane vessels, direct availability of spare-parts has a large influence on the vessels financial performance. As a result (a large) inventory for the MKS Mercurius becomes crucial. Considering the increased importance of minimizing downtime and decreasing the probability of failures with severe financial consequences, it is for this scenario recommended that MSG makes a substantial investment in inventory.

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

This section addresses the problem definition, the research objective, the research questions, the scope, the research approach and provides the outline of the report.

## 1.1 Background

Mercurius Shipping Group (MSG) consists of collaborations of inland shipping entrepreneurs. They develop, build, operate, charter and invest in a variety of inland barges. The organizational structure is rather complex, Mercurius holds interests in several subsidiaries and these subsidiaries are engaged in different activities surrounding the fleet. MSG owns a diversified fleet, consisting of numerous container vessels, container-crane vessels, stainless steel tankers and coated tankers. With its chemical tanker fleet Mercurius Shipping Group holds a strong position in the segment of inland chemical shipping (Mercurius, 2017).

MSG's strategy is investing in vessels with unique features which distinguishes them from conventional inland vessels and provide added value due to these properties. For this reason they invested in two container-crane barges which are able to load and unload cargo in remote areas, ports without crane capacity and deliver directly to companies located on inland rivers. The container-crane barges offer container pick-up and delivery services mainly to clients without shore crane capacity located in the Port of Rotterdam area. The idea behind this mode of transport is to fit the needs of their clientele by transporting containers in a fast, sustainable and efficient manner from large seaports to their remote locations, and while doing so reducing road congestion in the port.

Reliability of these barges is an important quality for the operational management. This is partly due to the fact that the crane mounted on these barges is an unique feature for inland barges, which means there are no comparable vessels operating in the area and no immediate replacement is available for these vessels in case of failure. As a consequence, failure results in large revenue losses and other high financial consequences related to alternative pick-up and delivery solutions for containers located at clients. For MSG this was reflected in 2016, when both crane barges were unavailable for a two week period. The first crane barge ('MKS Mercurius') had a scheduled docking to replace the crane cylinders; and the second barge ('MKS Transferium') experienced an equipment malfunction regarding the crane, of which the effects could have been mitigated when parts would have been easily available. Due to long delivery times for Liebherr's crane parts, multiple weeks, the technical department was forced to find alternative solutions in order to fix these problems. During this two week period these problems had a large impact on both revenue and costs, which were not solely repair costs but also large costs related to loss of business and lost opportunities. The total loss of business, including estimated revenue losses and recovery costs (loss of revenue in the weeks(s) after the failure had been restored), are estimated at approximately €100,000 – €130,000 (M. Kleijn, personal communication, April 7, 2017). These costs would have been mitigated with easily/timely available spare parts. Along with the high financial consequences, long downtime of the crane barges may also incur reputational damages to MSG and affect client trust. This makes reliability an important attribute for the crane barges to maintain/improve their position in the market and to be able to keep client trust.

Due to the mentioned importance of reliability for these vessels, MSG would like to explore the possible mitigation of risk (of failure) by holding spare crane components; and ultimately set up an optimized spare-part inventory for critical systems of the MKS Mercurius container-crane barge. For managing and maintaining this spare-part inventory several options can be considered. The first possibility is for MSG to fully own and control their own inventory. Alternatively MSG might consider to outsource their inventory management to either a directly involved manufacturer (Liebherr or strong competitor) or a third-party logistics provider. This research is intended to lay the foundation for an optimized overall approach regarding spare-part inventory strategy and maintenance strategy for both (and perhaps newly acquired) crane barges.

## 1.2 Objective

This study will conduct a research on critical components/systems of the cargo handling gear for the Mercurius container-crane barge and propose a related spare-part inventory strategy, including a list of spare-parts.

The main aim of the research is to increase reliability of the container-crane barge MKS Mercurius by proposing an optimized spare-part inventory. This should ultimately result in less downtime, which will increase revenues and reduce the total costs of operating and maintaining the crane barge. Reducing these costs will play an important role in ensuring profit maximization for MSG. Reliability is in this case defined as the ability to consistently perform its intended or required functions. Increasing reliability thus reduces the risk of failure, resulting in less (optimized) downtime and an increase in operational capacity.

## 1.3 Research questions

The research objective will be achieved by answering several research questions, which are described in this section. The following main research question is defined:

*For which crane components/parts will keeping a spare-part inventory result in a cost-effective improvement of the reliability for the container-crane vessel MKS Mercurius?*

Where cost-effective is defined as a relation between effectivity and its costs, meaning optimum result for the given expenditure. In this case effectivity is quantified by the effect of keeping inventory on the container-crane vessels expected financial result. Keeping a component in inventory will therefore be cost-effective if its 'potential' financial gain is larger compared to the costs of keeping it in inventory, i.e., a consideration is made comparing risk of failure (difference in impact when spare-parts are directly available) to the costs of keeping inventory. As previously mentioned, reliability is defined as the ability to consistently perform its intended or required functions, resulting in minimal downtime.

This main research question will be answered through division into the following sub-questions:

1. Which systems and components form the cargo handling gear of the MKS Mercurius?

2. Which failure probabilities can be attributed to these systems and components?
   (a) Which failure probabilities can be attributed to compound systems/component groups?
   (b) Which failure probabilities can be attributed to single components?
3. How does the availability of spare-parts affect the duration of the failure?
4. How does the availability of spare-parts influence the costs of repair for the failure?
5. Which restrictions to the operability of MKS Mercurius can be defined as a result of failure of these systems and components?
6. What are, given the duration and the restrictions to operability, the financial consequences/failure costs for MSG as organisation? And how is this affected by 'direct' availability of spare-parts?
7. Which costs are associated with keeping a spare-part inventory and what are these costs for the described systems and components?
8. For which components/parts is it, from a long-term financial perspective, cost-effective to store them in a spare-part inventory?
9. How do uncertainties in the assumptions made in this research affect the proposed inventory strategy? And how sensitive are the results regarding these uncertainties?

These questions will be answered throughout the report and serve as a guideline for the research.

## 1.4 Scope

The research focusses on the container-crane barges of MSG, in particular the MKS Mercurius and, due to their similarities, also to the MKS Transferium. The MKS Transferium is a successor of the MKS Mercurius and considered an improved version of the container-crane barge concept. Due to previous experience of MSG, the MKS Mercurius is defined as the least reliable barge (P. den Haan, personal communication, April 12, 2017). For this reason, MKS Mercurius being the oldest and least reliable barge, the focus of the research is on (crane) systems and component of the MKS Mercurius. For systems and components unrelated to the cargo handling gear a widely spread network of maritime suppliers is available. As a result these parts are usually quickly delivered and of high quality. Especially due to the low priority of the two container-crane barges for Liebherr, and due to the large distance to the crane manufacturer located in Austria, this is not the case for parts related to the crane (P. den Haan, personal communication, April 12, 2017). Therefore the focus of this research is with systems and components related to the cargo handling gear of the MKS Mercurius. A risk assessment of critical systems is made on main component level for the MKS Mercurius. Main differences with the MKS Transferium are mentioned, but not used in further analyses. Research data is largely collected by gathering data within MSG and obtaining data from suppliers. Some additional data is obtained by literature.

To conduct a risk assessment, the current condition of components or (residual) life expectancy is required. A value for the life expectancy can be obtained/assumed by: a static approach, where theoretical life expectancies are defined, which are based on technical expertise and experience; or a dynamic approach where, with extensive data, the actual residual life at any point in time can be determined/estimated. For this reason the feasibility of these approaches needs to be determined. This requires a concise analyses of the current maintenance strategy to determine the type and amount of available data, at MSG, on the state of parts/components related to the crane. However, exploring options to improve the current maintenance approach, developing an alternative (advanced/preventive) maintenance approach, or analysing the effects on the proposed spare-part inventory is out of the scope of this project.

For the optimization problem there is a trade-off between risk (costs of vessel downtime) and costs of keeping an inventory. The outcome of the research should therefore quantify the effect of storing crane parts in inventory on the reliability (downtime) and ultimately on the financial result of the MKS Mercurius. The findings of this research are therefore solely based on an economic assessment, other considerations, such as environmental or social influences are out of the scope of this research.

A risk assessment is made where critical systems and components are identified. Furthermore cost models are made which will generate input for a cost-benefit assessment. This analysis should be the basis for optimization of the spare-part inventory for the container-crane barge 'MKS Mercurius' and, neglecting minor discrepancies, the 'MKS Transferium'.

## 1.5 Methodology / Research Approach

Defining the research approach helps structuring the research. It is a schematic representation of the objective and includes the appropriate steps that need to be taken to obtain an adequate result for the stated problems. A further description of methods based on the sub questions which were defined in Section 1.3 can be found in Chapter 3.

The study can be described as applied research, which means the findings are based on strong methodological substantiation with which a numerical application is made for MSG. Therefore it is necessary to implement data obtained from field research and to estimate values based on previous experience, which entails analyzing maintenance processes and component functionality as well as experienced malfunctions and problems. In the research cost models will be developed to quantify the reduction in (financial) risk of failures by having spare-parts 'directly' available and to determine the costs of keeping a spare-part inventory. Due to the fact that MSG is currently equipped with two container-crane vessel, availability of the second barge MKS Transferium in case of failure of the MKS Mercurius has an effect on the impact of failure. Since, in the future, MSG might want to relocate one of the container-crane vessels, the failure impact is determined for both: (1) MKS Mercurius taking into account availability of the MKS Transferium in case of failure, and (2) MKS Mercurius as MSG's single container-crane vessel. The cost models provide input for a cost-benefit assessment where the potential financial benefit, quantified by the risk reduction, is compared to the inventory costs. After which an optimized spare-part inventory can be proposed. A schematic representation of the research approach is presented in Figure 1.1.

During the preliminary phase of the project a general overview of the current maintenance strategy of the MKS Mercurius and the organisational structure of the MKS Mercurius is defined. This will contribute to define the link between issues related to spare-parts and

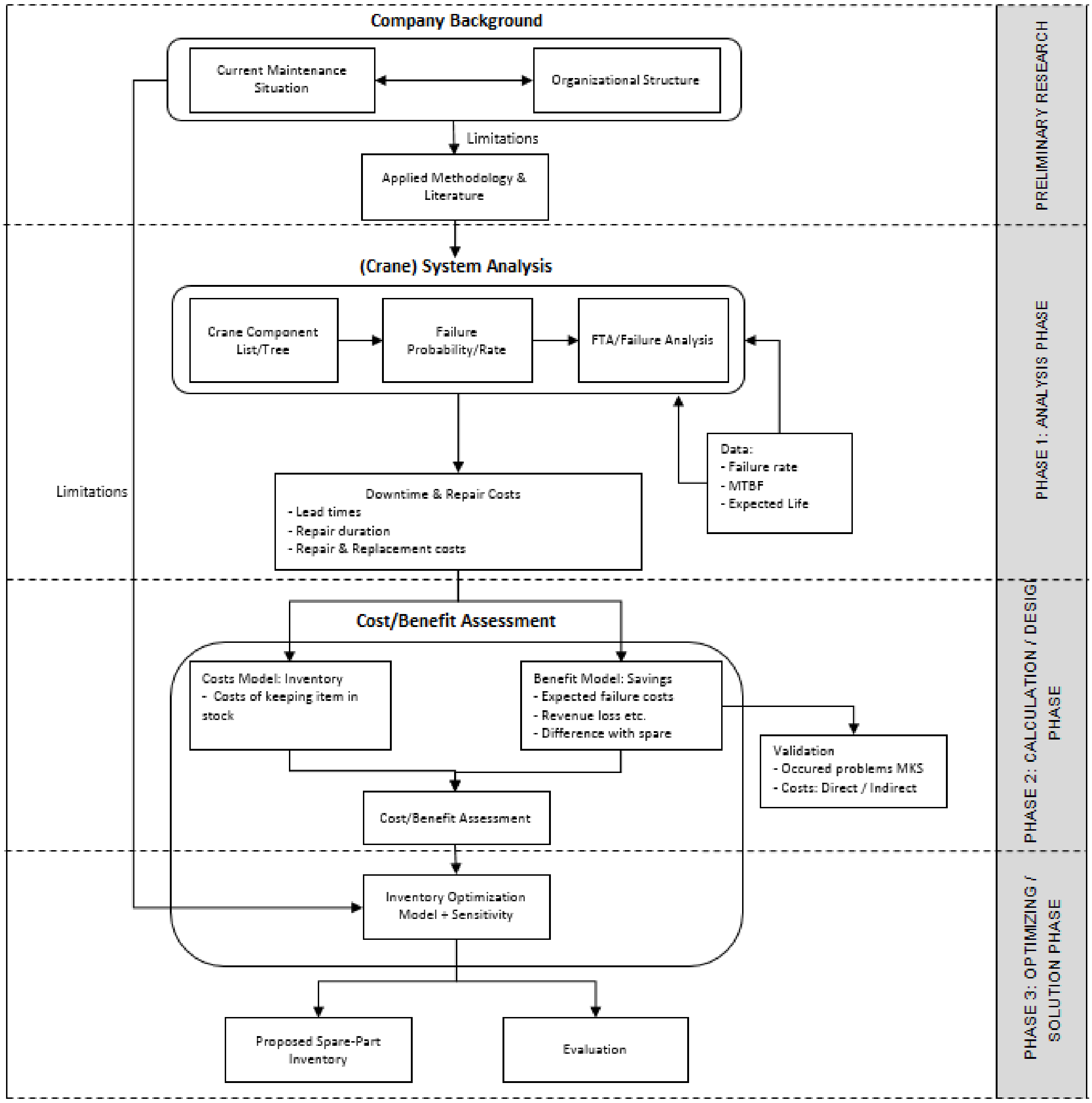



FIGURE 1.1: Research Approach

*Note*: Own Composition

replacement durations to the organisation MSG. Subsequently a 'system analysis' is made (analysis phase). First a component breakdown is composed where all systems and parts related to the vessels cargo handling gear are defined. For these components failure probabilities are derived, after which a failure analysis is performed for the MKS Mercurius. In the last part of the analysis phase the downtime of the vessel in case of component failure is determined, this downtime will be based on lead times and repair/replacement durations for the parts. A comparison in downtime is made for when spare parts are directly available and when parts need to be delivered.

During the second phase, the calculation/design phase, the financial consequences of component failure with or without direct availability of spare-parts are determined. With the information and data obtained in the first phase a cost model is developed in which, for each component and related failure duration (lead time, repair time, total downtime) the financial effects are calculated. The resulting difference in failure duration with direct availability of spare-parts ultimately results in a difference in failure costs, meaning a reduction in the impact of failure. Since longer durations result in larger effect, which means larger impact, this reduction in failure duration translates to the 'potential' financial benefit of keeping a spare-part inventory. Secondly, a cost model is developed to determine the costs associated with keeping a spare-part inventory. These outcomes provide the input for a cost-benefit assessment, obviously when the 'potential' benefits exceed the total costs it is considered beneficial to keep the item in a spare-part inventory.

The last phase of the research, the optimization/solution phase, will involve a sensitivity analysis of variables and assumptions made during the process and will describe how these affect the proposed inventory. During this phase the optimization model describes recommendations as to which items, knowing the effect and sensitivity of made assumptions, to store in inventory. Finally an evaluation of the research is made, conclusions are drawn and future recommendations are proposed.

## 1.6 Thesis outline

The order of the previously formulated sub questions reveals an outline for the structure of the report (Fig. 1.2). Each chapter corresponds with one or more sub questions. At the end of each chapter, a conclusion is formulated in which an answer is provided to the corresponding sub question(s). Finally, in the conclusion of the report an answer to the main research question is formulated.

The introduction is incorporated in the current chapter (Chapter 1). Chapter 2 describes practical boundary conditions to the research design, which originate from the organizational structure of MSG and the maintenance strategy of the container-crane vessels. Chapter 3 (Methodology & Related Literature) addresses the research approach and literature used to define this approach. The sections: Organizational Structure & Maintenance Strategy (Chapter 2) and Methodology & Related Literature (Chapter 3) define the preliminary research. The remaining chapters describe the main research and are subsequently divided:

Chapter 4 describes the component tree for the MKS Mercurius focussing on the systems and components related to the crane and describes the derived failure probabilities (failure rates) for these components.

Chapter 5 provides a thorough analysis of the influence of spare-part availability on the duration and repair costs in case of component failure.

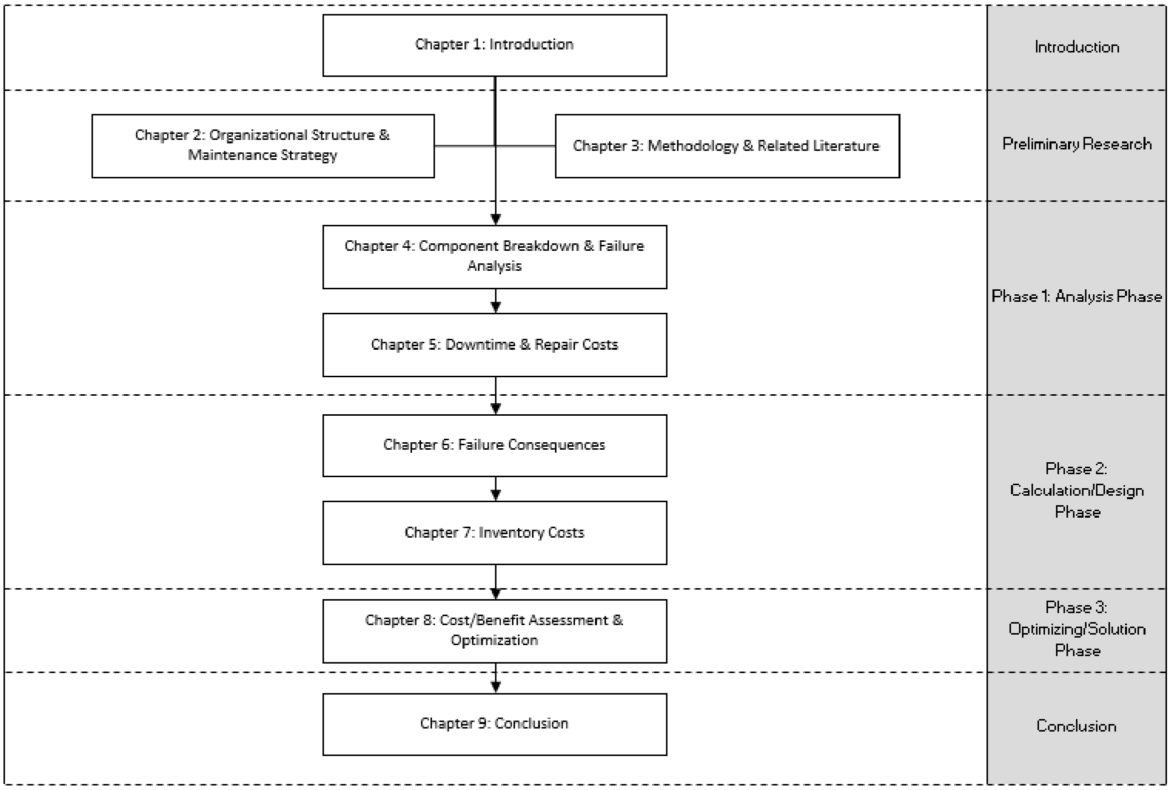



FIGURE 1.2: Thesis Outline

Chapter 6 describes the operational and financial consequences of component failure and describes how this is affected by 'direct' availability of spare-parts.

Chapter 7 gives a description of costs associated with keeping a spare-part inventory and describe the magnitude of these costs for the systems and components of the MKS Mercurius.

Chapter 8 addresses the cost-benefit assessment for the components, proposes an optimized spare-part inventory and describes the sensitivity analyses regarding assumptions made throughout the research.

Finally, the answer to the main research question is formulated in the conclusion (Chapter 9), whereas the appendices (A till E) give extensive background information.

# Chapter 2

# Organizational Structure & Maintenance Strategy

This chapter addresses the link between problems regarding spare-part inventory management and the organisation MSG, and describes how this affects the proposed research design. This requires an analysis of the organizational structure of MSG, an analysis of the current maintenance strategy for the container-crane vessels and an analysis of inventory management strategy of MSG. At the end of this chapter, limitations towards the research design, that originate form MSG's organizational structure and embraced maintenance strategy, are defined. As a result an answer to the following exploratory (sub) question is provided: How do the organizational structure and current maitenance strategy influence the research design?

The first part of this chapter addresses the division of management and ownership structure of the container-crane vessels and the second part addresses the current maintenance strategy.

## 2.1 Background MSG

Mercurius Shipping Group invests in inland barges and provides multiple supporting services concerning inland shipping. These services include: newbuilding, brokerage, chartering, administration and financial support (Mercurius, 2017). One of the core philosophies of the company is to form collaborations with inland shipping entrepreneurs, an important part of the organisation therefore is Mer-Franchising. With Mer-Franchising MSG supports starting inland shipping entrepreneurs, either financially and/or by providing supporting services, in setting up their own enterprise in the inland shipping industry. MSG's core activities include:

- Accompanying new-builds
- Supporting in vessel exploitation
- Investing in innovative solutions for inland shipping
- Operating own diversified fleet

MSG holds interests in several subsidiaries of which some are fully and others are partially owned by Mercurius, an organisation chart of MSG is shown in Figure 2.1. These subsidiaries concern themselves with: management of one or multiple barges they have full

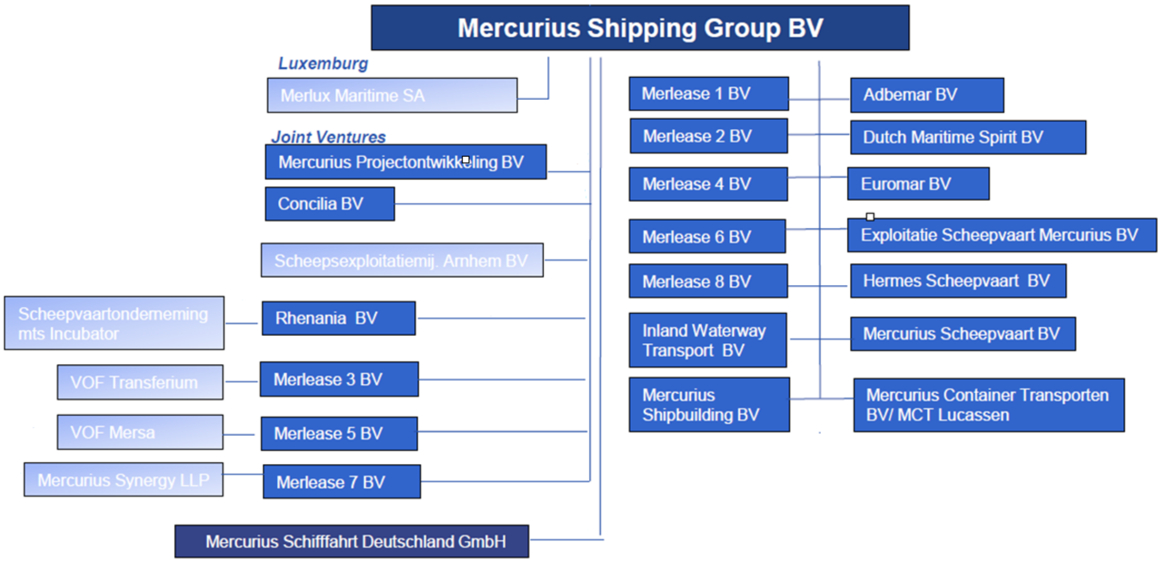



FIGURE 2.1: Organogram Mercurius Shipping Group

*Source*: Mercurius (2017)

ownership of, exploitation of one or multiple barges they have no ownership of, management and/or exploitation of barges they partially own, freight forwarding and other shipping related activities such as crewing.

## 2.2 Operation & Management Container-Crane Barge(s)

The container-crane vessels are designed to load and unload cargo in remote areas, ports without crane capacity and deliver directly to companies located on inland rivers. For the crane of this vessel, Liebherr manufactured, the hull of the vessel is strengthened to be able to lift containers with a maximum weight of 40t. The vessels have a limited capacity of 2150 ton and available space for 144 TEU containers. The vessels are usually loaded with a combination of loaded and empty 40-foot (2xTEU) containers, but have the ability to transport a barge alongside to increase capacity. Besides their main activities the container-crane vessels provide lifting services for transshipment of other barges which are not equipped with their own crane or the vessels can be rented out for other lifting operations.

The ownership structure in combination with the managerial structure of the MKS Mercurius is shown in Figure 2.2, the connections indicate revenue streams between subsidiaries and the organisation MSG as a whole. This structure defines how activities are allocated and coordinated for daily operation/management of the vessel. As shown there are several subsidiaries, which are fully owned by MSG, involved in operating and maintaining the vessel.

MCT Lucassen (short MCT) is a barge-operator for inland shipping specialized in the Antwerp-Rotterdam-Amsterdam area (MCT, 2017) This freight agency is part of MSG and arranges freight charters for the container-crane vessels. Due to its operational area, which is mainly the Port of Rotterdam area, and the regular clientele the vessel mostly operates with long-term contacts of affreightment. Essentially, MCT can be accounted for the external revenue stream of the vessel for MSG. The operating company responsible for crewing is Merlux, which is also a subsidiary of MSG. Since 2017 the vessel is fully owned by MSG (Merlease 1

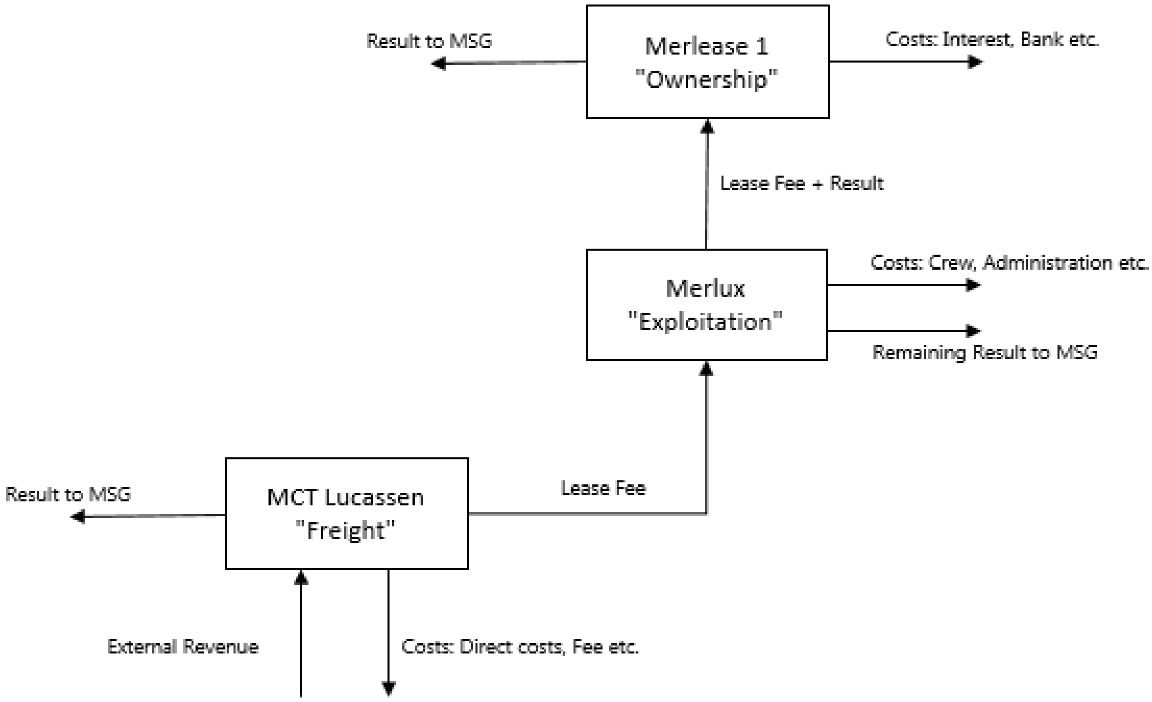



FIGURE 2.2: Organisational Structure 'MKS Mercurius'

*Note*: Own Composition based on input from MSG

BV), which means that MSG has full ownership of both the vessel and subsidiaries responsible for daily management (Fig. 2.1).

The organizational structure of the MKS Mercurius shows that there are several subsidiaries involved in (daily) management of this vessel. As a result data and information for this research must come from different sources, this means the result is affected by the expertise of these sources and the quantity of data they are able to provide. Furthermore the organisational structure shows that management, exploitation and maintenance of the MKS Mercurius is fully controlled by MSG. As a result for this vessel (MKS Mercurius) MSG is the sole decision-maker regarding decisions for investments, expenses and maintenance of the vessel. Furthermore, since MSG fully owns the barge they are also sole cost-carrier for the vessel and sole beneficiary of generated profits.

## 2.3 Maintenance

This section addresses the maintenance strategy applicable to MSG's container-crane vessels, describes how the maintenance strategy is affected by inventory management, and addresses how restrictions/limitations resulting from this maintenance strategy affect the research design.

### 2.3.1 Maintenance Policy

A clear definition for the term maintenance policy is defined by Pintelon and Parodi-Herz (2008), where it is defined as a policy that dictates which parameter (for example, elapsed time or amount of use) triggers a maintenance action. A suitable list consisting of six maintenance policies, consistent with this definition, has been formalized by Tinga (2010) and Goossens and Basten (2015):

- *Failure-based maintenance:* maintenance is performed correctively only, meaning that one deliberately waits for something to break or fail
- *Calendar-time based maintenance:* maintenance actions are performed at fixed time intervals
- *Use-based maintenance:* the actual use triggers maintenance, such as operating hours
- *Use-severity based maintenance:* not the use, but its severity triggers maintenance, for instance the amount of operating hours performing above a certain load compared to total amount of operating hours
- *Load-based maintenance:* maintenance is triggered by measured internal loads, such as the measured strain in a certain structural component
- *Condition-based maintenance:* a measured condition dictates maintenance actions, such as particular levels of vibration or amount of dissolved metal parts in oil

These maintenance policies can be divided in two main policies, a corrective maintenance policy (CM) and a preventive maintenance policy (PM) including periodic and condition based maintenance (Grimmelius, 2003; Tinga, 2010; Goossens and Basten, 2015; Poppe et al., 2017). With a CM policy, maintenance is only performed after the component has failed and is then replaced or repaired. Next to its simplicity, the main advantage of this policy is that no remaining useful life of components is wasted, meaning that the minimal number of parts is used and the minimal number of maintenance actions is required. The main drawback of the CM policy is that when maintenance is required, the resources have not been scheduled to be sent yet, which means that costly emergency measures may be required resulting in high failure costs. With a PM policy maintenance (repair or replacement) is triggered after a certain period, intensity of use or when measurements indicate deterioration of the component. The main advantage of this policy is that it reduces the number of unexpected failures, since the component is replaced before it breaks down. This relates to the main drawback of this policy, which is that the lifetime of components is not fully utilized.

Maintenance is often based on the basis of availability, if no back-up or stand-by system is available (or not reliable), maintenance becomes more crucial (Grimmelius, 2003). Striking the right balances governing maintenance is important for ship-owners, too much maintenance will result in high cost, but too little maintenance can result in failure, which in turn also results in high costs. To be able to perform maintenance, various resources are required: spare parts, trained personnel, facilities, tools and test equipment. If these resources are not available, maintenance cannot be performed (Poppe et al., 2017).

MSG is equipped with a small technical department, this department has a practically oriented vision to ensure minimal downtime for its vessels. This department combined with the vessel crew is responsible for maintenance of the vessel and responsible for dealing with unforeseen equipment failures. The currently embraced maintenance policy for most of the container-crane vessels' equipment is a corrective maintenance approach, which means these components are used until failure. This is the easiest strategy to deploy and the main idea is to return equipment to service as quickly as possible. This approach especially holds for the cargo handling equipment, this is largely due to the fact that the crane is a unique facet of the inland barge. Because of its unique nature there is a gap in knowledge for the equipment on critical components and possible preventive maintenance tasks or activities. With the corrective maintenance approach mainly one-time solutions are proposed for each specific failure (ad hoc approach). For any malfunctions or problems with the vessels technical state, experienced by the crew, the technical department is informed. Of this department their first contact visits the vessel and determines the damages and required actions for any repairs. He requests quotations, orders parts, does minor repairs and handles all other aspects of the repair. The fact that a corrective maintenance approach is used means there is a lack of available data on the state/condition of components during usage.

There are two different ways to deal with the usage of components in inventory: a static approach where theoretical life expectancies are assumed, which are based on technical expertise and experience; and a dynamic approach where the actual residual life of the components are determined. The relatively simple static approach assumes that the spare-parts in inventory have a fixed life span, and this assumptions does not change during usage of the component. With the more advanced dynamic approach the residual life of components is determined/based on extensive data from measurements. The life expectancy of components can possibly effect the failure probability, level of inventory, inventory costs etc. and therefore has an impact on the research design. The lack of an advanced preventive (condition based) maintenance program and resulting lack of data on the condition of the components makes the dynamic approach unfeasible for this research.

At MSG the means and expertise to set up an advanced preventive maintenance strategy are currently not available. However, the goal of the organisation is to expand the technical department and direct more attention towards preventive maintenance in the near future. Before a preventive maintenance strategy for components related to the cargo handling gear can be set up more exploration and research in this field is needed.

### 2.3.2 Inventory Management

Currently there is a limited inventory of spare-parts for the MKS Mercurius container-crane vessel. At times parts for the cargo handling gear are hard to quickly obtain. This is mainly due to the fact that the manufacturer is located in Austria; and the lack of availability of parts due to the specific characteristics of the crane mounted on the vessel.

There are several studies done which discuss the effects of maintenance policy on inventory management. Hmida, Regan, and Lee (2013) and Poppe et al. (2017) showed that inventory costs could be significantly reduced (for large inventories) by implementing a preventive (condition based) maintenance program to identify (almost) exactly when these parts are required. This means that the level of inventory is lower and the time of acquisition is closer to the moment these parts are required, which reduces both capital and warehousing costs. Currently at MSG no such preventive maintenance program is in place, which means for this research the technically sub-optimal approach is used where at any given point in time all identified parts will be stored in inventory (maximum inventory). Which means inventory costs are likely to be higher, compared to inventory costs with a preventive maintenance policy in place. These studies are mentioned to indicate the diversity of considerations to take into account regarding maintenance and inventory, but developing a preventive (condition based) maintenance program or quantifying possible effects of PM on the optimized spare-parts inventory is out of the scope of this project (see Section 1.4). What can be derived from these studies is that: when the effects of failure, meaning the effects of uncertainties regarding scheduling resources, are reduced, the currently employed corrective maintenance approach can be improved and the failure costs can be reduced.

## 2.4 Intermediary Conclusion

This chapter described the ownership structure, maintenance strategy and inventory management strategy of the container-crane vessel(s) and indicated the influence on the research design. As a result it provides an answer to the following exploratory (sub) question:

*How do the organizational structure and current maintenance strategy influence the research design?*

The division of management and ownership structure (organisational structure) showed that there are several subsidiaries involved in management of the vessel. This means the result and methodology of the research is affected (limited) by the expertise of these sources and the quantity of available data that these sources can provide. Furthermore it showed that, since MSG fully owns both the vessel (MKS Mercurius) and the subsidiaries involved in daily management that, MSG is the sole decision-maker, sole cost-carrier and sole beneficiary of the vessel. As a result the effect of failure on the expected financial performance of the vessel will be determined, but allocation of these effects to its subsidiaries (cash flow schemes etc.) is disregarded since it has little contribution to the main objective.

The current maintenance strategy showed that there is a lack of available data on the condition of components related to the crane. The current maintenance approach could be best described as a corrective maintenance strategy, which means components are used until failure. This simplifies/limits the research to a (static) approach where the current condition of components is neglected and theoretical life expectancies are assumed, which are based on technical expertise and indications from suppliers. This assumption is independent on intensity of use and does not change during the components life. A more advanced method would be to determine actual residual life of the components with extensive data obtained from measurements (dynamic approach). This would mean that the components residual life is dependent on intensity of use and the amount of physical deterioration, which is measured and calculated. As a result the moment these parts are required can be identified, which means the level of inventory is lower and the time of acquisition is closer to the moment these parts are needed. This (dynamic) approach requires an extensive maintenance and monitoring program, which is related to a preventive (condition based) maintenance strategy. Currently at MSG the means and expertise to develop an advanced preventive maintenance strategy are not available (and developing this is out of the scope of this project). This means for this research a technically sub-optimal solution is obtained, with maximum level of inventory. This does not necessarily mean that this is also the economically sub-optimal solution, since developing and using a preventive maintenance program also has costs (which may or may not be recovered).

Ultimately it can be concluded that the sole focus of the research is a consideration of risk of failure (financial) compared to costs of keeping inventory. Where the risk of failure is quantified by multiplying the failure probability with the failure costs (impact), which are mitigated with direct availability of spare-parts. The mitigation of risk of failures, by developing an optimized spare-part inventory, translates to an increase in reliability, since it leads to less downtime and an increase in operational capacity.

# Chapter 3

# Methodology & Related Literature

Chapter 2 described restrictions to the research design (including methodology) that originated from the organizational structure of MSG, and the maintenance strategy of the MKS Mercurius. This chapter addresses the applied methodology in answering the sub questions stated in Section 1.3, and describes the related literature used to define this approach. For each of the sub questions the method, used literature, general sources of information and relevance with obtaining an answer to the main research question are discussed in a separate subsection.

The proposed methods for answering the sub questions is addressed in Sections 3.1 till 3.10, and conclusions regarding feasibility of the research are discussed in Section 3.11.

## 3.1 Defining Systems & Components

In order to ultimately propose a spare-part inventory it is first important to understand what systems and components the cargo handling gear consists of. For this reason a system and component breakdown of the container-crane vessel is composed. This results in the methodology associated with the following sub question:

1. *Which systems and components form the cargo handling gear of the MKS Mercurius?*

A method to structure this breakdown is by constructing a component tree. A component tree is a method to structure, and decompose, components and systems following a top down approach. It follows a hierarchy form where the final product or function is located at the top of the hierarchy and each level down sub-categorizes the above function or component group in smaller elements. A different approach could be to structure the components in a list or web structure. Comparing structuring the items in a list to a component tree method, the list wouldn't evidently indicate the relations between components or vessel functions. Turan et al. (2011) showed that structuring a system breakdown in a web structure could be used for small systems describing main component groups, but this method is unsuitable for larger complex structures with multiple levels of depth (division of components into smaller elements).

Ultimately the component tree structure is chosen because: it indicates relations between components; it gives a schematic visual representation of the components and systems involved; and because it can easily be modified to fit the practical application of the Fault Tree Analysis described in Section 3.2 (Fig. 3.1). For this research, the component tree contains a division in components related to the cargo handling gear and a section with components related to the vessels ability to self-propel. As previously mentioned, due to the dependency on Liebherr for spare-parts the focus of this research is with systems and components related to the cargo handling gear. As a result this (crane) section is specified in more detail.

The component tree is based on available system documentation provided by Liebherr, generated with the aid of the technical department and constructed largely based on field research with several vessel visits.

## 3.2 Deriving Failure Probabilities for Systems/Component Groups

Once the (main) systems and components related to the cargo handling gear are known, the probability of failure for these component groups provides further insight into the reliability of these components and ultimately quantifies the effects on reliability/availability of the container-crane vessel (failure analysis). The methodology for obtaining these failure probabilities for (main) component groups is described in this section, which correspond with finding an answer for the following sub question:

2. *Which failure probabilities can be attributed to these systems and components?*
   (a) *Which failure probabilities can be attributed to compound component groups?*

With a failure analysis the root causes of malfunctioning component groups and the probability of this failure occurring can be defined. There are several methods to conduct a failure analysis, the most used methods in reliability engineering are Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FMEA) and Reliability Block Diagrams (RBD) (Anthony et al., 2012; Peeters, Basten, and Tinga, 2017). The strengths, weaknesses and application of these methods will be discussed below. Subsequently, a decision is made defining the method used in this research.

Fault Tree Analysis is a top-down approach where an undesirable event is identified as the "top event" in the "tree" and the potential causes that could lead to the undesirable event are identified as "branches" below. An example of Fault Tree Analysis is introduced in Figure 3.1. FTA uses Boolean algebra (AND gates "half circles" and OR gates "moon shape") in a graphical representation to show the logical interrelationships between the initiating event (component failure) in a branch to other branches and the top event. The triangle shown in the figure replaces the branch described for pump system 1, since this system breakdown is identical for both pump systems. If the failure rate is available for all of the initiating events (component failures) in the fault tree, results (failure probability, reliability, etc.) can be calculated for the "top event" and each of the branches (Sinnamon and Andrews, 1997; CRgraph, 2014; Smith, 2017):

For an AND Gate:

$$P_{sys}(t) = P_a \times P_b \times P_c \times .... \times P_n \tag{3.1}$$

For an OR Gate:

$$P_{sys}(t) = 1 - (1 - P_a) \times (1 - P_b) \times (1 - P_c) \times .... \times (1 - P_n) \tag{3.2}$$

The methodology to obtain failure rates or failure probabilities for these initiating events (single components) is discussed in Section 3.3. FTA is a widely used reliability tool used for different applications. Morello, Cavalca, and Silveira (2008) presented an application of FTA on gearboxes of commercial vehicles, Turan et al. (2011) used it to determine criticality of systems of an offshore vessel to improve its maintenance strategy, Laskowski (2015) used

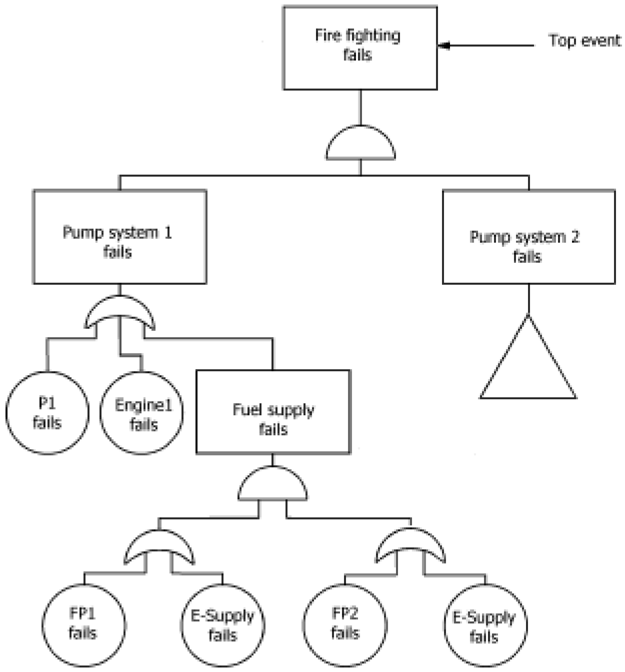



FIGURE 3.1: FTA Fire Fighting System

Source: Grimmelius (2003)

it (in combination with RBD) to model reliability for a marine main engine and Brocken (2016) used it to identify criticality and reliability of ship machinery in a study on unmanned shipping.

The second commonly used method for failure analysis is FMEA. The FMEA is a systematic method to map failure modes, effects and causes of technical systems or components (Peeters, Basten, and Tinga, 2017). It is a bottom-up method, where different failure modes of a component are identified after which additionally the consequences on a higher level are examined. For each component the failure modes and their effects on the rest of the system are written on a specific FMEA worksheet (Grimmelius, 2003). This worksheet contains: the component and its function; a description of (various) failure modes; the effect of the failure; and a severity ranking. FMEA is usually carried out with a diverse team of people with various expertise and carried out in the design stage. This is also the main drawback of this method, comparing this method to the FTA method: the FMEA method is more time-consuming and requires involvement of various experts, which are not available at MSG.

The final common method for failure analysis is Reliability Block Diagrams (RBD). RBD is a graphical representation of components that make up the system, showing network relationships. A RBD is drawn as a series of blocks connected in parallel or series configuration. It shows which systems and components need to function in order for the network to function, it is therefore an opposite of the FTA method and can be converted to an FTA by replacing the (parallel or series) paths with Boolean algebra. The RBD method is mostly used for electrical networks and in software engineering (Anthony et al., 2012).

Considering the applicability, strengths and weaknesses of the discussed methods for a failure analysis (FTA, FMEA and RBD), the FTA method is considered as the most optimal method, since compared to the other methods it: focusses on interrelationships between component failures and vessel functions; it provides a graphical, structured and easily understandable image; and it highlights the important elements of components related to system failures. Compared to the FTA method, the RBD method looks at combinations for success instead of resulting failures, which means the RBD has an opposite approach and for this application considered a more complicated method. As a result the RBD method is not used in this research. The FMEA method is not used since compared to FTA: it is a more time-consuming method, and in order to be successful it needs a large team of experts with comprehensive knowledge of systems and components related to the cargo handling gear. As a result the FMEA method isn't a valid and practical method to conduct at MSG.

The fault tree set-up and corresponding Fault Tree Analysis is based on system documentation available at MSG, literature studies and findings during vessel visits. The fault tree is constructed with the aid of the technical department.

## 3.3 Deriving Failure Probabilities for Single Components

As described in the previous section, to calculate failure probabilities and reliability of (main) component groups, using an FTA, first the failure probability of single components, which compose the 'compound' (main) component groups, must be known. This is addressed by the following sub question:

2. *Which failure probabilities can be attributed to these systems and components?*
    (b) *Which failure probabilities can be attributed to single components?*

Failure rate or failure probability is the relative frequency at which an engineered system or component fails, expressed in failures per unit of time and is highly used in reliability engineering (Antony, 2008). The failure rate is often shown as a function of operating time t, this function resembles a "bathtub curve" (Fig. 3.2). The curve shows different failure rates in stages of a components life, initially a decreasing failure rate in the burn in stage, secondly a constant failure rate during the useful (design) life and finally an increasing failure rate when the component has reached the wear out phase.

The failure rate or failure probability over time can be defined as a deterministic value or can be determined by a probability distribution. A deterministically assumed failure probability can be chosen as the same uniform failure rate for all components or a different failure probability must be assumed (educated guess) for each separate component. In practice, due to for example different loads, different stresses and different materials, there are different failure rates for different components and as described these failure rates vary over time. For the probabilistic approach the failure rate or failure probability over time can be determined by a probability distribution. There are different suitable distributions available, such as the negative exponential distribution, normal distribution, or the Weibull distribution (Grimmelius, 2003; Smith, 2017). Based on the probability distribution different failure rates over time can be obtained, constant for an exponential distribution, increasing with a normal distribution and varying with a Weibull distribution.

The negative exponential distribution, applicable to useful life phase with constant failure rate, is the most used distribution in reliability and availability studies. The constant failure rate assumes random failures, usually related to fluctuations of stress exceeding component strength, as the main failure causes (see Table 3.1). This method makes use of one single

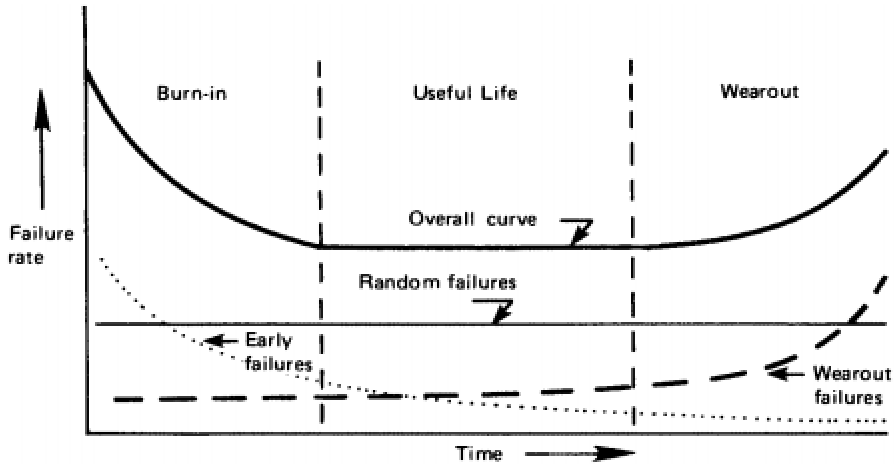



FIGURE 3.2: Bathtub Curve Failure Rate

Source: Smith (2017)

TABLE 3.1: Failure rate applicability

| | **Known as** |
|---|---|
| Decreasing failure rate | Infant mortality |
| | Burn-in |
| | Early failures |
| Constant failure rate | Random failures |
| | Useful life |
| | Stress-related failures |
| | Stochastic failures |
| Increasing failure rate | Wearout failures |

Source: Smith (2017) (Adjusted)

parameter, the average life expectancy ($\eta$) of the component, with which the failure probability at time t can be determined (Formula 3.3). The normal distribution is suitable for wear, corrosion and other age related failures. The normal distribution is usually applied to the wear out phase (increasing failure rate) of a component (see Table 3.1). This is a slightly more complicated method which uses the average life expectancy ($\eta$) as well as standard deviation ($\sigma$) (Formula 3.4). The final method is the Weibull (two-parameter) distribution, this function allows for widely different shapes of functions and can therefore capture the entire range of the bathtub curve by varying its parameters (Formula 3.5).

Negative exponential distribution:

$$f(t) = \frac{1}{\eta} e^{-(\frac{1}{\eta})t} \tag{3.3}$$

Normal distribution:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(t-\eta)^2} \tag{3.4}$$

Weibull distribution:

$$f(t) = \beta \frac{t^{\beta-1}}{\eta^{\beta}} e^{-(\frac{t}{\eta})^{\beta}} \tag{3.5}$$

For the Weibull distribution, the shape parameter or slope ($\beta$) of the curve can be adjusted to correspond with one of the three different characteristics areas of the bathtub curve (Smith, 2017):

- The infant mortality – decreasing failure rate of the bathtub curve – corresponds to $\beta$ < 1
- The useful life period – constant failure rate – corresponds to $\beta$ = 1
- The wear-out – increasing failure rate – corresponds to $\beta$ > 1

The most advanced method to define failure probabilities would be a probabilistic approach with use of the Weibull distribution where the parameters are estimated with extensive (historical) failure data. This failure data isn't available at MSG and this lack of data would significantly complicate this method. As a result, for this research, a probabilistic approach with the negative exponential distribution is used because: it is the most used calculation method in reliability and availability studies; the most achievable method; and calculations are straight-forward and relatively simple. Using this distribution ultimately results in an uniform failure probability during the components useful (design) life and is applicable to random failures (Table 3.1). Concluded by literature from Grimmelius (2003), Antony (2008), Smith (2017), and Brocken (2016) the useful (design) life is of most interest and this method is used in most practical applications. The normal distribution isn't used because it isn't suitable for general failure functions, but mainly suitable for wear out (aging) failures. Since with the use of the negative exponential distribution an uniform failure rate is calculated based on components average life expectancy, the deterministic approach loses its value because it is more time-consuming, requires expert opinions and is less substantiated with (likely) less accurate results.

To determine the failure rate an indication of lifetime or achievable running hours of these components must be known. Indications of component lifetime are based on experience of MSG's technical department and/or obtained from suppliers.

## 3.4 Determining Failure Durations

An important aspect that influences the decision making process for keeping a spare-part inventory is vessel downtime in case of failure (or duration of deviation from optimal vessel state in case of failure). The difference in failure duration in case of 'direct' availability of spare-parts, compared to the duration (in case of the same failure) without 'direct' availability of spare-parts provides insight in the effect of keeping a spare-part inventory on vessel availability and (ultimately) vessel reliability. This aspect is addressed by the following sub question:

3. *How does the availability of spare-parts affect the duration of the failure?*

The failure duration is dependent on the lead time of spare-parts and on the duration of component repair/replacement. For simplicity only failure durations in case of complete component replacements are taken into account, which is of most interest when spare-parts are required. The lead time can, for example, be dependent on the location of the spare-part and whether or not the part needs to be assembled. The duration of the repair/replacement can be dependent on: the need for necessary equipment, the need for hired technicians, required man-hours and/or (maybe) the need of shipyard based services. Direct availability of spare-parts will obviously have a large effect on the lead time, and therefore on the failure duration.

The resulting lead time and repair/replacement durations for the components can be assumed as deterministic values based on: historical data (previous failures), data from suppliers of MSG and/or experience from the technical department. Alternatively, the durations can be probabilistically determined values with different probabilities attached to different durations of lead or repair time.

At MSG technical expertise is available with insight in the container-crane vessels and broad experience with repairs. For this reason, this research will apply deterministic values to lead times and repair/replacement durations for the components in consultation with the technical department. These durations will be based on a combination of (partial) data from suppliers and input of the technical department.

## 3.5 Calculation of Repair Costs

Once the duration of the failure is known, the repair costs are determined to (partially) determine the impact/financial effects of the failure. The repair costs are part of the total failure costs, therefore the difference in repair costs with 'direct' availability of spare-parts partially quantifies the benefit of keeping a spare-part inventory. This aspect is addressed by the following sub question:

4. *How does the availability of spare-parts influence the costs of repair for the failure?*

The repair/replacement costs are dependent on required equipment, possible hire of technical personnel, additional man-hours of the crew, costs of (possible) shipyard based services and costs of delivery. The effect of 'direct' availability of spare-parts can have significant impact on these costs. The largest effect will obviously be on the delivery costs, when crane parts need to be flown in from Liebherr (based in Austria) this has high additional costs compared to 'directly' available spare-parts located in inventory. It may also have an effect on other related costs. For example, for the acquisition of parts in case of urgency to repair the vessel the price can be higher compared to when these are obtained without pressure and sufficient time to request multiple quotations etc.

The costs are calculated based on known values (such as hourly rates of personnel), based on indications from known suppliers of MSG and assumed in accordance with expertise of the technical department.

## 3.6 Defining Operational Restrictions of Failure

In order to define the total costs related to failure of a component, first the effect of component failure on operability of the vessel must be known. Failure of a component could lead to different restrictions on the operability of the vessel, this is addressed by the following sub question:

5. *Which restrictions to the operability of MKS Mercurius can be defined as a result of failure of these systems and components?*

To determine the effect on operability it is first determined in what different vessel states or vessel conditions the vessel can be deployed. For example, failure of a component can result in inability to use the crane. In this condition however the vessel can still be used as a conventional barge. Furthermore component failure could lead to restrictions in the use of the crane, with a weight limitation or limited rotation speed. Several more states/conditions after component failure(s) can be indicated.

To describe the effects of these vessel conditions on daily operations of the container-crane vessel (in a given time-frame) a division is made in 2 scenarios. The first scenario is when component failure of MKS Mercurius results in one of the derived vessel conditions, with MKS Transferium fully functioning as back-up to be able to (partially) take over capacity; and the second scenario is when component failure of MKS Mercurius results in one of the derived conditions as a single-acting vessel (MKS Transferium unavailable). For both scenario's a table is set up where the effects on container pick-up and delivery services for each condition are defined.

There is a wide spectrum of possible effects which can be related to the vessel condition and duration of the failure. These effects can have an impact on delivery of containers located in the holds, container pick-up from client locations or pick-up and delivery of containers at a terminal. Furthermore effects can include: planning adjustments, re-scheduling, potential loss of business or opportunity costs, possible vessel hire, alternative container pick-up and delivery methods, fines and/or compensation and estimated long-term damages. These effects, for failure resulting in one of the conditions, are derived based on experience of the operations department of freight operator MCT (subsidiary). These effects are described for both scenarios and all relevant vessel states.

After these consequences on operability are mapped, the FTA (SQ2) is further expanded to indicate which component failures lead to the derived vessel states. In the FTA blocks are added which describe the condition of the vessel (vessel state) and indicate which component failures result in this condition. This approach visualizes the relation between component failure and resulting vessel condition.

With the aid of the technical department the resulting vessel state after failure of the components will be identified.

## 3.7 Calculation of Financial Effects of Failure

In previous sections the methodology is described to obtain: the failure duration after component failure, the resulting vessel condition after component failure and the effect of this failure (condition combined with duration) on operability of the container-crane vessel. Once these aspects are defined the corresponding total failure costs can be determined to quantify the reduced failure impact with an optimized spare-part inventory. This reduced impact is quantified for both scenarios: (1) MKS Mercurius, taking into account availability of the MKS Transferium in case of failure, and (2) MKS Mercurius as MSG's single container-crane vessel. This is addressed by the following sub question:

6. *What are, given the duration and the restrictions to operability, the financial consequences/failure costs for MSG as organisation? And how is this affected by 'direct' availability of spare-parts?*

To determine the total failure costs a division can be made in: opportunity costs (revenue loss), container removal costs, additional costs (planning), business recovery costs and previously determined repair costs (SQ4).

The opportunity costs or revenue losses are related to the profits the vessel could have obtained without the (downtime due to the) failure. Which could be a loss of profit due to a reduction of crane work, a profit loss from (less) container deliveries to a terminal, or a combination of both. These costs are therefore equal to the obtainable net revenue (or a percentage of net revenue) multiplied by the failure duration. After failure it could be possible that containers cannot be picked up and/or delivered by MSG. This is for example the case for full containers on shore which in case of failure are removed empty in consultation with the client, after which no invoices can be send for these containers. This lost revenue is equal to the container movement rate multiplied by the number of alternatively transported containers. Container removal costs are related to the alternative transportation solutions that need to be arranged for containers located in the holds and at client location. This could include the need for vessel hires, costs for terminal deliveries (and trucking etc.), and fined/demurrage costs. Additional costs can entail costs related to planning adjustments and rescheduling. Business recovery costs are related to revenue losses in the week(s) after the failure has been restored, where business needs to restart and increase to its full potential.

To determine and calculate these costs a cost model is set up where for all vessel states, in both scenarios (SQ5), the total failure costs are calculated in different time-frames. These time-frames are defined based on failure durations and operational consequences after the failure. To determine the failure costs for each vessel state (and eventually each component), first a baseline scenario is defined where default values are chosen for the input variables. These for example contain: quantity of containers located in the vessels holds, quantity of container movements on shore at client locations, revenue per container movements, transfer rates for (unplanned) delivery of containers to a container terminal, and fine/demurrage rates. With this model the failure costs for each vessel state are determined. Since the condition after failure; the failure durations; and the effect of availability of a second container-crane vessel (MKS Transferium) on the operational consequences are known; the resulting failure costs for each component (in case of failure) can be determined.

Figure 3.3, based on default values to provide an example, shows the possible development of total failure cost over time. The effect of 'direct' availability of spare parts on the failure costs is shown in the figure. The failure durations for when the components are located in inventory and for when the components need to be ordered and delivered is previously determined (SQ3). Choosing the failure duration without spare-part as input for the model

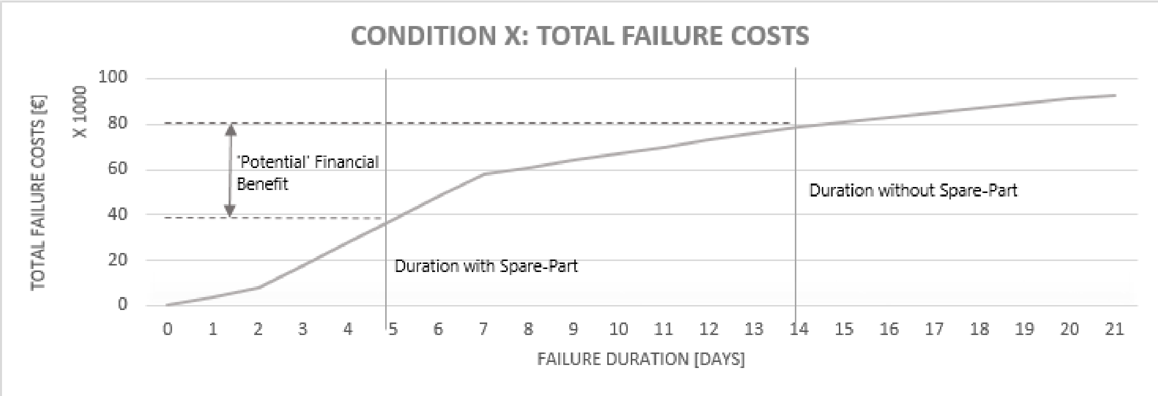



FIGURE 3.3: Approach to obtain 'potential' Financial Benefit

*Note*: Own Composition

then provides the total costs of failure in case the component is not directly available (in the figure ≈ €80,000) and vice versa the failure duration with 'direct' available spare-parts as model input provides the total failure costs with parts readily available (in the figure ≈ €37,000). The failure costs are related to the impact of failure, the risk of failure is quantified by multiplying the failure probability with the impact of failure (Eq. 3.6). The failure probability for components is unaffected by keeping an inventory, but the impact is mitigated. The mitigation of risk in case of inventory can therefore be determined with Equation 3.7.

$$Risk = Probability \times Impact \tag{3.6}$$

$$\Delta Risk = Probability \times (Impact\ without\ Inventory - Impact\ with\ Inventory) \tag{3.7}$$

This difference in risk, equal to the reduced impact, is identified as the potential financial benefit of keeping a spare item in inventory (in this case ≈ €43,000). With this approach the effect of keeping a spare-part inventory on the impact of failure is quantified.

To determine the opportunity costs (revenue loss), an indication of the daily obtainable net revenue of the container-crane vessels and the revenue (price) of a container movement are required. An estimate of the (usual) daily net revenue is estimated on the basis of historical financial performance of the vessel and based on an indication of barge operator MCT. For simplicity, the revenue per container movement is assumed as a fixed rate independent of the type of container and based on indications from MCT. Container removal costs are dependent on the alternative transportation method for containers located in holds and on shore. The necessities in terms of vessel hires etc. and corresponding costs are based on previous experience and determined in accordance with MCT. Additional costs related to rescheduling and planning are assumed as constant daily rates. Business recovery costs are determined as a percentage of daily revenue. These costs are based on indications from MCT.

## 3.8 Calculation of Inventory Costs

The previous section provided insight in the reduced impact of failure, defined as the potential financial benefit, with a spare-part inventory. On the opposite there are also annual costs related to keeping a spare-part inventory. These costs are determined to (eventually) be able to determine the cost-effectiveness of keeping a spare-part in inventory. This aspect is addressed by the following sub question:

7. *Which costs are associated with keeping a spare-part inventory and what are these costs for the described systems and components?*

The annual costs of keeping a spare-part inventory can entail: interest/capital costs, insurance or risk costs, depreciation of goods and warehousing costs (Blauwens, De Baere, and Van De Voorde, 2016).

All inventory represents capital. The assets stored in inventory can either be financed by debt or with equity (or a combination), this relates to the interest or capital costs. Capital financed by financial institutions (debt) has a fixed interest rate. This interest is considered as costs. Equity used to store components in inventory can even have higher costs, since shareholders expect a return on investment larger than the fixed interest rate for debt. Therefore, to determine the capital costs of inventory the division debt/equity of MSG must be known. This can be determined with the Weighted Average Cost of Capital (WACC). The WACC is the average costs of these types of financing, each of which is weighted by its proportionate use. A value for this rate can, for example, be based on historical financial performance or the interest rate.

The goods can be insured against, fire, theft, deterioration etc. if the goods are not insured a risk premium should be taken into account, these costs are usually insignificant (Blauwens, De Baere, and Van De Voorde, 2016). This can simply be the insurance rate, or can be assumed as a percentage of item value.

In general, especially with goods intended for trade, economic depreciation is the main costs factor. The economic depreciation for these goods is more significant than depreciation through physical decline or deterioration. It is difficult to make generalizations about the level of depreciation costs. Depreciation can be highly dependent on the type of product and technological development in the products related industry. In the computer market, for instance, each item, irrespective of its age, can become obsolete at any moment in time due to technological progress. There are also cases where depreciation of goods is zero. For example, no depreciation costs are taken into account when a car manufacturer stores spare parts in inventory for a model they plan to build for years to come, since they are bound to be used (Blauwens, De Baere, and Van De Voorde, 2016). In this case, for depreciation, one should also take into account inflation regarding the components and the increasing difficulties in acquisition of these components at future times. Spare-parts are considered fixed assets when these are held in inventory for longer periods (over 1 year). For depreciation of inventory fiscal legislation prescribed, for parts that are considered as fixed assets, to systematically depreciate to the residual value of the item.

Finally, when considering the annual costs of inventory, warehousing costs must be included. Warehousing costs are dependent on the location of storage, the items located in storage (size) and whether or not the storage is owned by MSG or by an external company.

In this research the WACC is based on historical financial performance of MSG and based on an indication of the accounting department, this value is assumed at a 6% rate. Calculating the WACC with extensive financial data is considered undesirable since various sensitive information is required and the resulting rate will presumably not differ much from the indicated 6% value. The insurance or risk premium is usually insignificant and will be assumed as a percentage of purchasing price in accordance with expertise of the technical department. For depreciation of goods, the components stored in inventory for MSG are not intended for trade, but intended for personal use in the remaining life of the vessel. The remaining life of the vessel is assumed 20 years. For the inventory it is assumed that when a component is used a new component is ordered and stored in inventory, which means at the end of the vessels lifetime one full set of inventory is left-over. At the end of the vessels lifetime the components in inventory can for example be: sold to a third-party, sold-back to the crane manufacturer (Liebherr) or in some cases used as spare by the MKS Transferium. It may even be possible to arrange a buy-back deal with Liebherr when acquiring the inventory. For this reason a residual value of 50% is assumed the entire inventory. The components are therefore linearly depreciated over 20 years, assuming a residual value of 50% of purchasing price. This results in annual depreciation costs of 2.5% of purchasing price for each component. Finally, warehousing costs are assumed as a fixed price per square meter and based on indications of costs (hire) for available storage units in the Rotterdam/Dordrecht area. The warehousing costs for each item are related to the area of storage they cover.

## 3.9 Cost/Benefit Assessment & Inventory Optimization

Once the risk of failure, quantified by the reduction in failure impact with 'direct' availability of spare-parts, and annual inventory costs are determined, an analysis can be made to determine the cost-effectiveness of keeping certain parts in inventory. With this analysis an optimized spare-part inventory can be proposed and the effect on reliability of the container-crane vessel ('MKS Mercurius') can be determined, resulting in an answer to the main research question. This aspect is addressed by the following sub question:

8. *For which components/parts is it, from a long-term financial perspective, cost-effective to store them in a spare-part inventory?*

In this research all effects are determined as costs or potential financial gains (money values). The lead and repair/replacement durations ultimately led to a difference in failure duration for a failure with 'direct' availability of spare-parts compared to the same failure without 'direct' availability of spare-parts. This difference in downtime, or duration of non-optimal vessel state, ultimately led to a difference in total failure costs. This difference in total failure costs multiplied with the failure probability of the component (Eq. 3.7) was defined as the potential financial benefit of having a spare-part in inventory.

Since both sides are solely money values a simple cost calculation is made in order to quantify the decision to keep a spare-part inventory. At the end of the calculation the cost total (SQ7) is subtracted from the total benefits (SQ6) to obtain the net benefit. The benefits are limited to a financial benefit for MSG, external effects (social or environmental) are neglected since they are out of the scope of this project. For a positive net benefit, the potential financial benefits exceeding total costs, the decision should be made to keep a spare item for that component in inventory. Otherwise, for a negative net benefit, one should refrain from the decision to keep a spare item for that component. As a result, the first condition for the decision to store an item in inventory is set, which is: that the decision to store a component in inventory should only be made if the benefits outweigh the costs.

For the net benefit calculation, the benefits are determined as the reduction in failure impact that can be achieved with 'direct' availability of spare-parts multiplied with the failure probability. This failure probability is incorporated to determine the expected financial benefit per annum. Since the components usually have an average life expectancy of multiple years, the expected failure costs per annum can be determined by multiplying the total failure costs with the failure probability. The financial benefit (per annum) is than determined by the difference in these expected failure costs for 'direct' availability of spare-parts compared to not 'direct' availability of spare-parts. Alternatively, multiplying the previously determined financial benefit of 'direct' availability of spare-parts (SQ6) with the failure probability yields the same result. The costs are equal to the costs of keeping a spare-part inventory (SQ7), which are already determined as costs per annum (Section 3.8).

The second condition that must be met for the decision to store an item in inventory is: the remaining life of the vessel must be substantial compared to the average life expectancy of the (spare) component. This means it is guaranteed that, even without failure, the spare part will be used during the vessels (remaining) life. Since the container-crane vessels are niche vessels the life expectancy after construction was assumed 30 years, which is low for inland vessels. The MKS Mercurius therefore has approximately 20 years of service left, which means this second condition will most likely be met for all components and is therefore neglectable.

## 3.10 Executing Sensitivity Analysis

The last step in the research is to identify the effect of made assumptions and used parameters on the proposed inventory. This aspect is addressed in the last sub question, which is:

9. *How do uncertainties in the assumptions made in this research affect the proposed inventory strategy? How sensitive are the results regarding these uncertainties and how do they affect the financial outcome?*

In all models, parameters contain uncertainty and assumptions of any model are subject to change and error. Sensitivity Analysis (SA), broadly defined, is the investigation of these potential changes and their impact on conclusions to be drawn from the model. Pannell (1997), Saltelli et al. (2004), Cacuci, Ionescu-Bujor, and Navon (2005), and Saltelli, Chan, and Scott (2008) stated that a Sensitivity Analysis should be an integral part of any solution methodology and the status of a solution cannot be understood without such information.

In this research the main uses of the SA will be for decision making or development of recommendations and to provide an increased understanding or quantification of the system. It will be mainly used to define how robust (insensitive to changes in parameters) the optimal solution is and to analyse relationships between input parameters and output (list of spare-parts for optimal inventory). For this reason there is opted for a simple systematic approach, which entails the following steps:

1. Selection of parameters, identify a range (minimum, default, maximum) of values that realistically reflects the possibilities
2. Conduct sensitivity analysis for each parameter individually:, using the identified range and determine the effect on the (optimal) selection of spare-parts to store in inventory

3. Determine sensitivity indices for parameters to rank relative sensitivity of parameters to the model, by determining the difference in output for the maximum and minimum input values
4. Summarize results
5. Draw conclusions

After this process the effect of uncertainty to the optimized inventory, of systems and component related to the cargo handling gear, for the MKS Mercurius is defined.

## 3.11 Conclusion

From the concise literature research and the defined methodology it can be concluded that a feasible and suitable method is available to obtain an answer for each sub question. As a result a feasible and suitable approach is constructed to formulate an answer to the main research. The main difficulties, which can be encountered, throughout the research are due to a lack of available and reliable data. The data will be compiled in consultation with MSG's technical department and the sensitivity of used data to the conclusions and recommendations of the research will be determined to eliminate this concern. The application of aforementioned methodology is described in Chapter 4 till Chapter 8. In each chapter one or multiple sub questions are addressed. In Chapter 9 the answer to the main research question is formulated and recommendations for MSG's inventory strategy are proposed.

The obtained results in this thesis are mainly based on: (1) the development and analysis of cost models resulting in (2) a benefit/cost calculation; (3) field research; (4) expert opinions; and (5) literature research.

# Chapter 4

# Breakdown of Crane Components & Failure Analysis

This chapter provides a breakdown of systems and components of the MKS Mercurius and addresses the failure analysis of single components and compound systems related to the vessel's cargo handling gear.

## 4.1 Component (Tree) Breakdown

There are a variety of systems and components installed on the MKS Mercurius. These have different functions and criticality to the vessels operations. Most of these components are either related to the cargo handling gear or the vessels propulsion/drive shaft. Therefore, in the breakdown, a distinction is made in systems and components related to propulsion and systems and components related to the cargo handling gear. The focus of this research is with systems and components related to the cargo handling gear, as a result this (crane) section is specified in more detail. The full system and component breakdown of the cargo handling gear is shown in Appendix A (Fig. A.1).

In order to quantify the level of breakdown for the components a number of conditions are taken into account. The first condition includes that the component is only included in the breakdown (or the level of breakdown stops) when the component is self-contained, which means they can be ordered as single units, they can be replaced as single units and the components are not readily/easily available, which means delivery includes lead time. Furthermore, it is assumed that steel structure or housing is unlikely to fail, due to its strength and robustness, and is therefore not included in the breakdown. As third condition a practical aspect is taken into account, when the component is very large, but can be ordered/replaced entirely, and consists of several sub components which meet the other conditions, then the component is further broken down in these sub components. The decision diagram which is used to determine the level of breakdown of the components is given in Figure 4.1.

Following the decision diagram it can be seen that when components are single units and can be replaced and ordered (including lead time) as single unit the level of breakdown stops. For example, based on these conditions, a hydraulic pump for the cargo handling gear is included in the breakdown and not further expanded. This because it can be ordered and replaced as a single unit and considerable lead time is included as the pump is not easily available.

The cargo handling gear can be divided in a section with 'internal' components, these are implemented in the hull of the vessel, and the 'externally' mounted crane (Fig. 4.2). The

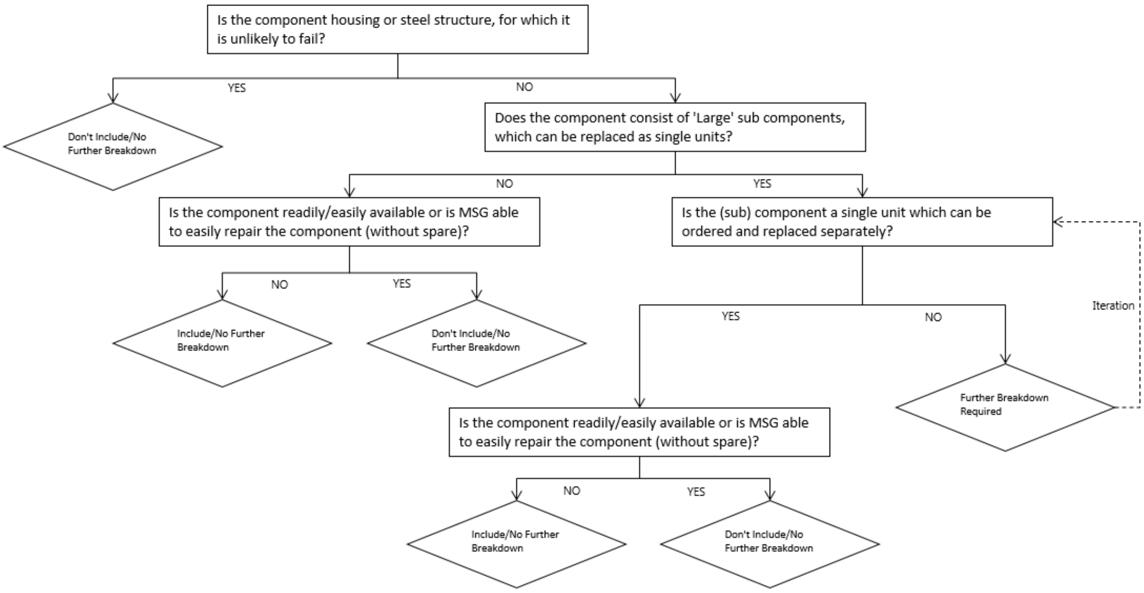



FIGURE 4.1: System & Component Level of Depth Decision Diagram

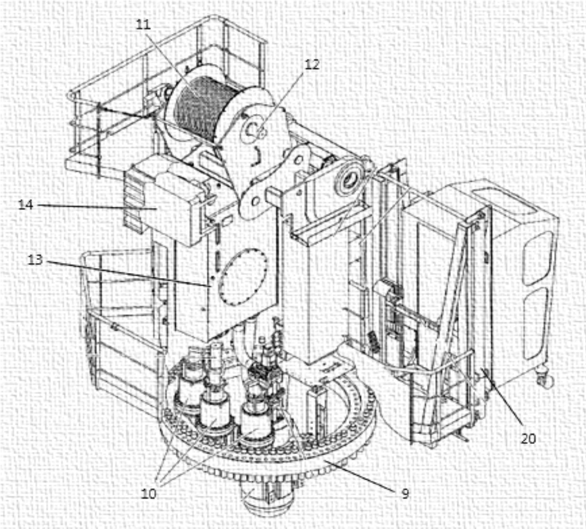
*Note*: Own Composition

main 'internal' systems are an Anti-Heeling System, consisting of a Contra-Weight System and a Pump Anti-Heeling System, and the power supply located in the engine room. The 'externally' mounted crane can be divided in a drive unit (Fig. 4.2b), which provides electric power for all the functions the crane must be able to perform, the crane itself (Fig. 4.2c) and the spreader, a device used to lift containers and unitized cargo.

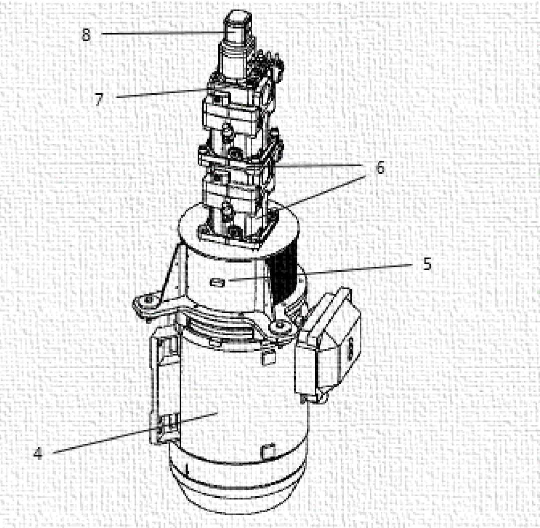
The Anti-Heeling System detects the angle (compared to its upright position) of the vessel during lifting and automatically corrects this. The Contra-Weight System consists of two weight blocks which exert an opposite force to balance the system. These weight blocks are driven by a power pack. The power pack consists of an electric motor that drives two hydraulic pumps, both hydraulic pumps drive two hydraulic motors which force movement of the weight blocks. These weight blocks are connected with a chain. The Pump Anti-Heeling System is divided in a front and back section each with two reversible axial pumps connected to the ballast tanks. A port-side and a starboard-side ballast tank are connected by the two reversible axial pumps; each of these is driven by an electric motor; combined with a butterfly valve, to regulate flow between the tanks; and a frequency regulator, to send a signal to the valves during lifting.

Both the Anti-Heeling System and the external crane are powered by a generator, which is mechanically connected to the main engine and located in the engine room. The full power supply, for both the crane and vessel propulsion, consists of two identical drive shafts. A drive shaft can either be used for propulsion or used to drive the crane and not provide to both needs at the same time. This means when the vessels' crane is used, using the port-side drive shaft for its power supply, the supply to the propeller (for the port-side shaft) is disconnected. To supply power to the crane these shafts are interchangeable, which means either the generator on the port-side shaft or the generator of the starboard-side shaft can be used for the crane.

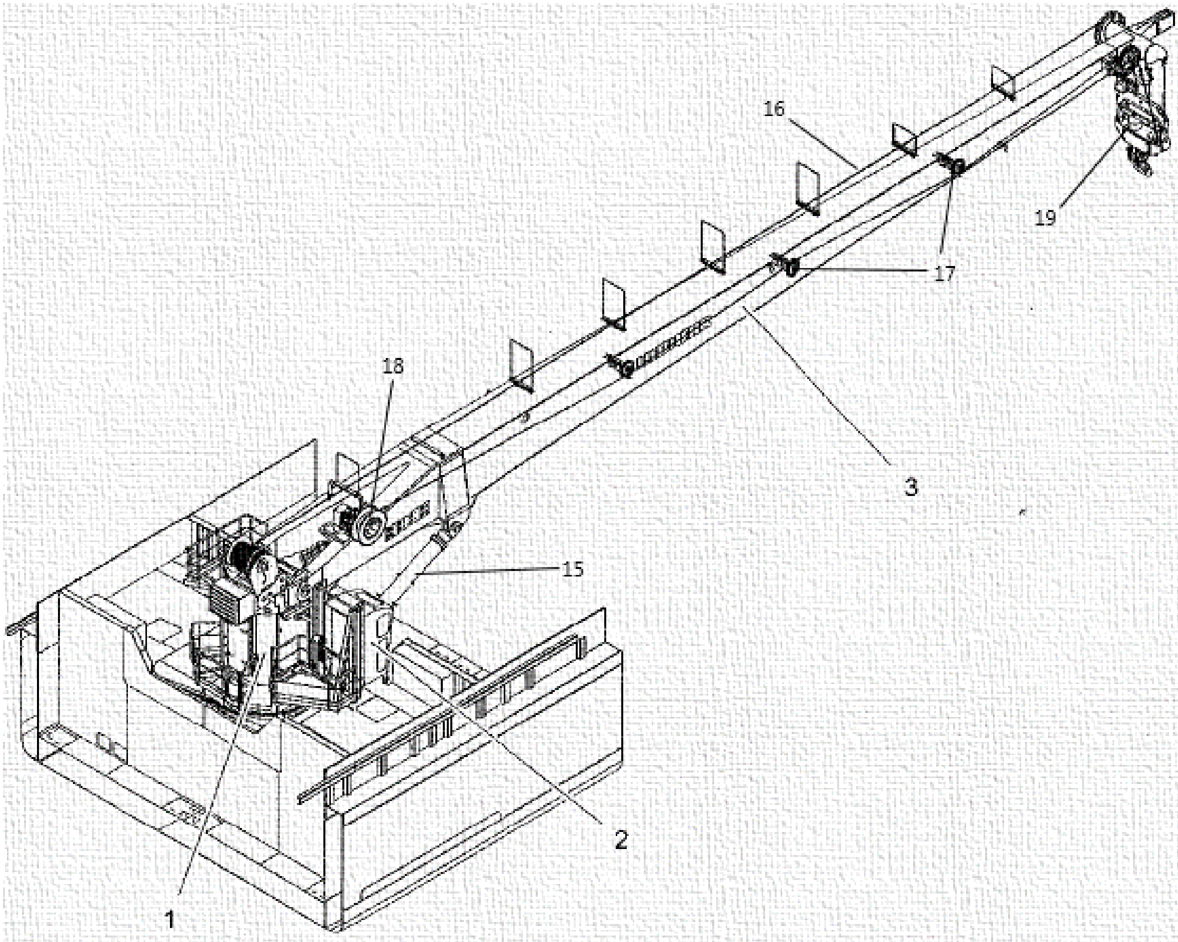
The drive unit (Fig. 4.2b) is mounted inside the slewing column of the crane. The drive unit consists of [#4] a central power unit/electric motor, [#5] a coupling and a hydraulic




(A) Slewing Column & Cabin




(B) Drive Unit




(C) Strengthened Hull & Mounted Crane

FIGURE 4.2: 'Externally' Mounted Crane

*Note*: Own Composition based on system documentation provided by Liebherr unit consisting of [#6] a double V-pump (main pump), an [#7] oil cooler pump, and [#8] a control pump. The two main pumps take care of the movement functions of the crane, they drive the cylinder to rotate the crane, the boom to in- or decrease the crane's reach and the hoisting cable to lift the containers. The oil cooler pump drives the cooling fan to prevent overheating and the control pump drives the cabin to adjust the height.

The Liebherr crane itself is divided in [#1] the slewing column, [#3] the crane boom and [#2] the operator cabin. Inside/at the slewing column (Fig. 4.2a) of the Liebherr crane is where most of the components are located. The column is able to rotate 360 degrees around its axis. The main component groups of the slewing column can be divided in the slewing ring, the hoisting gear, the hydraulic tank and the luffing gear which is connected to the slewing column as well as the crane boom. The slewing ring rotates the crane around its axis and is divided in [#9] a slewing ring roller bearing and [#10] three slewing gears. These gears are connected to the roller bearing and put the column in motion. The hoisting gear directs the cable and enables the crane to lift containers. The hoisting gear is separated in [#11] the hoisting winch and [#12] the hoisting gear hydraulics, consisting of an oil (hydraulic) motor and a pressure switch. The hydraulic tank [#13] supplies the system with enough fluid to keep operating and prevents the system from overheating. It consists of a suction pipe and [#14] an oil cooler. The luffing gear, which is the connection between the slewing column and the crane boom, consists of [#15] two hydraulic luffing cylinders. Some essential components are located at the jib of the crane, used for luffing of the crane boom and lifting of the containers. These elements include: [#16] the lifting cable; [#17] guide rollers to align the cable; [#18] the cable drum to roll in the cable; and [#19] the lifting hook. The cabin is where the crane can be manually controlled by the operator. It consists of [#20] two hydraulic cylinders which adjust the height of the cabin, two control modules with which the crane can be operated, a cable guide to direct cables towards the cabin and an electric safety sensor which indicates weight/reach limitations during lifting.

The spreader is attached to the crane and is used to connect (lock-in) the container when lifting. It has a locking mechanism at each corner to attach the container to the spreader. The spreader consists of the unit itself and an attachment set. The attachment set consists of two twist-locks which connect the container and two steel cables with which the crane is connected to the spreader.

## 4.2 Failure Probability

This section addresses the failure analysis for systems and components of the vessels cargo handling gear. It starts with the identification of important elements and components based on a qualitative analysis, after which failure probabilities are determined and a quantitative analysis is executed.

### 4.2.1 Fault Tree

Fault Tree Analysis (FTA) is one of the basic methods of assessing reliability (see Section 3.2). FTA is a top-down approach where an undesirable event is identified as the "top event" in the "tree" and the potential causes that could lead to the undesirable event are identified as "branches" below. As a result, FTA can model the possible combinations of equipment failures that lead to a specific top event. In this case the undesirable top event is failure of the vessels cargo handling gear, for which the top of the fault tree is shown in Figure 4.3.

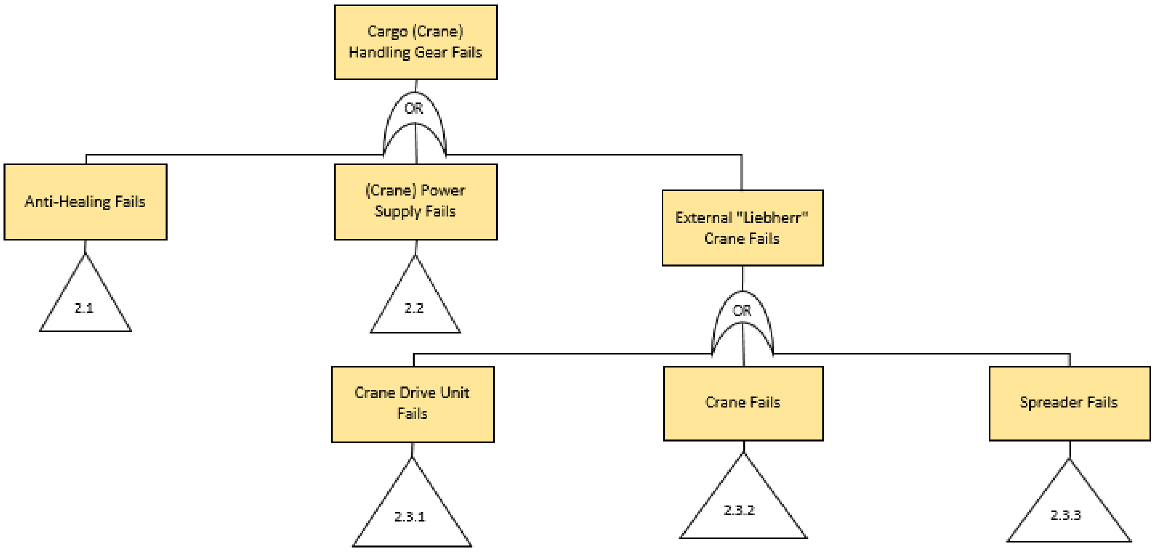



FIGURE 4.3: Fault Tree Top Event

*Note*: Own Composition

The crane fails if either the Anti-Heeling System, the (crane) Power Supply or the External "Liebherr" Crane fails (which fails if the drive unit, crane itself or the spreader fails). The numbered triangles indicate the branch that need to be attached to this event. The entire fault tree, including all numbered branches, is given in Appendix B.

The fault tree for failure of the drive unit is shown in Figure 4.4. This branch is used to clarify the illustration. As previously described (Section 4.1), the drive unit consist of a central power unit (electric motor), a coupling and an hydraulic power unit. Failure of either of these 'components' leads to failure of the drive unit, which is indicated with an OR gate. The hydraulic unit consists of a double V-Pump (main pump), which both need to function to move the crane, which means failure of either of these leads to failure of the drive unit (OR gate). Failure of the remaining hydraulic pumps simultaneously also results in failure of the drive unit.

### 4.2.2 Fault Tree Analysis (Qualitative)

Once the fault tree is constructed, the structure of the tree can be examined qualitatively to understand the mechanisms of failure. This information is valuable as it provides insight into the modes of failure (i.e. all the combinations of component failures that lead to the top event). The qualitative analysis is used to: (1) identify critical components of the system, which in this case is the vessels cargo handling gear; (2) identify potential system weaknesses; and (3) gain insight in the potential risk of failure when parts are not in inventory.

This process (qualitative analysis) is known as minimal cut set analysis. Minimal cut set analysis is a mathematical technique to identify all combinations of events that result in the occurrence of the top event. These basic event combinations, called cut sets, are then reduced to identify those "minimal" cut sets, which contain the minimum sets of events necessary and sufficient to cause the top event. Single component minimum cut sets mean that failure of this component directly leads to the top event; double component minimum cut sets mean both components must fail to lead to the top event, etc. This means that small minimal cut

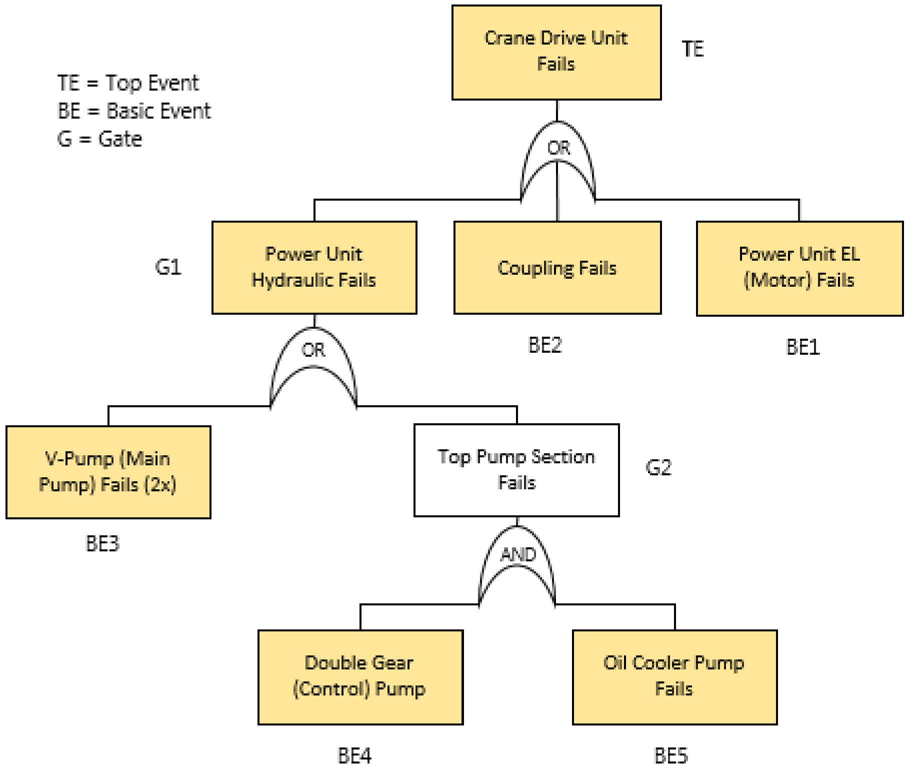



FIGURE 4.4: Fault Tree Drive Unit

*Note*: Own Composition

sets represent less redundancy and therefore have higher criticality to the system. However, the qualitative analysis can also be misleading, it is possible that larger cut sets have a higher failure frequency than smaller ones (CCPS, 2000). This will be evaluated in Section 4.2.4.

Depending on the complexity of the fault tree, inspection can be difficult and formal means need to be applied, such as Boolean Analysis or inspection with the aid of software tools. Boolean Analysis is used to algebraically convert the tree to a Boolean expression defining the top event in terms of a combination of all lower events. The top event is defined as TE, basic events (component failures) as BE and gates as G. Conventionally, the symbol "+" is used to represent the logical OR operator and the symbol "x" is used to represent the logical AND operator. For the crane drive unit (Fig. 4.4) this would lead to the following equations for each gate of the tree:

$$TE = BE1 + BE2 + G1 \tag{4.1}$$

$$G1 = BE3 + G2 \tag{4.2}$$

$$G2 = BE4 \times BE5 \tag{4.3}$$

Which due to substitution leads to:

$$T = BE1 + BE2 + BE3 + (BE4 \times BE5) \tag{4.4}$$

The top event (in this case failure of the drive unit), therefore, contains 3 single component minimum cut sets and 1 double component minimum cut set. Whether or not this can be done algebraic or needs to be done with software tools depends on the complexity of the fault tree.

The fault tree for the cargo handling gear is rather large, which means a large amount of minimal cut sets can be identified. To identify critical components based on a qualitative analysis the smallest minimal cut sets (or single component minimal cut sets) are of most interest, since these components lead directly to the top event (Smith, 2017). For this reason the single component minimum cut sets are presented in Table 4.1. Whether or not there are other components that have a high contribution to the failure frequency of the top event is identified by the quantitative analysis in Section 4.2.4.

The components presented in the table, of which failure would lead directly to the inability to use the cargo handling gear, are all part of the external crane. This is mainly due to the fact that the internal systems, such as Anti-Heeling and (Crane) Power Supply, include redundancy for most components.

### 4.2.3 Component Failure Probability

The failure rate or failure probability of components must be known to determine the likelihood of failure in a specific time-frame. The failure rate ($\lambda$) is defined as the relative frequency at which an engineered system or component fails, expressed in failures per unit of time, and is highly used in reliability engineering (Antony, 2008). The probability of an occurrence – or the probability of a certain failure rate – is mathematically described by defining a suitable probability distribution.

TABLE 4.1: Single Components Minimum Cut Sets Cargo Handling Gear

| Component | Location/Branch |
|---|---|
| Power Unit EL (Motor) | Crane Drive Unit |
| V-Pump (Main Pump) | Crane Drive Unit |
| Coupling | Crane Drive Unit |
| Slew Ring Roller Bearing | Slewing Column |
| Luffing Cylinder | Slewing Column |
| Luffing Bearing (Cyl.) | Slewing Column |
| Hoisting Winch | Slewing Column |
| Lifting Cable/Rope | Crane Boom |
| Cable Drum | Crane Boom |
| Rope Guard | Crane Boom |
| Cargo Block | Crane Boom |
| Motor Swivel Gear | Crane Boom |
| Control Module | Cabin |
| Blockchain | Spreader |
| Twistlock | Spreader |

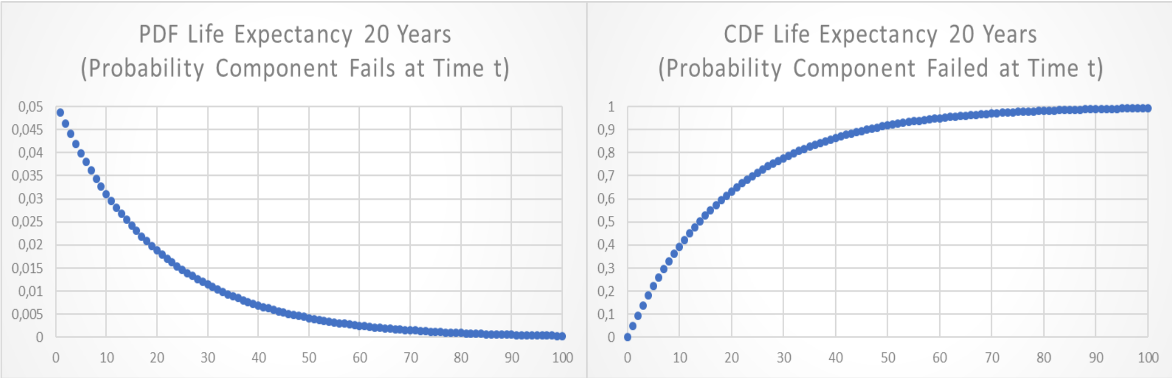
*Note*: Own Composition

To determine the failure probability of components related to the cargo handling gear a negative exponential distribution is assumed, because the negative exponential distribution provides a constant failure rate over the components lifetime (see Section 3.3). The negative exponential distribution is the most used distribution in reliability and availability studies (Grimmelius, 2003). This method makes use of one single parameter, the average life expectancy ($\eta$) of the component, with which the failure probability at time t can be determined.

$$F(t) = 1 - e^{-(\frac{1}{\eta})t} = 1 - e^{-\lambda t} \tag{4.5}$$

Figure 4.5 shows the probability density function (PDF) and cumulative distribution function (CDF) for the negative exponential distribution. These functions are directly related, since the PDF is the derivative of the CDF. The CDF (Eq. 4.5) (or PDF) enables us to calculate the probability of various outcomes, or events. By definition the CDF indicates the probability that the random variable takes on a value less than or equal to t. Similarly, with the CDF you can calculate the probability that the variable takes on a value larger or equal to t, the probability that the random variable falls into some interval ($t_1$;$t_2$) and the probability that the value falls into some interval ($t_1$;$t_2$) after serving a defined amount of time until $t_1$.

The last mentioned probability is the one used to define the failure probability of the various components. The probability of failure in a fixed interval of usage (for instance a period of one year) can be determined with Equation 4.6. In case of an infinitely small interval this leads to Equation 4.7. The probability that the component didn't already fail before this interval ($t_1$;$t_2$) can be determined with Equation 4.8. Combining these equations provides the probability that the component fails in a specific interval, including the condition that the component didn't previously fail (Eq. 4.9). The failure rate is mathematically defined by Equation 4.10 (Antony, 2008). As a result (Eq. 4.11) it can be seen the failure probability for components at time t is equal to the failure rate (which is equal to $1/\eta$).




(A) Probability Density Function f(t)

(B) Cumulative Distribution Function F(t)

FIGURE 4.5: Negative Exponential Distribution

*Note*: Own Composition

$$P(t_1 \leq X \leq t_2) = \int_{t_1}^{t_2} f(t)dt = F(t_2) - F(t_1) \tag{4.6}$$

$$P(t_1 \leq X \leq t_2) = \int_{t_1}^{t_2} f(t)dt = F(t_2) - F(t_1) \approx f(t_2) \tag{4.7}$$

$$P(X \leq t_1) = 1 - F(t_1) \tag{4.8}$$

$$P(t_1 \leq X \leq t_2 | X \leq t_1) = \frac{F(t_2) - F(t_1)}{1 - F(t_1)} \tag{4.9}$$

$$\lambda = \frac{f(t)}{1 - F(t)} \tag{4.10}$$

$$P(t_1 \leq X \leq t_2 | X \leq t_1) = \frac{F(t_2) - F(t_1)}{1 - F(t_1)} = \frac{f(t_2)}{1 - F(t_1)} = \lambda = \frac{1}{\eta} \tag{4.11}$$

This method, with a constant failure rate, has no memory of prior usage. Specifically, within any fixed period of usage, the probability of failure is the same. This method is used to provide a failure probability for the components (in % per year) regardless of the age of the component and is identical during the components entire useful (design) life.

The failure rate and failure probabilities for the previously indicated most 'critical' components of the cargo handling gear is shown in Table 4.2. The defined probabilities of failure for the components is also shown in the fault tree in Appendix B. As seen in the table the failure probability (in % per year) for all components is equal to 1/lifetime (i.e. average life expectancy). This means the resulting failure probabilities are dependent on the expertise of the technical department and/or the reliability of the data (from suppliers) used to define this approach.

TABLE 4.2: Failure Probability 'Critical' Single Components

| Component | $\eta$ (years) | Failure Prob. (%/year) | $\lambda$ (per hour) | Failure Prob. (%/hour) |
|---|---|---|---|---|
| Power Unit EL (Motor) | 20 | 5.0 | $5.7 \times 10^{-6}$ | $5.7 \times 10^{-4}$ |
| V-Pump (Main Pump) | 15 | 6.7 | $7.6 \times 10^{-6}$ | $7.6 \times 10^{-4}$ |
| Coupling | 15 | 6.7 | $7.6 \times 10^{-6}$ | $7.6 \times 10^{-4}$ |
| Slew Ring Roller Bearing | 20 | 5.0 | $5.7 \times 10^{-6}$ | $5.7 \times 10^{-4}$ |
| Luffing Cylinder | 15 | 6.7 | $7.6 \times 10^{-6}$ | $7.6 \times 10^{-4}$ |
| Luffing Bearing (Cyl.) | 10 | 10.0 | $1.1 \times 10^{-6}$ | $1.1 \times 10^{-4}$ |
| Hoisting Winch | 10 | 10.0 | $1.1 \times 10^{-6}$ | $1.1 \times 10^{-4}$ |
| Lifting Cable/Rope | 22 | 4.5 | $5.2 \times 10^{-6}$ | $5.2 \times 10^{-4}$ |
| Cable Drum | 25 | 4.0 | $4.6 \times 10^{-6}$ | $4.6 \times 10^{-4}$ |
| Rope Guard | 12 | 8.3 | $9.5 \times 10^{-6}$ | $9.5 \times 10^{-4}$ |
| Cargo Block | 18 | 5.6 | $6.3 \times 10^{-6}$ | $6.3 \times 10^{-4}$ |
| Motor Swivel Gear | 15 | 6.7 | $7.6 \times 10^{-6}$ | $7.6 \times 10^{-4}$ |
| Control Module | 9 | 11.1 | $1.3 \times 10^{-6}$ | $1.3 \times 10^{-4}$ |
| Blockchain | 8 | 12.5 | $1.4 \times 10^{-6}$ | $1.4 \times 10^{-4}$ |
| Twistlock | 5 | 20.0 | $2.3 \times 10^{-6}$ | $2.3 \times 10^{-4}$ |

*Note*: Own Composition

### 4.2.4 Fault Tree Analysis (Quantitative)

Given the final structure of the fault tree and estimated frequency of probability for each basic event (component failures), it is possible to calculate the top event frequency or probability. This calculation is normally done using the minimal cut set approach by defining the Boolean expression for the system, as described in Section 4.2.2. This approach is applicable to both large and small trees. An alternative is the simpler gate-by-gate approach (Eq. 3.1 and 3.2). The gate-by-gate approach can be used for large fault trees if dependency (repeated events) is taken into account. It is susceptible to numerical error in the predicted top event frequency if the tree has a repeated event in different branches of the tree.

The gate-by-gate approach starts with the basic events of the fault tree and proceeds upward toward the top event. All inputs to a gate must be defined before calculating the gate output. All bottom gates must be computed before proceeding to the next higher level. This is therefore comparable to the Boolean expression, with the probability of the top event given by the probability of the union of the minimum cut sets. The mathematical relationships used in the gate-by-gate technique are shown in equations 3.1 and 3.2, these equations are presented again for clarification.

For an AND Gate:

$$P_{sys}(t) = P_a \times P_b \times P_c \times .... \times P_n \tag{3.1}$$

For an OR Gate:

$$P_{sys}(t) = 1 - (1 - P_a) \times (1 - P_b) \times (1 - P_c) \times .... \times (1 - P_n) \tag{3.2}$$

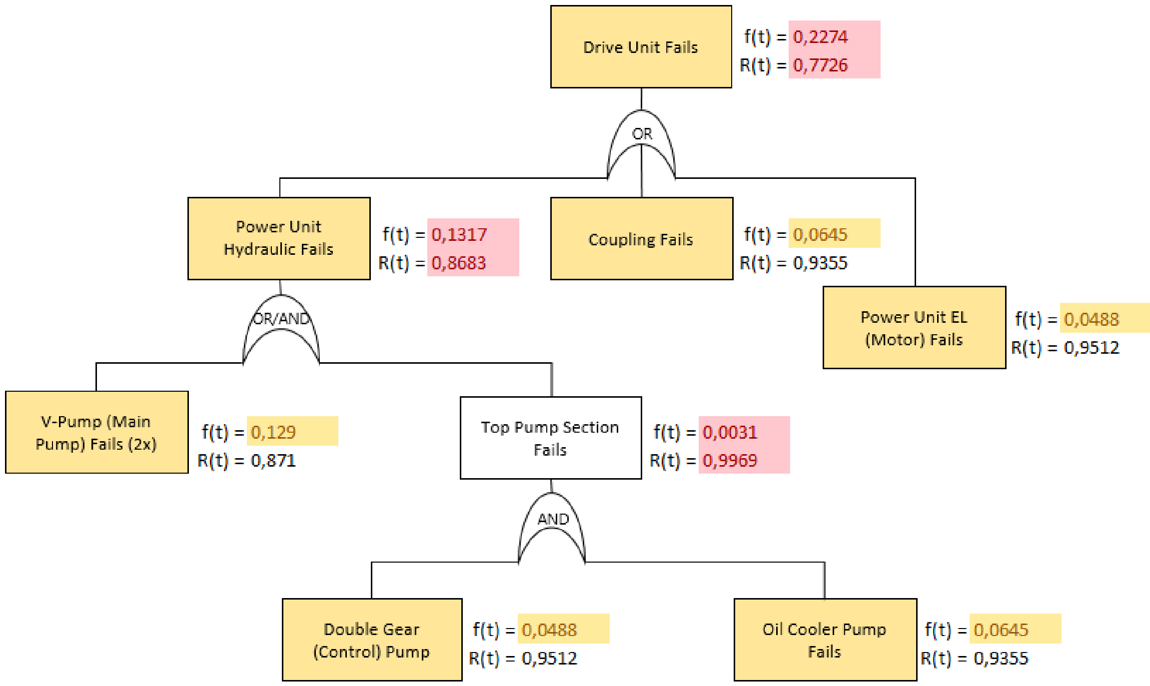



FIGURE 4.6: Quantitative Fault Tree Analysis Drive Unit

*Note*: Own Composition

The quantitative analysis is mainly used to provide quantitative estimates of failure frequencies and likelihoods, and define relative importance of various failure sequences and contributing events. Depending on the size and complexity of the tree the gate-by-gate approach, or defining a Boolean expression, might be difficult and the aid of software tools is required.

To provide an example a quantitative analysis for the crane drive unit is shown in Figure 4.6. For the crane drive unit, with inability to use the crane drive unit as top event, using the aforementioned equations, the top event frequency or probability is determined. The top of the tree, with top event inability to use the cargo handling gear is shown in Figure 4.7. The quantitative analysis for the full tree, with top event inability to use the cargo handling gear (and for the level above, which is vessel shutdown) is provided, for probability per service year, in Appendix B.

What can be concluded from the quantitative analysis is that failure of the cargo handling gear is most likely to occur due to failure (of a component) of the external crane ($\approx$ 80% per year), compared to the Anti-Heeling System or the Drive Shaft (both $\approx$ 4% per year). Which can be explained by the fact that these systems contain more redundancy (AND gates) which makes it less likely that these systems (entirely) fail. This is conclusive with the critical components identified in the qualitative analysis (Table 4.1). The 80% annual failure probability of the crane might seem like a high probability, but based on previous experience with malfunctions this rate can be accounted for. Previous malfunctions showed, for a period of 4 years (2013 till present), three major breakdowns and a similar amount of minor failures. The major breakdowns can be attributed to components included in the fault tree: the hoisting winch, a luffing cylinder and the cable drum. This means a yearly probability of 80% related to inability to use the crane is considered a realistic value.

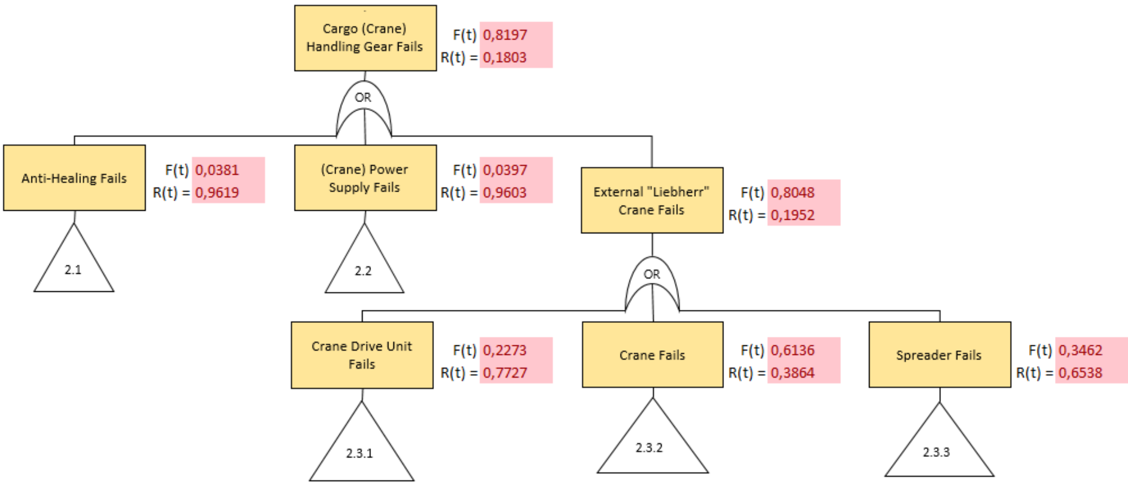



FIGURE 4.7: Quantitative Fault Tree Analysis Top

*Note*: Own Composition

Furthermore it can be seen that contribution from components related to the slewing column, crane boom, drive unit and spreader are most accountable for the probability of the top event. The components with most importance to the reliability of the crane are: for the drive unit: the double V-pump (Main pump), coupling, and the Power Unit EL (Motor); for the slewing column: the luffing gear, hoisting winch and slewing ring; for the crane boom: the lifting cable/rope, the cable drum, and the lifting hook; and for the spreader: the double hook with suspension and the twist locks. This is conclusive with the result found in the qualitative analysis (see Section 4.2.2).

## 4.3 Conclusion

This chapter provides a breakdown of systems and components related and the cargo handling gear of the MKS Mercurius and describes a failure analysis, where important elements are indicated and failure probabilities are determined. This chapter therefore addresses both SQ1 and SQ2.

1. *Which systems and components form the cargo handling gear of the MKS Mercurius?*

The system and component breakdown showed that the cargo handling gear consists of approximately 35 different components. These components can be allocated to 'internal' systems, which are implemented in the hull of the vessel, or the 'externally' mounted crane. Most of the components are related to the 'externally' mounted crane, specifically the slewing column and the crane boom. The internal systems composed of an Anti-Heeling System, consisting of a Contra-Weight System and a Pump Anti-Heeling system, and the Power Supply located in the engine room. The 'externally' mounted crane composed of the drive unit, the spreader and the crane itself. The drive unit consists of an central power unit (electric motor), a coupling and a hydraulic unit. The crane mainly consists of slewing gear, luffing gear, hoisting gear, a lifting cable, and a lifting hook. Finally, the spreader consists of the unit itself and an attachment set.

2. *Which failure probabilities can be attributed to these systems and components?*
   (a) *Which failure probabilities can be attributed to compound systems/component groups?*
   (b) *Which failure probabilities can be attributed to single components?*

Each of these components have different characteristics, some are essential for the crane's functioning, others are supportive components. This means component failures can have different impact on operability and different financial consequences. Before these effect can be determined, the failure probabilities of systems/groups and components are determined in this chapter.

With respect to the failure probabilities of the individual components it is proposed to apply the negative exponential distribution. With this distribution a constant failure probability over the components lifetime is determined, which is equal to 1 divided by component lifetime. As a result the failure probabilities of the components vary between 4% and 20%, depending on their average life expectancy.

Compound probabilities can be obtained by union of minimum cut sets or formulas for a (similar) gate-by-gate approach. In essence, the minimum cut sets identify all combinations of component failure(s) necessary and sufficient to result in the top event. The top event in this case being inability to use the cargo handling gear. Based on the failure model described in this chapter it can be concluded that the cargo handling gear is most likely to experience a malfunction due to failure (of a component) related to the external crane. This contributed to an annual probability of 80% that the vessels cargo handling gear will fail. Which is in line with findings from MSG's container-crane vessels (limited) failure data, observed in a period of 4 years.

# Chapter 5

# Downtime & Repair Costs

In Chapter 4 the failure probability of components is determined and the ‘critical’ components related to the cargo handling gear are identified. Before the (total) impact of failure and the effect of keeping an inventory on this impact can be quantified, the duration in case of failure and the costs of repair for these failures need to be determined. Other downtime related costs (failure costs) are not included in the repair costs and are separately discussed in Chapter 6.

This chapter addresses vessel downtime in case of failure for the various components (or duration of deviation from optimal vessel state in case of failure) and the resulting repair costs after these failures occur.

## 5.1 Failure Duration

The duration of the failure is dependent on the lead time and on the repair time. Spare-parts are only required when the component needs to be replaced. Therefore in the determination of failure duration only estimates of repair time for a complete component replacement is taken into account. As a result the failure duration is equal to the expected repair (replacement) time plus the lead time.

The repair times are based on experience of the technical department of MSG, this department is equipped with personnel with broad experience in repairs. The repair time is estimated as objectively as possible and considered reliable (enough) for the application in this research. For large components the repair times are conservatively estimated, conservatively in the sense that it is unlikely that the component is not replaced within the given time-frame. The lead time is based on: data from suppliers, historical quotations and based on estimates provided by the technical department. The lead time is dependent on whether or not Liebherr (or other supplier) has the component on shelf. Which is thus dependent on the moment of the failure. For this reason a difference in lead time is incorporated in the model, divided in expected lead time and guaranteed (supplier) lead time. Guaranteed lead times are applicable when at the moment of ordering the part, this part has to be completely manufactured and send to MSG. This is thus a very conservative estimate provided by the supplier, which entails a 100% likelihood of being delivered within this time-frame. In reality the lead time can be (and is usually) substantially lower. For this reason expected lead times are estimated, based on experience and data provided by suppliers and determined, in consultation with the technical department. To determine and quantify the benefits of keeping a spare-part inventory the expected lead times, and corresponding failure durations, are used in calculations. The impact of failure with longer (guaranteed) lead times is described in Section 6.3.2 and the sensitivity of the lead times in relation to the benefit of keeping a spare-part inventory is described in Chapter 8.

In general, for Liebherr related crane components a lead time of 10 days is taken into account. With pressure to locate a spare-part and to speed up the process it is likely that components, which do not require large rebuilds, will be delivered within this time-frame (P. den Haan, personal communication, Oktober 17, 2017). For components which are highly specific to the crane mounted on this vessel and require custom build (Liebherr), the specified guaranteed lead time is applied to determine the failure duration. This is the case for some specific high costs components, for example the slewing ring which is: specific to this crane; expensive; and requires a certain building process, which means it is unlikely to be on shelf. For components which are not Liebherr specific and/or can likely be obtained from other suppliers a lead time is taken into account of 7 days.

Considering the spare-part is in inventory, the lead time can be significantly reduced. In case of a fully owned and controlled spare-part inventory by MSG the lead time reduces to a minimum. Since the container-crane vessels mainly operate in the Rotterdam area, a strategically located spare-part inventory can reduce the lead time to a few hours. For this reason (in case of a fully owned and controlled inventory by MSG) the availability of spare-parts is considered direct and lead time is neglected. The lead time and failure durations for the previously determined 'critical' components (Chapter 4) are presented in Table 5.1. The failure duration for the situation where spare-parts need to be delivered and the duration when these parts are directly available is given.

From the table it can be seen that for the 'critical' components of the crane the expected lead times do not differ much. Which can be explained by the fact that these components are all specific Liebherr components. The lead times are still considerable, which is mainly due to the type and size of the crane, which is incomparable to shore cranes or cranes for the heavy lift segment. It can also be seen that there is more variation in guaranteed lead times, which is likely related to the required work hours to manufacture the component. In overall the expected lead times are 7 to 10 days, with the exception of two major components. This means availability of spare-parts has a large effect on failure duration. With spare-parts directly available all failures are dealt with within 14 days (independent on lead time).

## 5.2 Repair Costs

This section addresses the repair costs for failure of components related to the cargo handling gear and the influence of direct availability of spare-parts on these costs. Input for this section has been obtained in consultation with the technical department of MSG. All monetary values are based on current price levels (2017).

### 5.2.1 Breakdown of Repair Costs

The costs of repair (replacement) of a failed component can entail: equipment/yard costs, hire of external personnel, delivery costs, and component price (increase in case of urgency).

Depending on the component the repair can either be executed aboard the vessel or require shipyard based services. In case shipyard based services are required, such as a crane, this entails costs (for lifting). On a regular basis MSG uses several shipyards in the Rotterdam/Dordrecht area for dockings of their various vessels. Since MSG is a regular client the

TABLE 5.1: Failure Durations 'Critical' Components

| Component | Repair time (Days) | Lead time* (Days) | Duration Without Spare (Days) | Duration With Spare (Days) |
|---|---|---|---|---|
| Power Unit EL (Motor) | 5 | 10 (30) | 15 | 5 |
| V-Pump (Main Pump) | 2 | 10 (30) | 12 | 2 |
| Coupling | 1 | 10 (30) | 11 | 1 |
| Slew Ring Roller Bearing | 14 | 70 (70) | 84 | 14 |
| Luffing Cylinder | 14 | 60 (60) | 74 | 14 |
| Luffing Bearing (Cyl.) | 2 | 10 (14) | 12 | 2 |
| Hoisting Winch | 7 | 10 (60) | 17 | 7 |
| Lifting Cable/Rope | 3 | 10 (60) | 13 | 3 |
| Cable Drum | 3 | 10 (60) | 13 | 3 |
| Rope Guard | 1 | 7 (30) | 8 | 1 |
| Cargo Block | 1 | 7 (65) | 8 | 1 |
| Motor Swivel Gear | 3 | 10 (14) | 13 | 3 |
| Control Module | 1 | 10 (60) | 11 | 1 |
| Blockchain | 1 | 7 (14) | 8 | 1 |
| Twistlock | 1 | 7 (14) | 8 | 1 |

*Expected lead times used for failure durations, supplier guaranteed lead times stated between brackets

Source: Technical Department of MSG

site costs are free of charge, in case of failure, and the shipyard only charges a fee for usage of cranes and other equipment. For this reason a fee of €300 per day is taken into account when shipyard based services are required for the repair.

The costs for external personnel need to be included when the technical department and crew are unable to perform the repair and external expertise is required. Whether or not external personnel is required is established in accordance with the technical department (for each separate component). For the hire of external personnel an hourly rate is taken into account of €100, with a maximum daily rate of €1,00. These costs are then simply the daily rate multiplied by the estimated repair time.

In case of failure components need to be flown in, from Liebherr based in Austria, which entails delivery costs. These delivery costs are dependent on the size (and weight) of the component that needs to be delivered. In case of urgent delivery the delivery cost increase. For the components a substantiation is made in small, medium and large sized components. Under normal circumstances (no urgency) the delivery costs are assumed €500 for small components, €750 for medium components and €1000 for large components. In case of failure the components are usually ordered with urgent delivery. Urgent delivery approximately doubles the delivery costs.

The acquisition of parts in case of urgency to repair the vessel can be higher compared to when these parts can be obtained without pressure and with sufficient time to request multiple quotations etc. As a result of this urgency, the (paid) price of acquired parts are estimated between 10% – 30% higher compared to the prices paid under normal circumstances. For this reason a price increase is implemented in the model assumed as a 15% price increase of components when spare-parts need to be delivered (case without inventory). The price of components is based on quotations from suppliers and/or estimates provided by the technical department.

### 5.2.2 Repair Costs per Component

One of the major breakdowns of the crane in previous years was a failure of the hoisting winch in November 2013. This breakdown required a full replacement of the hoisting winch. The total repair costs for this replacement were equal to €10,400 (based on invoices of Liebherr), not including the price of the winch. Of these total costs, approximately €6,300 are accounted for by labour costs and €1,500 by delivery costs. The remaining costs consisted of costs for inquiry, examination, small material, service charges, and costs of small equipment.

A breakdown of repair costs for the most 'critical' components regarding the cargo handling gear, identified in the qualitative analysis of the fault tree (see Section 4.2.2), is shown in Table 5.2. These repair costs are calculated values based on the previously described costs model (Section 5.2.1). This table includes the calculated value, based on the model, of the repair costs for the (same) hoisting winch which experienced the malfunction in 2013. The calculated total repair costs for replacement of the hoisting winch (for the case without inventory) is equal to €14,150, of which €5,600 is related to labour costs and €2,000 (normal + surplus) to delivery costs. Furthermore in these total costs a surplus of €4,450 is taken into account related to the component price. This surplus is not included in the 'real' repair costs of the winch. As a result, without including this price increase as costs, the total (calculated) repair costs are equal to €9,700. This means that the labour costs, delivery and also the total repair costs are all close to the actual (previously experienced) costs, therefore this method to determine the repair costs is considered well enough for this application.

From the calculated repair costs it can be seen that in case external personnel and/or equipment (shipyard) is required this has a large effect on total repair costs. These costs are inevitable since they are independent on the availability of spares. Furthermore it can be seen that the price increase taken into account in case of urgency can have a significant impact on total repair costs.

### 5.2.3 Influence Spare-Part Inventory on Repair Costs

The total repair costs in case spare-parts need to be delivered compared to these costs when parts are directly available is shown in Table 5.2. What can be seen from the table is that repair costs can be significantly reduced when parts are directly available.

This decrease in costs is due to a reduction in delivery costs and a reduction in purchasing price of the component. When parts need to be delivered the delivery costs increase due to the urgent delivery fee. The same applies for the purchasing prices, without inventory and with lead time the purchasing price that is paid for these components is (likely to be) a significantly increased rate. The costs for external personnel and for required equipment are the same in both cases, since the rates and necessity of these elements are independent on the availability of spare-parts. Therefore when equipment and/or (external) personnel is required these costs are unaffected by direct availability of spare-parts. Overall the effect of a spare-part inventory on the repair costs is quantified by the difference in component price and delivery costs which are caused by the urgency of part delivery.

TABLE 5.2: Repair Costs 'Critical' Components

| Component | Component Price* | Costs (in €) Yard Equipment | Personnel (External) | Delivery | Total (in €) With Inventory | Surplus (in €) Delivery | Component Price | Total (in €) Without Inventory |
|---|---|---|---|---|---|---|---|---|
| Power Unit EL (Motor) | 21 000 | 1 500 | 4 000 | 1 000 | 6 500 | 1 000 | 3 150 | 10 650 |
| V-Pump (Main Pump) | 8 400 | 0 | 1 600 | 750 | 2 350 | 750 | 1 250 | 4 350 |
| Coupling | 1 800 | 0 | 0 | 750 | 750 | 750 | 250 | 1 750 |
| Slew Ring Roller Bearing | 98 000 | 4 200 | 11 200 | 1 000 | 16 400 | 1 000 | 14 700 | 32 100 |
| Luffing Cylinder | 60 000 | 4 200 | 11 200 | 1 000 | 16 400 | 1 000 | 9 000 | 26 400 |
| Luffing Bearing (Cyl.) | 3 500 | 600 | 1 600 | 500 | 2 700 | 500 | 550 | 3 750 |
| Hoisting Winch | 29 500 | 2 100 | 5 600 | 1 000 | 8 700 | 1 000 | 4 450 | 14 150 |
| Lifting Cable/Rope | 8 200 | 0 | 2 400 | 1 000 | 3 400 | 1 000 | 750 | 5 650 |
| Cable Drum | 5 100 | 0 | 2 400 | 750 | 3 150 | 750 | 750 | 4 650 |
| Rope Guard | 3 400 | 0 | 0 | 750 | 750 | 750 | 500 | 2 000 |
| Cargo Block | 2 100 | 0 | 0 | 750 | 750 | 750 | 300 | 1 800 |
| Motor Swivel Gear | 8 200 | 0 | 0 | 1 000 | 1 000 | 1 000 | 1 250 | 3 250 |
| Control Module | 4 200 | 0 | 0 | 750 | 750 | 750 | 650 | 2 150 |
| Blockchain | 2 100 | 0 | 0 | 750 | 750 | 750 | 300 | 1 800 |
| Twistlock | 450 | 0 | 0 | 750 | 750 | 750 | 50 | 1 550 |

*Note*: Component price mentioned, but not included in total repair costs (Own Composition)

## 5.3 Conclusion

This chapter provided an analysis of vessel downtime (or deviation from optimal vessel state) in case of failure, for components related to the vessels cargo handling gear; and determined the corresponding repair costs for these failures. Other downtime related costs are addressed in Chapter 6. As a result this chapter addressed the answer to SQ3 and SQ4.

3. *How does the availability of spare-parts affect the duration of the failure?*

The failure durations for components related to the cargo handling gear showed that the failure duration is mainly dependent on the lead time. The lead time is on average 7 – 10 days, when applying expected lead times and 5 to 10 weeks for guaranteed lead times. As a result availability of spare-parts has a large effect on the failure durations. With the spare-parts for the cargo handling gear located in inventory failure durations only consist of the estimated repair time. Depending on the component this reduces the failure duration to a minimum of 1 – 7 days (with two exceptions equal to 14 days).

4. *How does the availability of spare-parts influence the costs of repair for the failure?*

From the determined repair costs it can be concluded that the largest effect of direct availability of spare-parts on these costs are related to the urgency to fix/replace the component in case of a malfunction. This urgency translates to an increase in delivery costs and a price increase of the component. As a result with direct availability of spare-parts the repair costs can be significantly reduced. Depending on the component a costs reduction between €750 and €15,000 can be achieved with direct availability of spare-parts, which is equal to a 20% – 75% costs reduction.

# Chapter 6

# Failure Consequences

In order to quantify the benefits of keeping a spare-part inventory insight is required in the effect of having spare-parts available in case of a failure event. This benefit of keeping a spare-part inventory is determined by comparing the impact of failure with and without direct availability of spare-parts. The benefit of keeping a spare-part inventory is therefore equal to the reduced (financial) failure impact with available spare-parts, which is quantified by the reduction in total failure costs resulting from component failures. The failure costs are defined as a function of operational impact/consequences, failure duration and availability (residual capacity) of the MKS Transferium. With the failure durations known (Chapter 5), these resulting total failure costs can be determined. As a result, the reduction in failure impact and the benefits of keeping a spare-part inventory can be quantified.

This chapter addresses the operational and related financial consequences of component failures. The failure costs are determined and the effect of keeping a spare-part inventory on the financial impact of failure is quantified.

## 6.1 Operational Consequences of Failure

This section addresses the effect of component failure on vessel operability, which mainly consist of sailing (propulsion), manoeuvring and executing lifting operations. These effects are translated to restrictions to the vessels operational profile. Based on these restrictions various conditions are determined, which the vessel can be assigned to after component failure. The severity of these effects are discussed for (1) MKS Mercurius as sole container-crane vessel and (2) MKS Mercurius affected by failure with MKS Transferium able to (partially) takeover capacity.

### 6.1.1 Vessel State/Condition after Failure

Under normal/optimal operating conditions the vessel is able to sail at design speed, manoeuvre through the Port of Rotterdam and use the vessels cargo handling gear to serve clients at locations where no shore cranes are available, i.e. the vessel is fully functioning and operational as intended. Component failures can have different effects on the operability of the vessel, as a result the state of the vessel differs from the normal operating condition. For instance, when a critical component of the crane fails, the vessel might not be able to use the cargo handling gear and wouldn't be able to perform lifting operations. As lifting is the vessels core operational activity this has a large effect on deployment. Without the vessel able to perform lifting operations the vessel can be used as a conventional inland barge. The following (after failure) conditions are defined:

1. Baseline: fully operational
2. No cargo handling capacity (crane defect) and propulsion fully functioning
3. Restricted cargo handling capacity
    (a) Only able to lift empty or light weight containers (Weight restriction)
    (b) Reduced handling speed and number of movements (Speed restriction)
4. No propulsion ability but with cargo handling gear fully functioning
5. No Bow Thruster (Bow Thruster Defect)
6. Total shutdown

Component failure without significant effect on vessel operability form the baseline in which the vessel can normally operate (Condition 1). The revenue stream is unaffected and the only failure costs are related to the repair, other operational expenses are unaffected by the failure. The second condition is component failure which results in shut down of the cargo handling gear. This has significant impact on operability since the main service conditions include container movements by the vessel crane, not being able to perform these activities results in large revenue losses and operational expenses. Since in this case the vessel is still able to sail the vessel can still be used as a conventional inland barge. Component failure can also lead to restrictions in the usage of the crane (Condition 3), this can either be a weight restriction or a speed restriction. If component failure results in a weight restriction, the crane is unable to load at its full capacity of 40ton. This usually means that only empty containers can be transported by the vessel. A speed reduction might result in accumulation of work and endanger timely deliveries, resulting in additional operating costs. The fourth condition occurs when the failure has fatal consequences regarding propulsion. Without being able to self-propel the vessel can still be towed alongside a different barge and the crane can still be used. In this case containers can be loaded/unloaded on a different barge, since the vessel is unable to transport them by itself. The fifth condition applies to failure related to the bow thruster (or crucial components of the bow thruster). The bow thruster (Condition 5) is used to manoeuvre in ports and to hold the vessel in place during lifting operations. Therefore, this is a different condition to those already listed since the vessel is still able to self-propel and the crane can be used without any problems. In case the vessel is unable to manoeuvre an additional barge is required to guide the vessel. At MSG a barge (the Salland) equipped with a bow thruster is able to guide the vessel in case of failure. The last condition is the unlikely event of component failure which results in total shut down of the vessel.

For this research the main focus is on systems and components related to the vessels cargo handling gear. This means condition 4 and condition 5 have less relevance to this research, but these conditions are included for the sake of completeness. The resulting vessel state or condition after components fail is incorporated in the fault tree, which can be found in Appendix B. Obviously, failure of systems or components related to the cargo handling gear, which affect the vessels operability, can result in condition 2 or condition 3. Failure of systems or components related to the vessels ability to self-propel might result in condition 4. And a combination of both failed propulsion and failed cargo handling gear results in condition 6. Component failures without an effect on operability lead to condition 1, which is not indicated in the fault tree.

### 6.1.2 Effect without back-up vessel MKS Transferium

In case of (crane malfunction) failure of the container-crane vessel alternative transportation solutions must be arranged for at least two urgent situations. These include: (1) unloading of the containers already located in the vessel holds, and (2) pick-up of previously delivered containers at client locations. In case there are containers located at container terminals it is possible to fall back on road transportation (Van Dorsser, 2013). For previously delivered containers timely removal is essential, due to the rapidly increasing demurrage costs for clients and MSG.

The response in order to deal with these two urgent situations after failure for each vessel state (as defined in Section 6.1.1) are given in Table 6.1.

When the vessel experiences a crane defect, depending on the severity of the defect, the most likely solution for containers located in the vessels holds is to deliver these containers to a terminal, after which these are transported to the client by truck. If the vessel also lost the ability to self-propel, the vessel must be towed by a pusher tug or transported alongside a different barge to offload the previously loaded containers at a container terminal. For empty containers located at clients, which need to be lifted from the quay, supply crane barges can be hired which are able to load empty containers at a limited speed. Full containers must then be emptied in consultation with the client, otherwise alternative transportation must be arranged for these full containers. For failure conditions which are less severe, meaning a weight restriction or a speed restriction for the crane, these actions may not be required or may only be required for a certain amount of containers. Alternatively containers could be loaded and/or offloaded by a floating derrick (equipped with a crane) or a mobile crane on shore. However, due to low cost-effectiveness in case of a floating derrick and insufficient or unknown quay strength at (most) client locations to operate a mobile crane, these options are in-feasible (Van Dorsser, 2013).

For the time-frame in which these measures are required, in general, it can be stated that the first two days, after the failure, no measures are taken for both containers located in the vessels holds and containers at client locations. Since during this time-frame first an assessment of the damages is made and the containers can remain at the quay for two days without noticeable consequences for the client. After these initial two days measures are taken to clear out all containers. These measures should be sufficient to clear out all containers between two days and one week after the failure (M. Kleijn, personal communication, May 24, 2017). After one week all containers are cleared and (depending on the severity of the defect) the vessel can either be used as a conventional inland barge, or perform restricted lifting operations at limited speed.

### 6.1.3 Effect with back-up vessel MKS Transferium

Section 6.1.2 described the responsive actions to arrange alternative pick-up and delivery solutions for (1) containers already located in the vessel holds, and (2) pick-up of previously delivered containers at client locations, with MKS Mercurius as sole container-crane barge. In case the MKS Transferium is available and able to (partially) take-over capacity the required actions to clear out containers can differ. The required actions with MKS Transferium available and MKS Mercurius in one of the aforementioned vessel states are given in Table 6.2.

TABLE 6.1: Actions for Alternative Pick-up/Delivery of Containers in case of Failure (Only MKS Mercurius)

| **Delivery of Containers in Holds** | **Pick-Up of Containers at Client Locations** |
|---|---|
| ***Condition 1: Baseline: Fully Operational*** | |
| No effect on operations or ability to serve clients, containers delivered by MKS Mercurius | No effect on operations or ability to serve clients, container pick-up by MKS Mercurius |
| ***Condition 2: No Cargo Handling Capacity (Crane Defect)*** | |
| Containers must be delivered to a container terminal and transported by truck. This entails possible demurrage for empty returns and scheduling problems | Need to hire (multiple) supply crane barges which are able to remove empty containers, full containers emptied in consultation with the client. This entails possible missing of closure for export containers, demurrage for empty returns and scheduling problems |
| ***Condition 3a: Weight Restriction*** | |
| Full containers must be delivered to a container terminal and transported by truck | Only able to remove empty containers, full containers must be emptied in consultation with the client or alternative transportation must be arranged |
| ***Condition 3b: Speed Restriction*** | |
| May experience scheduling problems, missing of closure for export containers and demurrage for empty returns. In case of large speed reductions the same measures apply as described for Condition 2 | May experience scheduling problems, missing of closure for export containers and demurrage for empty returns. In case of large speed reductions the same measures apply as described for Condition 2 |
| ***Condition 6: Total Shut Down*** | |
| Must hire inland barge or pusher tug for vessel transportation and deliver containers to terminal and transport them by truck. This entails possible missing of closure for export containers, demurrage for empty returns and scheduling problems | Must hire inland barge for container transportation and must hire (multiple) supply crane barges which are able to remove empty containers, full containers emptied in consultation with the client. This entails possible missing of closure for export containers, demurrage for empty returns and scheduling problems |

Source: Own Composition based on Personal Communication with M. Kleijn (Owner MCT Lucassen)

TABLE 6.2: Actions for Alternative Pick-up/Delivery of Containers in case of Failure (Back-Up MKS Transferium)

| **Delivery of Containers in Holds** | **Pick-Up of Containers at Client Locations** |
|---|---|
| ***Condition 1: Baseline: Fully Operational*** | |
| No effect on operations or ability to serve clients, containers delivered by MKS Mercurius | No effect on operations or ability to serve clients, container pick-up by MKS Mercurius |
| ***Condition 2: No Cargo Handling Capacity (Crane Defect)*** | |
| MKS Transferium used to unload containers from MKS Mercurius' holds. Containers that are planned to be handled by MKS Transferium which do not require crane operations taken over by other barges, freeing up capacity. This entails possible demurrage for empty returns and scheduling problems | MKS Transferium used to load containers with MKS Mercurius used as conventional inland barge. Containers that are planned to be handled by MKS Transferium which do not require crane operations taken over by other barges, freeing up capacity. This entails possible missing of closure for export containers, demurrage for empty returns and scheduling problems. Might need to hire an additional inland barge to transport containers |
| ***Condition 3a: Weight Restriction*** | |
| MKS Transferium used to load, unload and transport full containers. Containers planned to be handled by MKS Transferium which do not require crane operations partially taken over by other barges, freeing up capacity. Requires planning adjustments | MKS Transferium used to load, unload and transport full containers. Containers planned to be handled by MKS Transferium which do not require crane operations partially taken over by other barges, freeing up capacity. Requires planning adjustments |
| ***Condition 3b: Speed Restriction*** | |
| MKS Tranderium used to load, unload and transport (a quantity of) containers depending on the severity of the speed reduction. In case of large speed reductions the same measures apply as described for Condition 2 | MKS Tranderium used to load, unload and transport (a quantity of) containers depending on the severity of the speed reduction. In case of large speed reductions the same measures apply as described for Condition 2 |
| ***Condition 6: Total Shut Down*** | |
| MS Transferium used to load, unload and transport containers from MKS Mercurius' holds. Containers that are planned to be handled by MKS Transferium which do not require crane operations taken over by other barges, freeing up capacity. May require additional inland barge or pusher tug for vessel transportation. Demurrage claims and scheduling problems | MKS Transferium used to load, unload and transport containers from quay. Containers that are planned to be handled by MKS Transferium which do not require crane operations taken over by other barges, freeing up capacity. May require additional inland barge for container transportation. This entails possible missing of closure for export containers, demurrage for empty returns and scheduling problems |

Source: Own Composition based on Personal Communication with M. Kleijn (Owner MCT Lucassen)

What can be derived from the tables, comparing both cases (MKS Mercurius with and without back-up from MKS Transferium), is that the consequences of failure of the MKS Mercurius can be substantially reduced depending on the MKS Transferium's residual (lifting) capacity. This influences the effects for both the delivery of containers in holds and container pick-ups after failure.

At the moment of failure of one of the container-crane vessels, the other vessel (in this case MKS Transferium) will free up capacity, to execute lifting operations, by removing regular container activities to other barges. This means that containers which are planned to be handled by MKS Transferium and not require crane operations are taken over by other barges chartered by MCT (barge operator). A rough estimate of time distribution for the container-crane vessels is: 25% of the time executing lifting operations, 35% of the time sailing for both containers destined for depots as containers meant for (lifting) delivery, 20% waiting time at terminals/quays and 20% of the time spend unloading at terminals operations (M. Kleijn, personal communication, November 9, 2017). As a result by removing regular container operations, which do not require the vessels own crane, enough residual capacity is created to execute MKS Mercurius' lifting operations (M. Kleijn, personal communication, November 9, 2017). Therefore, regarding container removal, the remaining effects include possible missing of closure, demurrage costs and planning/scheduling difficulties. Additionally, with failure of the MKS Mercurius (especially the crane) MSG is unable to execute 'special' lifting operations that require both container-crane vessels.

## 6.2 Financial Consequences of Failure

This section addresses the financial effects resulting from component failures. To determine these effects a breakdown of failure costs is made, after which a baseline scenario is established to describe the commencing situation at the moment of the failure. With this baseline scenario the financial effects for each resulting vessel state after failure are determined, after which the model is validated and the financial effects for each single component are determined. Input for this section has been obtained in consultation with barge operator MCT. All monetary values are based on current price levels (2017).

### 6.2.1 Breakdown of Failure Costs

After component failure the vessel could experience downtime (depending on the component), which involves costs. These costs are related to the failure and therefore defined as downtime related costs. Combined with the repair costs (Chapter 5) this results in the total failure costs. As a result the overall failure costs can be divided in: opportunity costs (revenue losses), container removal costs, additional planning costs, and business recovery costs. Estimates for these costs are based on previous malfunctions and experience of barge operator MCT.

The opportunity costs are equal to the net revenue (revenue - direct related costs) the vessel could have obtained without the failure. Without crane availability loaded containers on shore are difficult and costly to be removed, therefore MSG offers to remove these containers empty, after which no invoice is send. For containers that are delivered as intended (in agreement with the voyage charter) no revenue losses are included, because for these containers invoices are send to the client. As a result opportunity costs includes loss of business/opportunity as well as revenue lost from loaded containers on shore which are removed empty (in consultation with the client). The total revenue loss is dependent on the vessel state after failure, since this loss is different for crane defects compared to for instance just a weight restriction. The opportunity costs are determined by Equation 6.1. With $\alpha$ equal to the percentage of net revenue lost for the corresponding vessel state. The container-crane vessels main revenue stream is obtained by executing lifting operations, in general revenue obtained from crane work is equal to 85% of net revenue and 15% of the vessels net revenue is related to regular container operations. Which means the opportunity costs can be divided in a revenue loss due to a decrease in crane work and/or a revenue loss due to a decrease in regular container operations. These costs can both be determined by Equation 6.1. When the repair requires shipyard based services, which means the vessel is unable to operate during repair, $\alpha$ is assumed 100% for the duration of the repair and these revenue losses are included as costs. The revenue lost from loaded containers on shore, which are removed empty and free of charge, is determined by the container rate multiplied by the number of (loaded) shore containers delivered at a terminal (Equation 6.2).

$$\textit{Revenue Loss (Opportunity)} = \alpha \times \textit{Daily Net Revenue} \times \textit{Duration} \tag{6.1}$$

$$\textit{Revenue Loss of Loaded Shore Containers} = \textit{Container Rate} \times \textit{Number of Containers} \tag{6.2}$$

Container removal costs are related to the alternative delivery solutions arranged for the containers in the vessels holds and on client locations at the moment of the failure. These include: costs related transfer of container from hold-to-terminal an from shore-to-terminal (including crane costs, trucking, delivery, etc.), costs for vessel hire(s) (if needed), and demurrage costs for late delivery. The 'transfer' costs are determined by multiplying the number of containers with the transfer rate. For hold-to-terminal deliveries the costs are related to: handling, trucking and delivery and are assumed as €175 per container. For shore-to-terminal deliveries this either includes additional handling on client locations, to load the container in the vessel, or involves truck handling and larger trucking costs, therefore these costs are assumed at €225 per container. For vessel hire(s), when needed, the costs are determined by multiplying the daily hire rate with the duration the vessels are required. The demurrage costs for late delivery are determined by multiplying the number of containers with the delay (in days) and the fine for demurrage (per day).

The additional costs, related to planning and rescheduling difficulties, are assumed as €500 per day until all containers are removed. For vessel conditions where the vessel is out of service for long durations (over two weeks), less crew is required for the vessel. For these states (and duration) a cost reduction is taken into account, related to reduced crew costs.

Business recovery costs are related to revenue losses in the week(s) after the failure has been restored, where business needs to restart and increase to its full potential. After failure all containers on shore are removed, this amount of shore containers therefore gradually increases to the continuous delivery schedule it was before the failure. For this reason business recovery costs are included as a loss of crane work after the failure has been restored. For failures resulting in vessel states with severe consequences (crane defect, loss of propulsion severe loss of crane functioning) these recovery costs are assumed as a 50% loss of crane work in the week after the failure. For failures with minor consequences the recovery costs are assumed negligible.

In addition (multiple successive) long failure durations may lead to a reduction of demand for MSG's container-crane vessels in the long-term, due to loss of client confidence and loss of trust in MSG's operational activities. For these long-term effects it is difficult to make a valuable cost estimate, since the effect is dependent on: client confidence; price and efficiency of alternative pick-up/delivery services; and only applicable after multiple successive long duration failures. Previous experience showed that due to the fact that the service provided by MSG has significant advantages for the clients business (cheaper, faster, and more efficient delivery and removal of containers) these effects are minor (M. Kleijn, personal communication, May 24, 2017). For this reason only business recovery costs are included in the model and additional long-term damages are neglected.

### 6.2.2 Baseline Scenario

The effects, and resulting failure costs, are dependent on the commencing situation at the moment of the failure (number of containers to be removed on shore, number of containers in holds), which constantly changes. In order to determine and quantify these effects a baseline scenario is established, in which the number of container movements that need to be carried out after the failure is determined, which is used to determine the resulting failure costs. The effect of the availability of a second container-crane vessel for the baseline scenario is also defined.

In general there are two main types of container movements which are of interest, these include: delivery of containers in the vessels holds, and removal of previously delivered containers on shore at client locations. Under normal circumstances the vessel is loaded with 50 containers (movements), which can vary (by $\approx 20$ movements) depending on the amount of additional regular container operations taken on by the vessel. Of these containers 60% is destined to be delivered by crane and 40% is related to regular container operations destined for terminal delivery. Since the pick-up and delivery of (shore) container is often simultaneous (delivery of new containers, removal of old containers) the amount of containers on shore at client locations is for the baseline scenario assumed fixed at 50 container movements. Of the containers handled by the vessels crane approximately 40% are loaded containers and 60% are empty containers. Of the containers related to depot work approximately 70% are loaded containers and 30% are empty containers.

In the fully functioning vessel states both container-crane vessels execute 560 crane movements per week on average (based on in-house statistics). This is equivalent to 40 crane movements per day per container vessel. On average, based on operational capacity, the container-crane vessels can execute 8 – 12 crane movements per hour. With availability of a second container-crane vessel (in this case MKS Transferium), at the moment of failure of one of the vessels the other vessel will free up capacity to execute lifting operations, by conveying regular container activities to other barges (additional 40% of time available for lifting). This means that containers which are planned to be handled by MKS Transferium and do not require crane operations are taken over by other barges. Considering the MKS Transferium is able to execute 8 – 12 crane movements per hour an additional 100 – 120 crane movements per day becomes available. This means at the moment of failure enough capacity is created to cover the other vessels lifting operations, doing this does require a support vessel for container transportation. This support vessel can possibly be the MKS Mercurius in case of a crane defect.

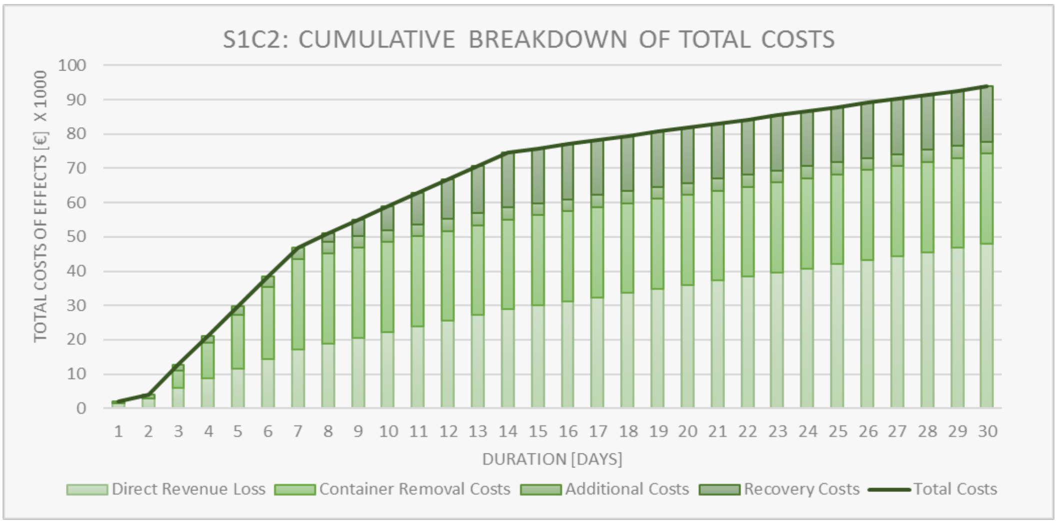
For this research as a baseline scenario it is assumed that, at the moment of failure: there are 50 container movements located in the vessels holds, of which 60% is intended to be delivered by the vessels crane and 40% is destined for depot work; and 50 movements on shore to be removed (by the crane) at the moment of failure. Of the containers handled by the crane 40% are loaded containers and 60% are empty containers. For containers related to depot work this division is equal to 70% loaded containers and 30% empty containers. With availability of MKS Transferium, by conveying regular container related activities to other barges, enough capacity is created to cover the other container-crane vessels lifting operations. This does require a support vessel for container transportation, which could be the MKS Mercurius in case of a crane defect.

### 6.2.3 Failure Costs per Vessel State

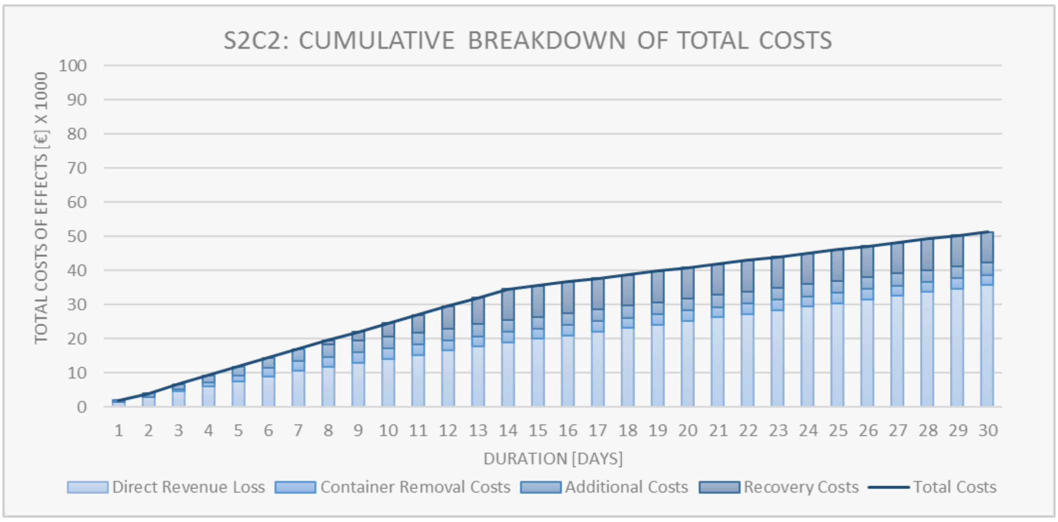
Failure costs are dependent on the consequences of the failure to the vessels operability, the availability of a second container-crane vessel (MKS Transferium), and the duration of the failure. A (cumulative) breakdown of the failure costs for the most severe condition regarding failure of the crane (crane defect) is shown in Figure 6.1. The development of failure costs for MKS Mercurius as single-acting vessel is shown in Figure 6.1a, and the development of failure costs with availability of MKS Transferium is shown in Figure 6.1b. Breakdown of failure costs for the other relevant vessel states can be found in Appendix C.

The financial consequences of failure (failure costs) are determined in default time-frames. The applied time-frames are between 0 – 2 days, 2 – 7 days, 7 – 14 days, and >14 days (in €/day). Obviously, the impact of failure increases with duration and as a result the total cumulative failure costs in these time-frames is determined, which is shown in Figure 6.1. The cost development within these time-frames is assumed linear, which means during these time-frames failure costs can be expressed in €/day applicable to that particular time-frame. The first two days after failure no measures are taken to remove containers, during this time-frame an assessment of the damages is made. For failures restored in less than two days containers can still be delivered inside normal laytime, which means no demurrage costs are involved and consequences for clients during this time-frame are minor. After these initial two days measures are taken to remove all container, these measures should be sufficient to clear out all containers between two days and one week after the failure. After one week business recovery costs are included, which are the result of revenue losses in the week after the failure is restored. These costs increase at a constant rate to the maximum revenue loss (50% loss of crane work). After 14 days all containers are removed and the effect of business recovery is included, which means that in this time-frame only direct revenue losses from inability to perform crane operations increases.

Estimates, based on assumptions, to determine direct revenue losses and business recovery costs during these time-frames for Condition 2: No cargo handling capacity (Crane Defect) are given in Table 6.3, which is provided as an example. Regarding revenue losses it is assumed that during container removal all revenue related to crane work (100%) is lost, which is equal to 85% of total net revenue. After all containers are removed the vessel can be used as a conventional inland vessel and as a result revenue from deport work increases. Initially this is equal to 15% of total net revenue and it is assumed that this increases by 200% in the time-frame between one and two weeks after the failure and increases by 300% for durations over two weeks. Since this vessel state results in severe consequences (operational and financial) a 50% loss of crane work is taken into account as business recovery costs for failure durations over one week. With availability of the MKS Transferium, revenue losses are determined as overall losses based on experience based estimates. These values are based on overall net revenue the vessel is still able to obtain after the failure, while MKS Transferium takes over crane operations by conveying regular container operations to other barges. During the time-frame between 0 – 2 days and 2 – 7 days, a certain percentage of the time the vessels are occupied by removing containers on shore, as a result revenue losses in




(A) Cumulative Breakdown of Downtime Related Costs in case of Crane Defect (Only MKS Mercurius)




(B) Cumulative Breakdown of Downtime Related Costs in case of Crane Defect (With MKS Transferium)

FIGURE 6.1: Development of Downtime Related Costs for Crane Defect (Condition 2)

*Note*: Own Composition

TABLE 6.3: Parameters Revenue Loss & Long-term Damages for Crane Defect (Condition 2)

| **Parameter** | **Unit** | **Duration (Days)** | | | |
|---|---|---|---|---|---|
| | | **0 - 2 Days** | **2 - 7 Days** | **7 - 14 Days** | **>14 Days** |
| ***Scenario 1: Only MKS Mercurius*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 50 | 100 | 100 | 100 |
| Revenue Loss Regular Work ($\alpha$) | % | 0 | 0 | -200 | -300 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 50 | 0 |
| ***Scenario 2: With MKS Transferium*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 50 | 50 | 40 | 35 |
| Revenue Loss Regular Work ($\alpha$) | % | 50 | 50 | 40 | 35 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 35 | 0 |

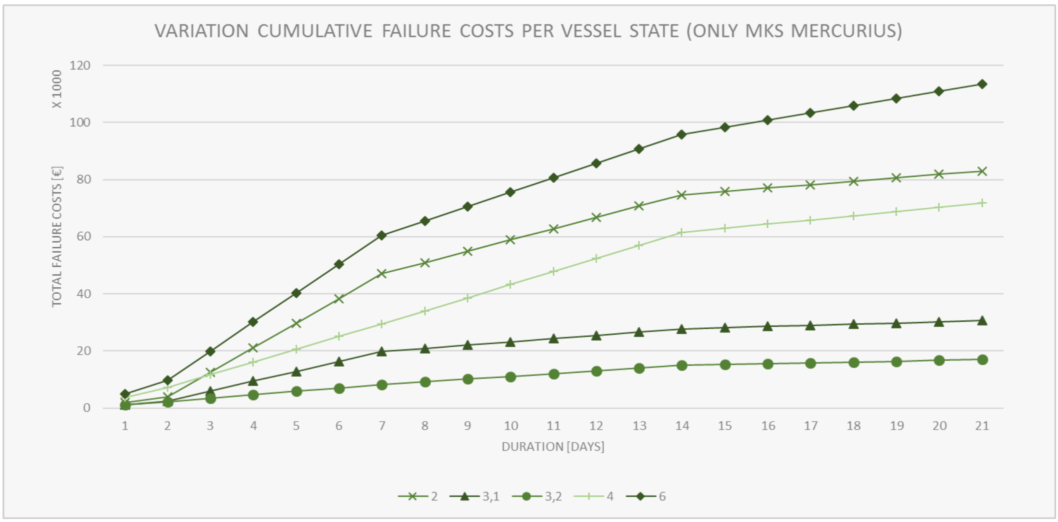
*Note*: Own Composition

this time-frame are higher compared to time-frames after removal. With availability of MKS Transferium, some of the crane work usually executed by MKS Mercurius is still performed, which means business recovery after the failure is also less severe. As a result a 35% loss of revenue from crane work is taken into account in the week after the failure has been restored.

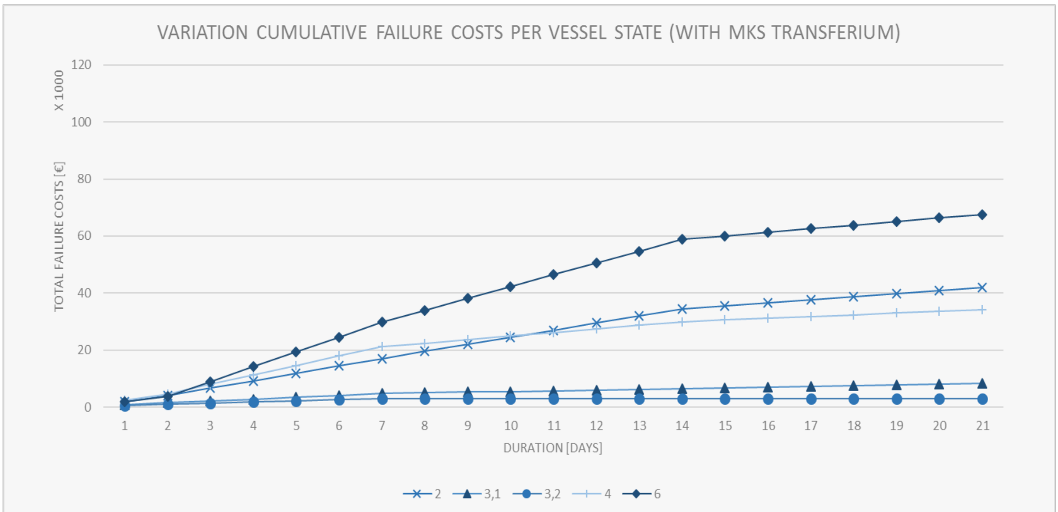
As shown in Figure 6.1a the largest costs are revenue losses and container removal costs, for longer durations the recovery costs increase and can have a significant impact on failure costs. Initially, during the first two days, effects are minor and the only effects are direct revenue losses and some additional costs related to planning. The largest rise in costs is experienced in the time-frame between 2 – 7 days, which is as expected since during this time-frame all containers in holds and on shore at client locations are removed. After this time-frame there are no additional container removal costs and planning related costs (additional costs). In the time-frame between 7 – 14 days business recovery costs are included which can have a significant impact on total failure costs. Obviously, for the entire window of failure durations opportunity costs (direct revenue loss) increase since the revenue stream is affected by the inability to perform lifting operations. With MKS Transferium available to take over MKS Mercurius' crane operations (by conveying regular container operations) the container removal costs decrease, because the containers are still removed by MSG's container-crane vessel(s). This can also be seen in the (cumulative) failure costs breakdown (Fig. 6.1b). Furthermore it can be seen that with availability of the MKS Transferium the failure costs mainly consist of opportunity costs (direct revenue loss), which is a consequence of less obtained net revenue due to less crane operations and/or transporting less containers to terminals.

Figure 6.2 shows the spread of failure costs for all defined vessel states. Figure 6.2a shows this spread for MKS Mercurius as single-acting vessel and Figure 6.2b shows the spread of failure costs with back-up from MKS Transferium.

The various vessel states show a large spread in failure costs. For example, with MKS Mercurius as single acting vessel a failure with severe consequences can result in failure costs up to €96,000 after 14 days, i.e. a failure with minor consequences, with the same duration, can result in total failure costs of €15,000 after 14 days. With respect to the cargo handling gear, failure which results in inability to use the crane are of most interest. This is because, for this vessel state, the operational consequences are significant and therefore the resulting




(A) Variation Downtime Related Costs per Vessel State (Without MKS Transferium)




(B) Variation Downtime Related Costs per Vessel State (With MKS Transferium)

FIGURE 6.2: Downtime Related Costs per Vessel State

*Note*: Own Composition

failure costs are also large. For the remaining vessel states related to (failure of) the crane, resulting in a weight and/or speed restriction, the effects are smaller and the accumulation of the failure costs is also limited. With availability of a second container-crane vessel (MKS Transferium) (Fig. 6.2b) it can be seen that failure costs for all vessel states are significantly reduced. For all vessel states the majority of failure costs in this case is related to opportunity costs (non-generated profits). A failure with severe consequences can result in failure costs of €59,000 after 14 days, i.e. failure costs in case of a weight or speed restriction are almost eliminated (≈ €3,000 – €6,500 after 14 days). Obviously, with MKS Mercurius in one of these vessel states and MKS Transferium taking over crane operations, the MKS Transferium will be more heavily utilized for the duration of the failure.

### 6.2.4 Validation

Previous sections described the model to determine resulting failure costs for the various vessel states after component failures. To determine if the model provides a good representation of reality it is important to validate the outcome the model produced. In this research it is difficult to accurately validate the outcome (resulting failure costs) of the model, which can be attributed to the following:

1. There is a minimal amount of failure data which can be used as reference, especially for the scenario with MKS Mercurius as single-acting vessel. Failure of both vessels simultaneously is unlikely and therefore historical failures are only applicable to the scenario with availability of a second container-crane vessel. Except for the failure in 2016 where at the moment of failure the second container-crane vessel was in dock (see Section 1.1)
2. Costs (vessel hires, crane, terminal, etc.), estimated revenue losses and recovery costs are highly dependent on price levels (supply and demand), and therefore the economic climate, at the moment of the failure.
3. Revenue losses and business recovery costs are rough estimates, based on what-if considerations. This means the determination of these costs are less robust and mathematically verifiable.

Despite these difficulties an attempt is made to validate the outcome of the model(s). This is done by comparing the calculated costs, with actual encountered costs for two previously experienced failures, which are described in this section.

In September 2016 both container-crane vessels were unavailable for a period of two and a half weeks (≈ 17 days). The first container-crane vessel had a scheduled docking to replace the crane cylinders, after which the second container-crane vessel experienced a malfunction which lead to inability to use the crane. This is therefore (relatively) equivalent to MKS Mercurius as single-acting vessel experiencing a failure which leads to a crane defect, the cumulative failure costs of which is captured in Figure 6.1a. Based on accounting records, the estimated direct revenue loss and revenue loss in the week(s) after the failure had been restored (business recovery costs) was between €100,000 – €130,000 (M. Kleijn, personal communication, April 7, 2017). Assuming the container-crane vessels are identical and in normal conditions obtain the same net revenue, of these opportunity costs €50,000 – €80,000 can be accounted for by unavailability of the MKS Mercurius. The calculated outcome, from the model, related to opportunity costs is equal to €48,500, which is on the lower bound of the estimated actual costs. This can be explained by the fact that the months before and after the failure were relatively busy months. As a result obtainable net revenue in this period could be assumed a little higher and this would affect the estimated revenue losses during this period. Container removal costs during this period are ≈ €40,000 (based on invoices), of which demurrage costs (≈ 18,000) were the largest contributor. The calculated container removal costs are slightly lower (≈ €30,000). This can be explained by the fact that, with a scheduled docking of one of the vessels, the other container-crane vessel was supposed to take over a large amount of crane operations during this period. Due to this lack of availability of a second container-crane vessel therefore some containers were already on a tight schedule (maybe even late), which means after failure demurrage costs increased (rapidly) and were applicable to more containers. This means that for the scenario with MKS Mercurius as single-acting vessel these costs could be lower.

In December 2013 the MKS Mercurius experienced a failure of the hoisting winch, which lead to inability to use the crane for a period of 10 – 12 days. During this failure the MKS Transferium was available to take over MKS Mercurius' lifting activities. This situation is equivalent to MKS Mercurius experiencing a crane defect with availability of MKS Transferium, the cumulative failure costs of which is captured in Figure 6.1b. Based on accounting records, the estimated direct revenue loss and revenue loss in the week(s) after the failure had been restored was between €20,000 – €25,000. The calculated outcome after 12 days is equal to €23,000, which is close to the estimated revenue loss. Container removal costs where minimal, since containers could be removed by the second container-crane vessel. On the basis of this case it can be stated, comparing the model to the experienced failure, that the outcome of the model seems to generate realistic costs.

In conclusion, it can be stated that it is difficult to accurately validate the model due to various uncertainties and limited failure data. However, for the cases considered, the outcome of the model(s) seems to represent likely costs which are in line with experience based estimates from barge operator MCT (M. Kleijn, personal communication, November 15, 2017).

### 6.2.5 Failure Costs per Component

Failure costs are different for each component and depend on operational consequences (vessel state), failure duration, availability of a second container-crane vessel, and the availability of spare-parts. With the failure costs per vessel state, failure durations, and effect of availability of a second container-crane vessel known the resulting failure costs per component can be determined. After which the reduction in failure impact (financial) with direct availability of spare-parts can be determined (Section 6.3.1). An overview, and division, of total failure costs for the 'critical' components regarding the cargo handling gear, identified in the fault tree analysis (Section 4.2), is shown in Table 6.4. Failure of the identified components directly leads to inability to use the cargo handling gear, therefore the values shown in the table correspond with the (cumulative) costs breakdown in Figure 6.1.

The failure costs are calculated values based on the previously described costs model (see Section 6.2.1). The total failure costs include the repair costs for each component, calculation of which is described in Section 5.2.

The total failure costs show a large spread. One of the aspects the failure costs are dependent on is the vessel state after failure. The components shown in the table relate to a crane defect, for which the impact on operations is large, as a result estimated failure costs are also large. For MKS Mercurius as single-acting vessel the majority of failure costs is related to opportunity costs (revenue loss) and container removal costs, which account for 64% – 86% of total failure costs (35% – 60% opportunity costs , 30% – 50% container removal costs). Container removal costs and additional (planning) costs are equally large for all components

TABLE 6.4: Failure Costs of 'Critical' Components (Without Inventory & Expected Lead Time)

| Component | Failure Duration (Days) | Costs without inventory (in €) Repair | Opportunity | Container Removal | Additional | Business Recovery | Total Failure Costs (in €) Without Inventory |
|---|---|---|---|---|---|---|---|
| **Only MKS Mercurius** | | | | | | | |
| Power Unit EL (Motor) | 15 | 10 650 | 30 000 | 26 300 | 3 500 | 16 100 | 86 550 |
| V-Pump (Main Pump) | 12 | 4 350 | 25 500 | 26 300 | 3 500 | 11 500 | 71 150 |
| Coupling | 11 | 1 750 | 23 900 | 26 300 | 3 500 | 9 200 | 64 650 |
| Slew Ring Roller Bearing | 84 | 32 100 | 112 800 | 26 300 | 3 500 | 16 100 | 190 800 |
| Luffing Cylinder | 74 | 26 400 | 100 800 | 26 300 | 3 500 | 16 100 | 173 100 |
| Luffing Bearing (Cyl.) | 12 | 3 750 | 25 500 | 26 300 | 3 500 | 11 500 | 70 550 |
| Hoisting Winch | 15 | 11 950 | 30 000 | 26 300 | 3 500 | 16 100 | 87 850 |
| Lifting Cable/Rope | 13 | 5 650 | 27 200 | 26 300 | 3 500 | 13 800 | 76 450 |
| Cable Drum | 13 | 4 650 | 27 200 | 26 300 | 3 500 | 13 800 | 75 450 |
| Rope Guard | 11 | 2 000 | 23 900 | 26 300 | 3 500 | 9 200 | 64 900 |
| Cargo Block | 11 | 1 800 | 23 900 | 26 300 | 3 500 | 9 200 | 64 700 |
| Motor Swivel Gear | 13 | 3 250 | 27 200 | 26 300 | 3 500 | 13 800 | 74 050 |
| Control Module | 11 | 2 150 | 23 900 | 26 300 | 3 500 | 9 200 | 65 050 |
| Blockchain | 8 | 1 800 | 18 900 | 26 300 | 3 500 | 2 300 | 52 800 |
| Twistlock | 8 | 1 550 | 18 900 | 26 300 | 3 500 | 2 300 | 52 550 |
| **With MKS Transferium** | | | | | | | |
| Power Unit EL (Motor) | 15 | 10 650 | 20 000 | 3 000 | 3 500 | 9 100 | 46 250 |
| V-Pump (Main Pump) | 12 | 4 350 | 15 300 | 3 000 | 3 500 | 5 200 | 31 350 |
| Coupling | 11 | 1 750 | 15 300 | 3 000 | 3 500 | 5 200 | 28 750 |
| Slew Ring Roller Bearing | 84 | 32 100 | 92 400 | 3 000 | 3 500 | 9 100 | 140 100 |
| Luffing Cylinder | 74 | 26 400 | 81 900 | 3 000 | 3 500 | 9 100 | 123 900 |
| Luffing Bearing (Cyl.) | 12 | 3 750 | 16 500 | 3 000 | 3 500 | 6 500 | 33 250 |
| Hoisting Winch | 15 | 11 950 | 20 000 | 3 000 | 3 500 | 9 100 | 47 550 |
| Lifting Cable/Rope | 13 | 5 650 | 17 700 | 3 000 | 3 500 | 7 800 | 37 650 |
| Cable Drum | 13 | 4 650 | 17 700 | 3 000 | 3 500 | 7 800 | 36 650 |
| Rope Guard | 11 | 2 000 | 15 300 | 3 000 | 3 500 | 5 200 | 29 000 |
| Cargo Block | 11 | 1 800 | 15 300 | 3 000 | 3 500 | 5 200 | 28 800 |
| Motor Swivel Gear | 13 | 3 250 | 17 700 | 3 000 | 3 500 | 7 800 | 35 250 |
| Control Module | 11 | 2 150 | 15 300 | 3 000 | 3 500 | 5 200 | 29 150 |
| Blockchain | 8 | 1 800 | 11 700 | 3 000 | 3 500 | 1 300 | 21 300 |
| Twistlock | 8 | 1 550 | 11 700 | 3 000 | 3 500 | 1 300 | 21 050 |

*Note*: Own Composition

shown in Table 6.4. This is due to the fact that all components have failure durations above 7 days, which is the time-frame in which all containers are removed and after this time-frame no additional container removal costs and planning related costs are incurred. For failures with less severe consequences, meaning a weight restriction or speed reduction for the crane (not shown in the table), the container removal costs are a less significant proportion of total failure costs. This is due to the fact that in these vessel states a smaller quantity of containers cannot be loaded by the vessels own crane, reducing the total container removal costs. In this case failure costs are mainly dominated by opportunity costs (revenue loss).

With availability of the MKS Transferium the total failure costs for 'critical' components are reduced by approximately €31,500 – €40,000. In general availability of MKS Transferium reduces the total failure costs by €2,000 – €40,000, depending on the type of component and the severity of failure consequences. As shown in the table with availability of the MKS Transferium the container removal costs are reduced to €3,000, which is due to the fact that MKS Transferium takes over lifting operations of the MKS Mercurius after failure. For this case all containers that are planned to be handled by the MKS Transferium that do not require crane operations are conveyed to other barges (which has effect on revenue). As a result no vessels need to be hired for container removals, no containers have to be delivered to a container terminal etc. and the remaining container removal costs are demurrage costs, which are equal to €3,000. Availability of a second container-crane vessel also has an effect on opportunity costs and business recovery costs. This is due to the fact that with a second container-crane vessel more crane work can be done after the failure, which reduces opportunity costs and business recovery in this scenario. This can also be seen in Table 6.4.

## 6.3 Effect of Keeping a Spare-Part Inventory

This section addresses the effect of keeping a spare-part inventory on the financial impact of failure. The effect of keeping inventory will be described for both the expected lead times and for guaranteed lead times.

### 6.3.1 Difference in Failure Costs/Impact with Inventory

The difference in expected failure costs with and without a spare-part in inventory provides insight in the reduction in failure impact with direct availability of spare-parts. This reduction in impact of failure is defined as 'potential' benefit of keeping a certain spare-part in inventory. An overview, and division, of total failure costs for the 'critical' components, regarding the cargo handling gear, with direct availability of a spare (kept in inventory) is shown in Table 6.5.

The total failure costs show a large spread in costs, which are dependent on failure duration which in this case is solely repair time (inevitable). With MKS Mercurius acting as single vessel for components with severe failure consequences (crane defect) a reduction in failure costs can be achieved between €50,000 – €65,000 (with two exceptions, due to very large expected lead time). In comparison for components with less severe consequences, for example a weight restriction, a reduction in failure costs can be achieved between €2,500 – €24,000. With availability of the MKS Transferium the effects are reduced and a reduction in failure costs can be achieved between €18,000 – €30,000 for components with severe consequences to operability (Table 6.5) and beween €1,000 – €14,000 for components with less severe consequences.

TABLE 6.5: Failure Costs of 'Critical' Components (With Inventory)

| Component | Failure Duration (Days) | Repair | Costs with inventory (in €) Opportunity | Container Removal | Additional | Business Recovery | Total Costs (in €) With Inventory | Reduction in € | in % |
|---|---|---|---|---|---|---|---|---|---|
| **Only MKS Mercurius** | | | | | | | | | |
| Power Unit EL (Motor) | 5 | 6 500 | 11 600 | 15 800 | 2 500 | 0 | 36 400 | 50 150 | 58 |
| V-Pump (Main Pump) | 2 | 2 350 | 3 000 | 0 | 1 000 | 0 | 6 350 | 64 800 | 91 |
| Coupling | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 61 900 | 96 |
| Slew Ring Roller Bearing | 14 | 16 400 | 28 800 | 26 300 | 3 500 | 16 100 | 91 100 | 99 700 | 52 |
| Luffing Cylinder | 14 | 16 400 | 28 800 | 26 300 | 3 500 | 16 100 | 91 100 | 82 000 | 47 |
| Luffing Bearing (Cyl.) | 2 | 2 700 | 3 000 | 0 | 1 000 | 0 | 6 700 | 63 850 | 91 |
| Hoisting Winch | 5 | 6 500 | 11 600 | 15 800 | 2 500 | 0 | 36 400 | 51 450 | 59 |
| Lifting Cable/Rope | 3 | 3 400 | 5 900 | 5 300 | 1 500 | 0 | 16 100 | 60 350 | 79 |
| Cable Drum | 3 | 3 150 | 5 900 | 5 300 | 1 500 | 0 | 15 850 | 59 600 | 79 |
| Rope Guard | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 62 150 | 96 |
| Cargo Block | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 61 950 | 96 |
| Motor Swivel Gear | 3 | 1 000 | 5 900 | 5 300 | 1 500 | 0 | 13 700 | 60 350 | 81 |
| Control Module | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 62 300 | 96 |
| Blockchain | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 50 050 | 95 |
| Twistlock | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 49 800 | 95 |
| **With MKS Transferium** | | | | | | | | | |
| Power Unit EL (Motor) | 5 | 6 500 | 7 500 | 1 800 | 2 500 | 0 | 18 300 | 27 950 | 60 |
| V-Pump (Main Pump) | 2 | 2 350 | 3 000 | 0 | 1 000 | 0 | 6 350 | 25 000 | 80 |
| Coupling | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 26 000 | 90 |
| Slew Ring Roller Bearing | 14 | 16 400 | 18 900 | 3 000 | 3 500 | 9 100 | 50 900 | 89 200 | 64 |
| Luffing Cylinder | 14 | 16 400 | 18 900 | 3 000 | 3 500 | 9 100 | 50 900 | 73 000 | 59 |
| Luffing Bearing (Cyl.) | 2 | 2 700 | 3 000 | 0 | 1 000 | 0 | 6 700 | 26 550 | 80 |
| Hoisting Winch | 5 | 6 500 | 7 500 | 1 800 | 2 500 | 0 | 18 300 | 29 250 | 62 |
| Lifting Cable/Rope | 3 | 3 400 | 4 500 | 600 | 1 500 | 0 | 10 000 | 27 650 | 73 |
| Cable Drum | 3 | 3 150 | 4 500 | 600 | 1 500 | 0 | 9 750 | 26 900 | 73 |
| Rope Guard | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 26 250 | 91 |
| Cargo Block | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 26 050 | 90 |
| Motor Swivel Gear | 3 | 1 000 | 4 500 | 600 | 1 500 | 0 | 7 600 | 27 650 | 78 |
| Control Module | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 26 400 | 91 |
| Blockchain | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 18 550 | 87 |
| Twistlock | 1 | 750 | 1 500 | 0 | 500 | 0 | 2 750 | 18 300 | 87 |

*Note*: Breakdown of Failure Costs for scenario without spare in Inventory is given in Table 6.4(Own Composition)

In overall with spare-parts in inventory opportunity costs are significantly reduced, but remain the largest remaining effect. Which is as expected, since 'downtime' is never completely eliminated (due to the repair) and as a result (some) opportunity costs are inevitable. With MKS Mercurius as single-acting vessel and spares in inventory container removal costs are small and in most cases completely eliminated. With availability of MKS Transferium the container removal costs where already a minor costs. The same applies for business recovery costs, failure durations and the effects on operations are small and as a result there are no recovery costs. Recovery costs are only relevant for very large and expensive components, which require long repair times.

### 6.3.2 Effect in case of longer (guaranteed) Lead Times

Previous sections described: the failure impact (financial) without direct availability of spare-parts, where the failure duration was based on expected lead time (Section 6.2.5); and described the effect of direct availabiltiy of spare-parts on this failure impact (Section 6.3.1). In case lead times of the components are longer than the determined expected lead times, for example maximal and equal to the guaranteed lead time, the failure impact can also increase. An overview of failure costs for the 'critical' components regarding the cargo handling gear, with failure durations based on guaranteed (maximum) lead times, is shown in Table 6.6.

In overall the effect of longer lead times is mainly reflected in opportunity costs. These opportunity costs are dependent on the operational consequences (vessel state) after failure. For failures leading to inability to use the crane failure costs increase by €5,500 – €74,000 (on average €40,000). Of these failure costs 40% – 71% is accounted for by opportunity costs. For failures with less severe consequences, meaning a weight or speed restriction to the crane, the total failure cost increase by €5,000 - €17,000 (on average €7,500). With these lead times for all 'critical' components, costs related to container removal, planning difficulties, and business recovery costs are the same. Which is due to the fact that all failure durations are above 14 days, after which the only remaining accumulating costs are opportunity costs.

## 6.4 Conclusion

This chapter provided: an analysis of the effect of component failures on the vessels operational profile; and provided an analysis of the corresponding financial effects, where the total failure costs for each component were determined. As a result the potential financial benefit of direct availability of spare-parts is determined. The resulting failure costs are determined for (1) MKS Mercurius as sole container-crane vessel and (2) MKS Mercurius affected by failure with MKS Transferium as back-up to takeover lifting opeations. As a result this chapter addressed the answer to both SQ5 and SQ6.

5. *Which restrictions to the operability of MKS Mercurius can be defined as a result of failure of these systems and components?*

The restrictions/limitations related to the vessels operability after component failure showed that a failure can lead to a vessel state that deviates from the optimal (as intended) operational profile. As a result six different vessel states are identified, of which three (full defect, weight restriction or speed restriction) are related to failure of the cargo handling gear.

TABLE 6.6: Failure Costs of 'Critical' Components (Without Inventory & Longer (Guaranteed) Lead Times)

| Component | Failure Duration (Days) | Costs without inventory (in €) Repair | Opportunity | Container Removal | Additional | Business Recovery | Total Failure Costs (in €) Without Inventory | Difference Failure* Costs (in €) |
|---|---|---|---|---|---|---|---|---|
| **Only MKS Mercurius** | | | | | | | | |
| Power Unit EL (Motor) | 35 | 10 650 | 54 000 | 26 300 | 3 500 | 16 100 | 110 550 | 24 000 |
| V-Pump (Main Pump) | 32 | 4 350 | 50 400 | 26 300 | 3 500 | 16 100 | 100 650 | 29 500 |
| Coupling | 31 | 1 750 | 49 200 | 26 300 | 3 500 | 16 100 | 96 850 | 32 200 |
| Slew Ring Roller Bearing | 84 | 32 100 | 112 800 | 26 300 | 3 500 | 16 100 | 190 800 | 0 |
| Luffing Cylinder | 74 | 26 400 | 100 800 | 26 300 | 3 500 | 16 100 | 173 100 | 0 |
| Luffing Bearing (Cyl.) | 16 | 3 750 | 31 200 | 26 300 | 3 500 | 16 100 | 80 850 | 10 300 |
| Hoisting Winch | 67 | 11 950 | 92 400 | 26 300 | 3 500 | 16 100 | 150 250 | 62 400 |
| Lifting Cable/Rope | 63 | 5 650 | 87 600 | 26 300 | 3 500 | 16 100 | 139 150 | 62 700 |
| Cable Drum | 63 | 4 650 | 87 600 | 26 300 | 3 500 | 16 100 | 138 150 | 62 700 |
| Rope Guard | 31 | 2 000 | 49 200 | 26 300 | 3 500 | 16 100 | 97 100 | 32 200 |
| Cargo Block | 66 | 1 800 | 85 200 | 26 300 | 3 500 | 16 100 | 138 900 | 74 200 |
| Motor Swivel Gear | 17 | 3 250 | 32 400 | 26 300 | 3 500 | 16 100 | 81 550 | 7 500 |
| Control Module | 61 | 2 150 | 85 200 | 26 300 | 3 500 | 16 100 | 133 250 | 68 200 |
| Blockchain | 15 | 1 800 | 30 000 | 26 300 | 3 500 | 16 100 | 77 700 | 24 900 |
| Twistlock | 15 | 1 550 | 30 000 | 26 300 | 3 500 | 16 100 | 77 450 | 24 900 |
| **With MKS Transferium** | | | | | | | | |
| Power Unit EL (Motor) | 35 | 10 650 | 41 000 | 3 000 | 3 500 | 9 100 | 67 250 | 21 000 |
| V-Pump (Main Pump) | 32 | 4 350 | 37 800 | 3 000 | 3 500 | 9 100 | 57 750 | 26 400 |
| Coupling | 31 | 1 750 | 36 800 | 3 000 | 3 500 | 9 100 | 54 150 | 25 400 |
| Slew Ring Roller Bearing | 84 | 32 100 | 92 400 | 3 000 | 3 500 | 9 100 | 140 100 | 0 |
| Luffing Cylinder | 74 | 26 400 | 81 900 | 3 000 | 3 500 | 9 100 | 123 900 | 0 |
| Luffing Bearing (Cyl.) | 16 | 3 750 | 21 000 | 3 000 | 3 500 | 9 100 | 40 350 | 7 100 |
| Hoisting Winch | 67 | 11 950 | 74 600 | 3 000 | 3 500 | 9 100 | 102 150 | 54 600 |
| Lifting Cable/Rope | 63 | 5 650 | 70 400 | 3 000 | 3 500 | 9 100 | 91 650 | 54 000 |
| Cable Drum | 63 | 4 650 | 70 400 | 3 000 | 3 500 | 9 100 | 90 650 | 54 000 |
| Rope Guard | 31 | 2 000 | 36 800 | 3 000 | 3 500 | 9 100 | 54 400 | 25 400 |
| Cargo Block | 66 | 1 800 | 73 500 | 3 000 | 3 500 | 9 100 | 90 900 | 62 100 |
| Motor Swivel Gear | 17 | 3 250 | 22 100 | 3 000 | 3 500 | 9 100 | 40 950 | 5 700 |
| Control Module | 61 | 2 150 | 68 300 | 3 000 | 3 500 | 9 100 | 86 050 | 56 900 |
| Blockchain | 15 | 1 800 | 20 000 | 3 000 | 3 500 | 9 100 | 37 400 | 16 100 |
| Twistlock | 15 | 1 550 | 20 000 | 3 000 | 3 500 | 9 100 | 37 150 | 16 100 |

*Note*: Difference indicates increase in failure costs compared to costs with expected lead times shown in Table 6.4

The analysis furthermore showed that in case of failure of the crane alternative transportation must be arranged for two urgent situations. These include: (1) unloading of the containers already located in the vessels holds, and (2) pick-up of previously delivered containers at client locations. Depending on the vessel state after failure these solutions may require vessel hires (inland barge and/or pusher tug) and/or container terminal services. With availability of a second container-crane vessel, after failure of the MKS Mercurius, lifting operations scheduled to be performed by the MKS Mercurius can be taken over by this second crane vessel. In order to do so containers which are planned to be handled by the MKS Transferium, which do not require crane operations are conveyed to other barges. Thus, with availability of the MKS Transferium operational consequences, after failure of the MKS Mercurius, are mitigated.

6. *What are, given the duration and the restrictions to operability, the financial consequences/failure costs for MSG as organisation? And how is this affected by 'direct' availability of spare-parts?*

The analysis of financial consequences of failure proposed a division in: opportunity costs; container removal costs; additional (planning) costs; and business recovery costs; in order to determine all downtime related failure costs. Furthermore it showed that the failure costs are highly dependent on: (1) the severity of operational consequences after the failure, which is the effect of diminished operability of the vessel; (2) the duration of the failure; and (3) the availability of a second container-crane vessel. The failure costs are therefore related to the vessel state, which the vessel can be assigned to after component failure. Depending on this vessel state failure costs after 14 days can reach up to €96,000 for failures with severe consequences and be as little as €15,000 for failures with minor consequences. For components related to the cargo handling gear the failure costs vary between €4,000 – €88,000 (with three exceptions which are $>$€170,000 due to very long failure durations). The majority of failure costs are related to opportunity costs and container removal costs, which contribute to 64% – 86% of total failure costs. With availability of the MKS Transferium the effects (costs) can be substantially reduced (by €2,000 - €40,000) depending on the type of component, with an average reduction of $\approx$50%.

The analysis with inventory showed that direct availability of spare-parts has a large effect on failure costs. For MKS Mercurius as single-acting vessel, with inventory, a reduction in failure costs between €50,000 – €70,000 (equal to 55% – 95%) can be achieved for components with severe consequences to operability and a reduction between €3,000 – €17,000 (equal to 30% – 85%) can be achieved for component with minor consequences. With availability of MKS Transferium the consequences are (partialy) mitigated and a reduction between €18,000 – €30,000 (equal to 60% – 90%) can be achieved for components with severe consequences to operability and a reduction between €1,000 – €10,000 (equal to 25% – 75%) can be achieved for component with minor consequences.

At last, the effect of longer lead times (guaranteed lead times from suppliers) showed that the failure costs can increase to €77,000 – €173,000 for the 'critical' components. This effect is caused by increasing opportunity costs (revenue losses) in these longer durations. Which contribute to 52% – 71% of total failure costs.

# Chapter 7

# Inventory Costs

In order to obtain the total overview of the effect of keeping a spare-part inventory on the performance of MSG's container-crane vessels, in comparison to the benefits of keeping a spare-part inventory (Chapter 6), the annual inventory costs need to be determined.

This chapter addresses the annual costs of keeping a spare-part inventory for components related to the cargo handling gear.

## 7.1 Breakdown of Inventory Costs

Besides the benefits of having a spare-part inventory, which is mainly the elimination of lead time, there are also (annual) costs related to keeping an inventory. The annual inventory costs entail: interest/capital costs; risk costs, including insurance and depreciation of goods; and warehousing costs (Blauwens, De Baere, and Van De Voorde, 2016).

Interest costs relate to the type of financing used to acquire the inventory, since the assets stored in inventory represent capital and are either financed by debt, with equity, or by a combination of both. To determine the interest/capital costs, an interest rate for the type of financing (or division of debt/equity) applicable to MSG must be known. This can be defined by the Weighted Average Cost of Capital (WACC). The WACC is the average costs of these types of financing, each of which is weighed by its proportionate use. A value for the WACC applicable to MSG is estimated at 6% (see Section 3.8). As a result the interest or capital costs can be determined by multiplying the component price with this interest rate/WACC.

The risk costs include an insurance premium and economic depreciation of goods. These costs are the result of a decrease in item value due to potential damages and/or aging of the item. The insurance rate is assumed as a rate equal to 1% of the purchasing price of the component. As a result the insurance costs can be determined by multiplying the component price by the insurance rate. The components stored in inventory are intended for personal use during the vessels residual life, which is assumed 20 years. To determine the depreciation costs the components are linearly depreciated to a residual value over the remaining lifetime of the vessel, as prescribed by fiscal legislation (see also Section 3.8). At the end of the vessels lifetime the components in inventory can for example be: sold to a third-party, sold-back to the crane manufacturer (Liebherr) or in some cases used as spare by the MKS Transferium. For this reason a residual value of 50% is assumed for components stored in inventory. As a result the annual depreciation costs are assumed 2.5% of purchasing price for each component.

Finally, when considering the annual costs of inventory, warehousing costs must be included. In case of a fully owned and controlled inventory by MSG a storage unit is required to store the items. This storage unit can be hired in the Rotterdam/Zwijndrecht area with a fixed rate of €20/m$^2$ per month (Shurgard, 2017). The components are divided in large sized, medium sized and small components. It is assumed that large components require an area of 2 m$^2$, medium sized components an area of 1 m$^2$ and small sized components an area of 0.5 m$^2$. This results in annual warehousing costs of approximately €500 for large sized components, €250 for medium sized components and €100 for small components.

## 7.2 Inventory Costs per Component

Annual inventory costs are a result of the components stored in inventory, all related costs are therefore allocated to (only) the components stored in inventory. The annual inventory costs for a component, if stored in inventory, can be determined with previously described cost model (Section 7.1). Table 7.1 shows the annual inventory costs for previously determined 'critical' components of the vessels cargo handling gear.

From the table it can be seen that annual inventory costs are mostly influenced by interest/capital costs. For low-value components (< €2,000 – €2,500) the warehousing costs can largely contribute to the annual inventory costs. For these components costs related to interest and risk can be insignificant. On the other hand, for high-value components (>10,000 €) the majority of inventory costs is related to interest and depreciation costs. Item value influences both interest/capital costs, insurance costs and depreciation costs. As a result the purchase value of the item has a large influence on annual inventory costs, and therefore important in the consideration of storing a component in inventory. For instance an investment of €98,000 (slew ring roller bearing), with annual recurring costs of €10,800, is only justifiable if the impact of failure without direct availability of this spare-part is substantially larger than the recurring inventory costs related to this component. This is further discussed in the benefit/cost calculations in Section 8.1.

Inventory costs are usually expressed as a percentage of item value (original purchase value) (Donders and Lejeune, 2015). The inventory costs for components related to the crane are, in general, between 11% and 28% of purchase value (with 2 or 3 exceptions caused by low prices of €300 – €500). This resulted in average inventory costs of 21% of item value per annum. There is limited research on the level of annual inventory costs, and on methods to determine these annual inventory costs. However, literature by Durlinger (2013), NEVI (2014), and Donders and Lejeune (2015) showed an experience based estimate of 20% – 25% annual inventory costs in percentage of item value. For spare-parts with high risk of becoming obsolete these costs can be even higher. The calculated inventory costs are therefore in line with the experience based estimate provided by literature.

TABLE 7.1: Annual Inventory Costs 'Critical' Components

| Component | Component Price | Interest | Risk/Insurance | Warehousing | Depreciation | Total Annual Costs in € | Total Annual Costs % of Price |
|---|---|---|---|---|---|---|---|
| | | Annual Costs (in €) | | | | | |
| Power Unit EL (Motor) | 21 000 | 1 250 | 400 | 500 | 550 | 2 700 | 13 |
| V-Pump (Main Pump) | 8 400 | 500 | 150 | 250 | 200 | 1 100 | 13 |
| Coupling | 1 800 | 100 | 50 | 250 | 50 | 450 | 25 |
| Slew Ring Roller Bearing | 98 000 | 5 900 | 1 950 | 500 | 2 450 | 10 800 | 11 |
| Luffing Cylinder | 60 000 | 3 600 | 1 200 | 500 | 1 500 | 6 800 | 11 |
| Luffing Bearing (Cyl.) | 3 500 | 200 | 50 | 100 | 100 | 450 | 13 |
| Hoisting Winch | 29 500 | 1 750 | 600 | 500 | 750 | 3 600 | 12 |
| Lifting Cable/Rope | 8 200 | 500 | 150 | 500 | 200 | 1 350 | 16 |
| Cable Drum | 5 100 | 300 | 100 | 250 | 150 | 800 | 16 |
| Rope Guard | 3 400 | 200 | 50 | 250 | 100 | 600 | 18 |
| Cargo Block | 2 100 | 150 | 50 | 250 | 50 | 500 | 24 |
| Motor Swivel Gear | 8 200 | 500 | 150 | 500 | 200 | 1 350 | 16 |
| Control Module | 4 200 | 250 | 100 | 250 | 100 | 700 | 17 |
| Blockchain | 2 100 | 150 | 50 | 250 | 50 | 500 | 24 |
| Twistlock | 450 | 50 | 0 | 250 | 0 | 300 | 67 |

*Note*: Own Composition

## 7.3 Conclusion

This chapter addressed the annual costs of keeping inventory for components related to the vessels cargo handling gear. As a result this chapter addressed the answer to SQ7.

7. *Which costs are associated with keeping a spare-part inventory and what are these costs for the described systems and components?*

From the inventory costs it can be concluded that the annual costs associated with keeping a spare-part inventory are interest/capital costs, risk (insurance and depreciation) costs and warehousing costs. For high-value components the interest costs and depreciation costs are likely to be the main contributors in total annual inventory costs. For low-value components these costs are insignificant and the main cost factor is warehousing. The inventory costs (expressed in percentage of item value) for components related to the cargo handling gear are between 11% and 28%, with average annual costs of 21%. This is in line with experience based estimates obtained by literature.

# Chapter 8

# Inventory Selection & Optimization

This chapter addresses the inventory selection and optimization for MSG's container-crane vessel MKS Mercurius. The inventory selection is based on a benefit/cost comparison. The benefit of direct availability of spare-parts is determined in Chapter 6 and the costs of keeping a spare-part inventory is determined in Chapter 7. By Monte-Carlo simulation the effect of keeping a spare-part inventory on expected annual costs (failure and inventory) is determined. At last, a sensitivity analysis is executed and a recommended spare-part inventory is proposed. A spare-part inventory is recommended for both: (1) MKS Mercurius, taking into account availability of MKS Transferium in case of failure; and (2) MKS Mercurius as MSG's only container-crane vessel.

## 8.1 Benefit/Cost Ratio per Component

To determine and optimize a spare-part inventory for MSG's container-crane vessels, a suitable standard is required to compare the benefits of keeping a spare-part inventory to its costs. A relation between annual benefits and annual costs can be described by the net benefit or by a benefit/cost ratio (BCR) for the components. The net benefit can be determined by comparing the benefits (Eq. 8.1) of having a component in inventory to its costs. Thus the net benefit is equal to the annual benefit reduced by the annual costs (Eq. 8.2). A positive net benefit therefore means that the benefits outweigh the costs, vice versa a negative net benefit means costs are larger than the expected benefit and one should refrain from storing the component in inventory. Another method to determine whether or not the investment should be made is by calculating the benefit/cost ratio (BCR). The BCR identifies the relationship between the cost and benefits of an investment, and provides a ranking based on this ratio. The BCR is calculated by dividing the total value of the benefits by the total value of costs (Eq. 8.3). Usually this is done by discounting all benefits and costs. Assuming the same discount factor for both the annual benefits and the annual costs and neglecting other effects, such as inflation etc., the BCR provides a constant (annually recurring) value. Note that the BCR may favour investments with small costs and benefits over those with higher net benefits. For this reason both the BCR and expected net benefit for each component is determined.

As shown in Equation 8.1, essentially a consideration of risk of failure (financial) compared to costs of keeping inventory is made to determine which items to store in inventory. Table 8.1 shows the net benefit and BCR for components related to the cargo handling gear.

$$(Risk =)\ Annual\ Benefit = Probability \times (Impact\ no\ Inventory - Impact\ with\ Inventory) \quad (8.1)$$

$$Net\ Benefit = Annual\ Benefit - Annual\ Inventory\ Costs \quad (8.2)$$

$$BCR = \frac{AnnualBenefit}{AnnualInventoryCosts} \quad (8.3)$$

As shown Table 8.1, there is a large spread of net benefit and BCR's for the various components. Without availability of a second-container crane vessel (Only MKS Mercurius) the net benefits (and BCR's) are larger compared to the scenario with availability of the MKS Transferium. Which is as expected, because the failure consequences without availability of a second container-crane vessel are larger and inventory costs are identical (not affected by failure). As a result this thus leads to an increase in net benefit and BCR's for the components. For MKS Mercurius as single-acting vessel this results in 23 crane components for which the benefits outweigh the costs (according to the model). With availability of a second container-crane vessel the reduced failure impact results in 14 crane components for which the benefits outweigh the costs. Obviously, when the BCR exceeds one this means that the components have a positive net benefit. However, some components have a higher net benefit, but due to larger annual inventory costs, a lower BCR. This should be taken into account when designing the inventory strategy.

For the Monte-Carlo simulation (Section 8.2) initially components in inventory are selected based on the condition that the annual costs are outweighed by the expected benefit (BCR>1). Based on this selection the initial investment for MKS Mercurius as single-acting vessel is €131,500, with annual inventory costs equal to €19,500. With availability of a second vessel, based on the model, the initial investment costs are €52,000, with annual inventory costs of €9,000.

## 8.2 Monte-Carlo Simulation (Long-term Analysis)

This section addresses the Monte-Carlo Simulation with which (by simulation) the effect of keeping a spare-part inventory is numerically evaluated, the annual expected costs (consisting of inventory costs and failure costs) are calculated, and the optimal level of inventory is determined.

### 8.2.1 Simulation Process

Monte Carlo Simulation is a mathematical technique that generates random variables for modelling risk or uncertainty of a certain system. By randomly generating the failure probabilities and resulting failures within a year, a distribution is generated where the resulting failure costs can be compared to the frequency of their occurrence. This can eventually be translated to a probability density histogram, which resembles (and has the same characteristics as) a probability density function (short pdf). With this pdf the expected value regarding failure costs can be determined or the probability that the failure costs lies in a specific interval can be determined.

TABLE 8.1: Benefit/Cost Ratio of Crane Components

| # | Component | Annual Failure Probability | Failure Impact Reduction (in €) | Expected Annual Benefit | Costs | Net Benefit | BCR |
|---|---|---|---|---|---|---|---|
| | | | **Only MKS Mercurius** | | | | |
| 1 | Twistlock | 0.200 | 49 800 | 9 960 | 300 | 9 660 | 33.2 |
| 2 | Luffing Bearing (Cyl) | 0.100 | 63 850 | 6 385 | 450 | 5 935 | 14.2 |
| 3 | Block Chain (Hook) | 0.125 | 50 050 | 6 256 | 500 | 5 756 | 12.5 |
| 4 | Cabin Control Module | 0.111 | 62 300 | 6 922 | 700 | 6 222 | 9.9 |
| 5 | Drive Unit Coupling | 0.067 | 61 900 | 4 127 | 450 | 3 677 | 9.2 |
| 6 | Rope Guard/Sheave | 0.083 | 62 150 | 5 179 | 600 | 4 579 | 8.6 |
| 7 | Oil Cooler Pump | 0.067 | 62 100 | 4 140 | 600 | 3 540 | 6.9 |
| 8 | Safety/Pressure Valve | 0.050 | 61 950 | 3 097 | 450 | 2 647 | 6.9 |
| 9 | Cargo Block | 0.056 | 61 950 | 3 442 | 500 | 2 942 | 6.9 |
| 10 | Check Valve/Hydr. (Cyl) | 0.050 | 52 100 | 2 605 | 500 | 2 105 | 5.2 |
| 11 | Force Measuring Strap | 0.100 | 20 900 | 2 090 | 500 | 1 590 | 4.2 |
| 12 | Guide Roller | 0.050 | 23 950 | 1 197 | 300 | 897 | 4.0 |
| 13 | V-Pump (Main Pump) | 0.067 | 64 800 | 4 320 | 1 100 | 3 220 | 3.9 |
| 14 | Motor Swivel Gear | 0.067 | 60 350 | 4 023 | 1 350 | 2 673 | 3.0 |
| 15 | Cable Drum | 0.040 | 59 600 | 2 384 | 800 | 1 584 | 3.0 |
| 16 | Steel Strip | 0.067 | 9 000 | 600 | 250 | 350 | 2.4 |
| 17 | Elec. Safety Sensor | 0.100 | 2 400 | 240 | 100 | 140 | 2.4 |
| 18 | Lifting Cable/Rope | 0.046 | 60 350 | 2 743 | 1 350 | 1 393 | 2.0 |
| 19 | Spreader | 0.067 | 64 600 | 4 307 | 2 400 | 1 907 | 1.8 |
| 20 | Cable Guide | 0.083 | 5 650 | 471 | 300 | 171 | 1.6 |
| 21 | Hoisting Winch | 0.100 | 51 450 | 5 145 | 3 600 | 1 545 | 1.4 |
| 22 | Oil Motor (Winch) | 0.050 | 56 800 | 2 840 | 2 050 | 790 | 1.4 |
| 23 | Double Gear (Control) Pump | 0.050 | 12 100 | 605 | 550 | 55 | 1.1 |
| 24 | Slip Ring Unit | 0.050 | 78 100 | 3 905 | 4 100 | -195 | 0.9 |
| 25 | Power Unit EL (Motor) | 0.050 | 50 150 | 2 507 | 270 | -193 | 0.9 |
| | | | **With MKS Transferium** | | | | |
| 1 | Twistlock | 0.200 | 18 300 | 3 660 | 300 | 3 360 | 12.2 |
| 2 | Luffing Bearing (Cyl) | 0.100 | 26 550 | 2 655 | 450 | 2 205 | 5.9 |
| 3 | Block Chain (Hook) | 0.125 | 18 550 | 2 319 | 500 | 1 819 | 4.6 |
| 4 | Cabin Control Module | 0.111 | 26 400 | 2 933 | 700 | 2 233 | 4.2 |
| 5 | Drive Unit Coupling | 0.067 | 26 000 | 1 733 | 450 | 1 283 | 3.9 |
| 6 | Rope Guard/Sheave | 0.083 | 26 250 | 2 187 | 600 | 1 587 | 3.7 |
| 7 | Oil Cooler Pump | 0.067 | 26 200 | 1 747 | 600 | 1 147 | 2.9 |
| 8 | Safety/Pressure Valve | 0.050 | 26 050 | 1 302 | 450 | 852 | 2.9 |
| 9 | Cargo Block | 0.056 | 26 050 | 1 447 | 500 | 947 | 2.9 |
| 10 | Check Valve/Hydr. (Cyl) | 0.050 | 19 100 | 955 | 500 | 455 | 1.9 |
| 11 | V-Pump (Main Pump) | 0.067 | 27 500 | 1 833 | 1 100 | 733 | 1.7 |
| 12 | Motor Swivel Gear | 0.067 | 27 650 | 1 843 | 1 350 | 493 | 1.4 |
| 13 | Cable Drum | 0.040 | 26 900 | 1 076 | 800 | 276 | 1.3 |
| 14 | Force Measuring Strap | 0.100 | 5 400 | 540 | 500 | 40 | 1.1 |
| 15 | Elec. Safety Sensor | 0.100 | 1 000 | 100 | 100 | 0 | 1.0 |
| 16 | Guide Roller | 0.050 | 5 850 | 292 | 300 | -8 | 0.9 |
| 17 | Lifting Cable/Rope | 0.046 | 27 650 | 1 257 | 1 350 | -93 | 0.9 |
| 18 | Steel Strip | 0.067 | 3 400 | 227 | 250 | -23 | 0.9 |
| 19 | Slip Ring Unit | 0.050 | 69 100 | 3 455 | 4 100 | -645 | 0.8 |
| 20 | Hoisting Winch | 0.100 | 29 250 | 2 925 | 3 600 | -675 | 0.8 |
| 21 | Spreader | 0.067 | 28 700 | 1 913 | 2 400 | -487 | 0.8 |
| 22 | Cable Guide | 0.083 | 2 650 | 221 | 300 | -79 | 0.7 |
| 23 | Luffing Cylinder | 0.067 | 73 000 | 4 867 | 6 800 | -1 933 | 0.7 |
| 24 | Oil Motor (Hoisting) | 0.050 | 28 600 | 1 430 | 2 050 | -620 | 0.7 |
| 25 | Power Unit EL (Motor) | 0.050 | 27 950 | 1 397 | 2 700 | -1 303 | 0.5 |

*Note:* Based on Expected Lead Times (Own Composition)

The failure probabilities of the components are determined in Section 4.2, whether or not a component fails in a given year is determined by a randomly generated number. A random number is generated for each single component. When the random number is lower than the failure probability, which corresponds with the component, the failure is triggered. In addition a sequence of component failures is randomly generated, with this sequence the residual duration, for the simulated year, is determined. With this the probability of the next failure is corrected for the duration (days) left in the year. If the randomly generated number is still lower than the failure probability, corresponding with the component, this failure is also triggered (iterative process). This order of failure is included since components cannot fail when these are not in use during repair. When not included multiple failures could be triggered in periods when the vessel already experiences downtime

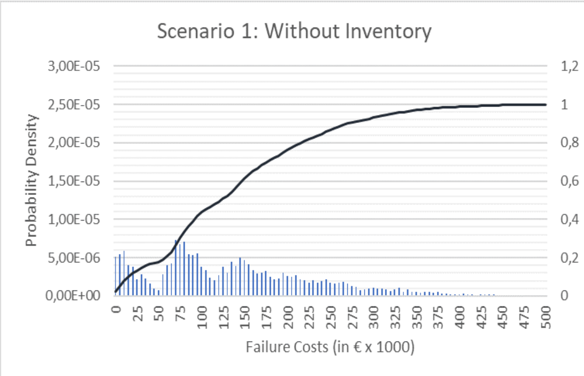
Based on the simulation an initial inventory selection is made for both scenario: MKS Mercurius as MSG's single container-crane vessel, and MKS Mercurius, taking into account availability of MKS Transferium in case of failure. For MKS Mercurius as MSG's single container-crane vessel this inventory consists of 23 components, and for the scenario taking into account availability of a second container-crane vessel the inventory consists of 15 components (see Table 8.1).

### 8.2.2 Comparison with/without Inventory

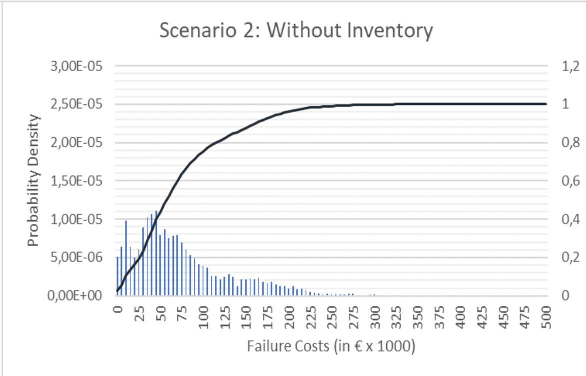
By comparing the results of the Monte-Carlo simulation for both the scenarios with and without inventory insight is gained in the effect of keeping a spare-part inventory on: the expected annual failure costs, and as a result the effect on vessel availability/reliability. With the Monte-Carlo simulation density histograms are obtained which describe the probability distribution of the annual expected failure costs. Figure 8.1 shows the density histograms. The cumulative distribution function, which indicates the probability that the failure costs will take a value less than or equal to x, is also plotted in the figure. Figure 8.1a shows the density histogram for MKS Mercurius as single-acting vessel without a spare-part inventory, Figure 8.1c shows the histogram for MKS Mercurius as single-acting vessel with the selected spare-part inventory, and Figure 8.1e shows the difference in probability for both cases. Figure 8.1b, Figure 8.1d and Figure 8.1f show these (same) graphs for the scenario with availability of a second container-crane vessel. The area below the graph represents probability of occurrence, the probability that the failure costs are within a specific interval can be determined by the area below the graph within that interval. The total area under the graphs is equal to 1, as defined by Equation 8.4.

$$P(-\infty \leq X \leq \infty) = P(0 \leq X \leq \infty) = \int_0^\infty pdf\ dt = 1 \tag{8.4}$$

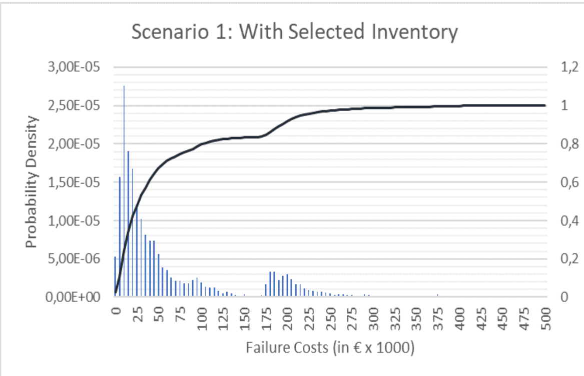
For MKS Mercurius as single-acting vessel, without inventory, the failure costs show a large spread. This spread is related to the fact that failures can have a large spread in costs, due to large failure durations and operational consequences. The expected value for the annual failure costs is equal to €136,000. As an example, the probability that the failure cost are below €100,000 is equal to 44%. With (selected) inventory a clear shift of probability density can be seen, creating a single peak with large probability density at lower annual failure costs. This is due to the fact that with availability of spare-parts in this scenario the failure costs, which are a result of component failure, are significantly reduced. Therefore in the simulation the failures have minor consequences and a large peak is formed with smaller failure costs. The expected value for the annual failure costs in this case is equal to €60,000



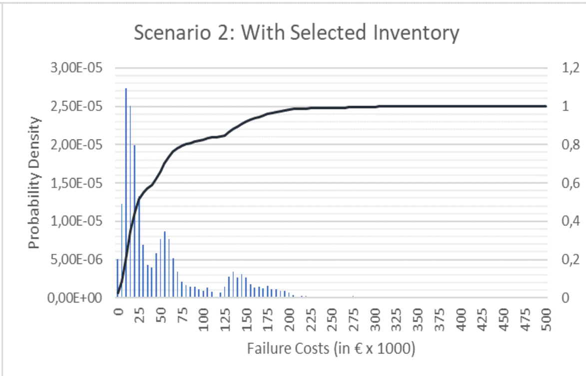

(A) Without Inventory (Only MKS Mercurius)



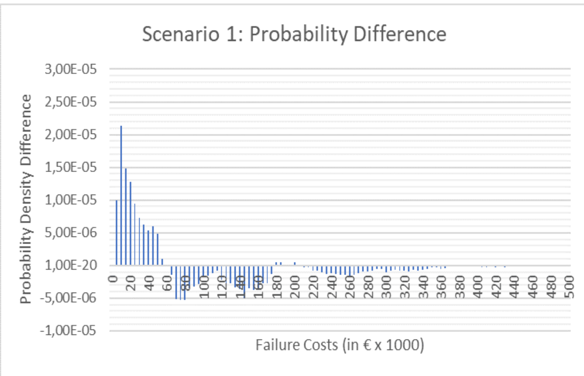

(B) Without Inventory (With MKS Transferium)



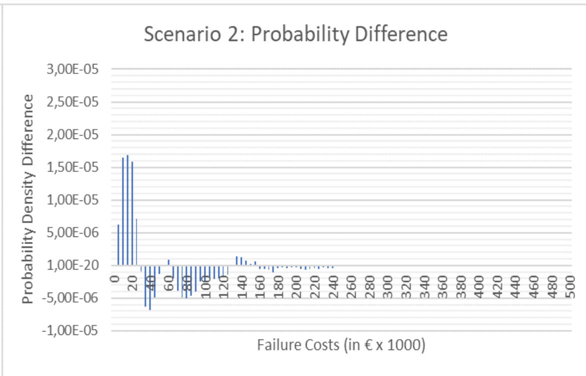

(C) With Inventory (Only MKS Mercurius)




(D) With Inventory (With MKS Transferium)




(E) Comparison (Only MKS Mercurius)




(F) Comparison (With MKS Transferium)

FIGURE 8.1: Density Histogram

*Note*: Both scenarios include a different selection of inventory: For scenario 1 (Only MKS Mercurius) this inventory includes 23 components requiring an investment of €131,690, for scenario 2 (With MKS Transferium) inventory of 15 components, required investment of €52,410 and the probability of failure costs below €100,000 is 71%, which is due to a large increase in availability (and reliability) of the vessel due to direct availability of spare-parts.

With availability of a second container-crane vessel it can be seen, even without inventory, that the spread of annual failure costs is significantly reduced. Which can also be explained by the fact that failure consequences with availability of the MKS Transferium are (partially) mitigated. The expected value for the annual failure costs is equal to €73,000. The probability that the failure cost are below €100,000 is equal to 76%. Again, in this case, with (selected) inventory a clear shift in density can be seen towards a peak with large probability density. The remaining "peak" is related to failures of components with severe consequences, for which a spare-part is not stored in inventory. The expected value for the annual failure costs in this case is equal to €50,000 and the probability of failure costs below €100,000 is 83%. Comparing both scenarios with inventory it can be seen that the expected annual failure costs are relatively alike ( €60,000 vs €50,000), but in the second scenario this is accomplished with a significantly smaller inventory (see Table 8.1).

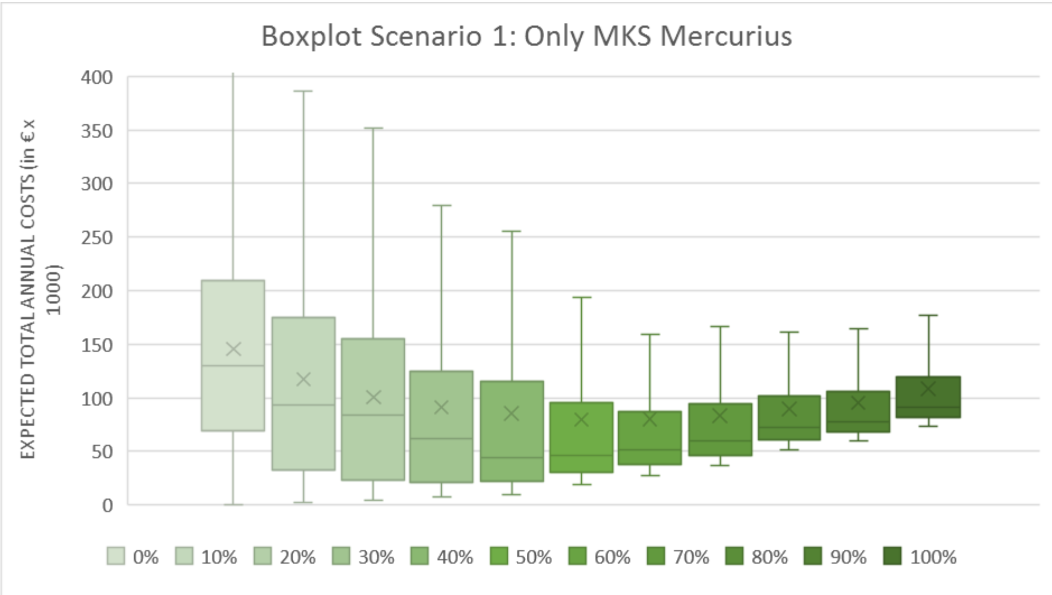
### 8.2.3 Optimal Level of Inventory

Previous section described: the expected annual failure costs without inventory; and described the decrease in failure costs with direct availability of spare-parts, which was a consequence of the increase in vessel availability due to the spare-parts kept in inventory. Obviously, for the case with direct availability of spare-parts, the results are dependent on which components are kept in inventory. As a result a theoretical optimum level of inventory can be determined, which could provide (more) insight in the relation between inventory, annual costs and vessel availability/reliability.

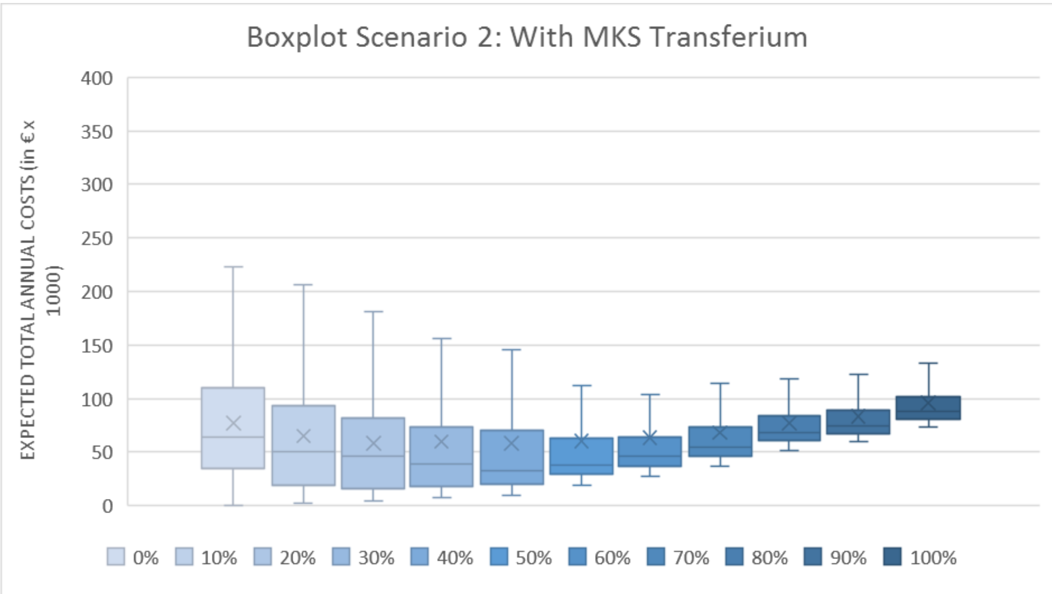
The level of inventory is based on the ranking provided by the BCR's of the components (see Section 8.1). For example, in case of an 80% inventory level, this means that 80% of the components are included in inventory based on the largest BCR's. For the different levels of inventory the distribution of annual costs (annual failure cost plus annual inventory cost) is visualized with box plots. A box plot allows a graphical display of the distribution (and spread) of annual costs. With box plots a clear summary of the data can be presented, which is especially useful to compare data from different simulations (Dekking et al., 2005). The box plot is a standardized way of displaying the distribution of data based on the five number summary: minimum, first quartile (25% of data below this value), median (50% of data below this value), third quartile (75% of data below this value), and maximum. In the boxplot the central rectangle spans the first quartile to the third quartile (equal to the interquartile range or IQR). Up from the upper quartile a distance of 1.5 times the IQR is drawn to indicate the "whisker" towards the largest observation that lies within this distance. All other observations beyond the whisker are called outliers.

Figure 8.2 shows the box plots for the various levels of inventory. Figure 8.3 shows the division of the total annual costs, in failure costs and inventory costs, and shows the development of these annual costs.

From the box plots (Fig. 8.2a and Fig. 8.2b), it can clearly be seen that the spread of expected failure costs reduces, as the level of inventory increases. This can be explained by the fact that with more components stored in inventory, the probability of component failures resulting in large failure costs decrease, which means that the resulting annual costs are more concentrated. Vice versa, with decreasing inventory level, reducing the amount of components stored in inventory, the probability of component failures with severe consequences increases and the resulting annual costs are more spread.



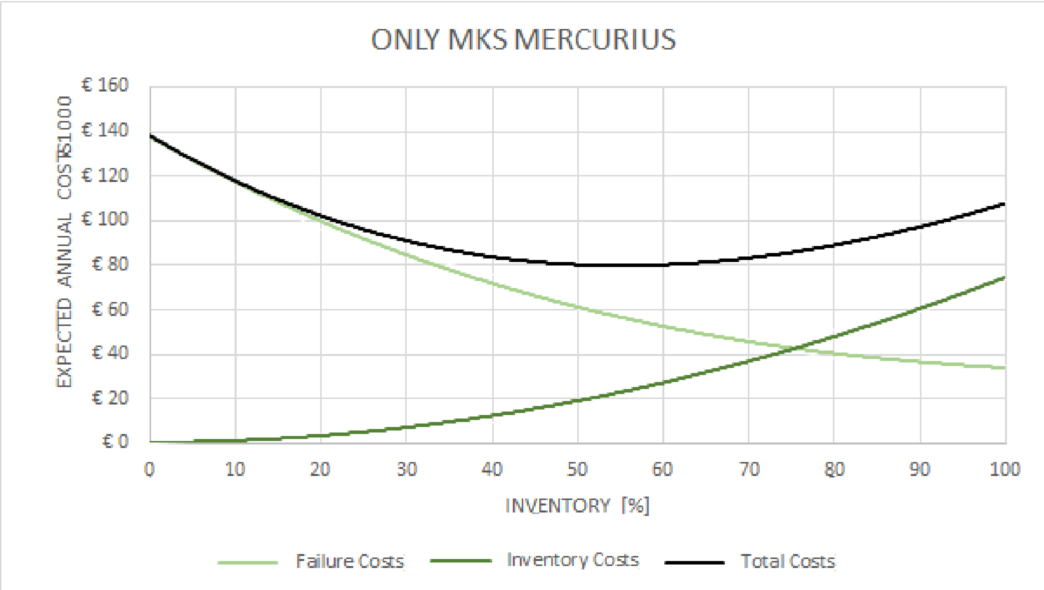

(A) Distribution of Annual Costs dependent on level of Inventory (Only MKS Mercurius)



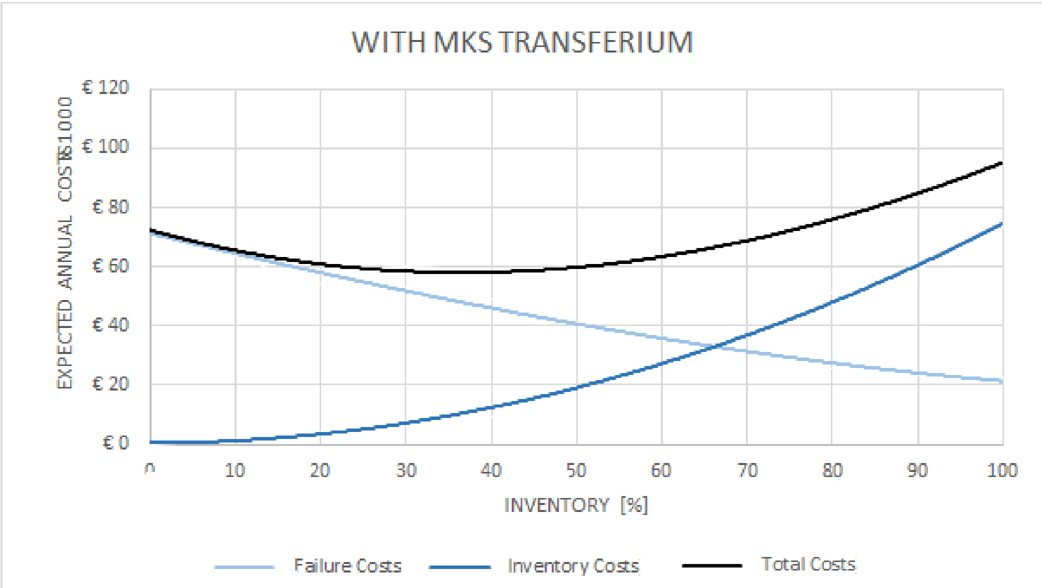

(B) Distribution of Annual Costs dependent on level of Inventory (With MKS Transferium)

FIGURE 8.2: Distribution of Annual Costs based on level of Inventory

*Note*: Own Composition




(A) Total Annual Costs (Only MKS Mercurius)




(B) Total annual Costs (With Transferium)

FIGURE 8.3: Distribution of Annual Costs (Failure, Inventory, Total) based on level of Inventory

*Note*: Own Composition

From Figure 8.3a and Figure 8.3b, it can clearly be seen that there is an optimum level of inventory, with respect to the total annual costs. For increasing inventory levels the failure costs decrease, which is the result of less downtime with direct availability of spare-parts. On the contrary annual inventory costs increase for larger inventory levels, due to an increase in the number (and value) of components stored in inventory. At a certain point the increase in annual inventory costs exceeds the decrease in annual failure costs, resulting in increasing total annual costs and establishing a clear optimum level of inventory. This optimum level of inventory is equal to ≈55%, for MKS Mercurius as single-acting vessel, and equal to 35% with availability of a second container-crane vessel.

Overall it can be concluded that, by increasing the level of inventory, vessel availability (thus vessel reliability) increases due to a decrease in vessel downtime. For large levels of inventories this results in large inventory costs, due to which the expected annual costs increase (non-optimal). This means at a certain point an increase in vessel availability (due to inventory) is only achievable with larger (expected) annual costs. Overall it can clearly be seen that the optimum level of inventory is far less than 100%. With two container-crane vessels the optimal level of inventory is ≈ 35%. After this level the increase of annual inventory costs exceeds the decrease of annual failure costs, resulting in an increase in expected annual costs. For MKS Mercurius as single-acting vessel the optimum is a slightly increased level of inventory at 55%. Which can be explained by the fact that without availability of a second crane vessel, the impact of failure is larger and as a result expected annual failure costs increase. This means that the line related to failure costs increases, which with identical annual inventory costs results in a shift of the optimum (to more inventory).

## 8.3 Sensitivity Analysis

This section addresses the sensitivity analysis, with which the effect of uncertainty, regarding data used in the research, on the proposed inventory is determined. First a selection and range of parameters is defined, after which the effect of each separate parameter on inventory selection is discussed.

### 8.3.1 Parameter Selection

The model(s) in this research, used to determine the annual costs and benefit of components stored in inventory, mainly consist of calculations to determine: annual failure probabilities, failure durations in case of a failure event; failure costs, and inventory costs, for each single component. The main parameters which can influence the selection of inventory are therefore: lead time, component life expectancy, failure costs, and inventory costs. Therefore the sensitivity analysis focuses on these parameters of the model(s).

To determine the effect of lead time on the inventory selection, the BCR for each component is determined for both expected lead times and guaranteed lead times. Note that the expected lead time has been defined as lead time in case full efforts are made to reduce the lead time and alternative solutions are sought for the repair. The effect of uncertainties regarding component life expectancy is determined by calculating the BCR's with a 10% increase in life expectancy of the components and a 10% decrease in life expectancy of the components. This same variation (±10%) is used to determine the effect of a change in failure costs, and the effect of a change in inventory costs on the outcome of the model(s).

### 8.3.2 Effect of Uncertainties (Lead time)

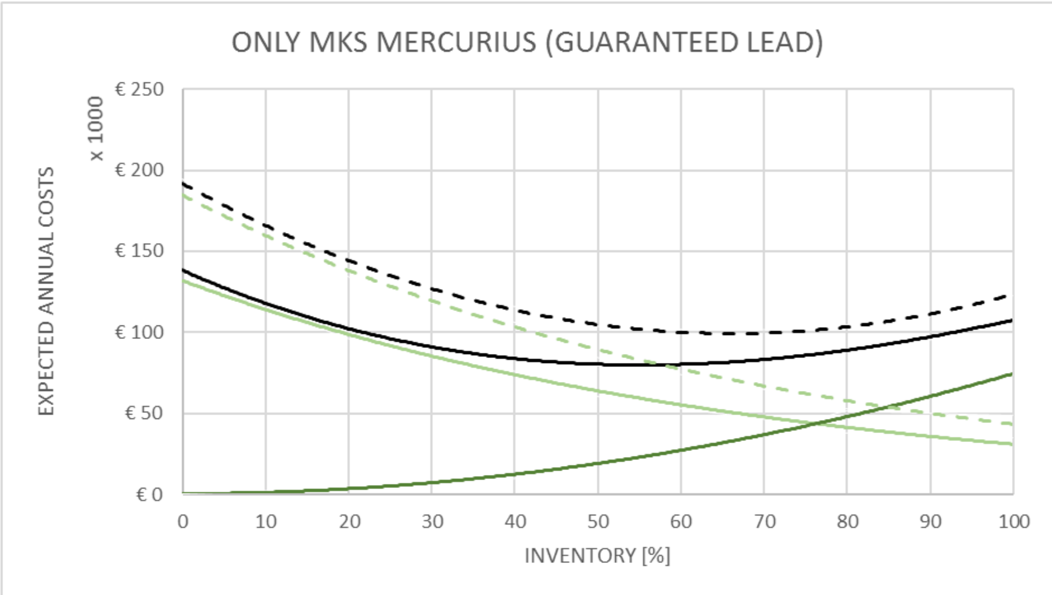
The lead time for the various components can differ significantly. A longer lead time has a significant effect on failure impact and on resulting failure costs (see Section 6.3.2). Figure 8.4 shows the increase in expected annual failure costs, indicated with a dotted line (light green/light blue), when expected lead times increase to guaranteed lead times. Due to the significantly increased failure costs, especially in case of lower levels of inventory, the total annual costs increase (dotted black line). With identical (unchanged) annual inventory costs this results in a rightwards shift of the optimum. Which means the optimal level of inventory and therefore the amount of components, for which it is beneficial to store them in inventory (BCR>1), increases. This result is also clearly reflected in the BCR's of the components, an overview of which is provided in Appendix E. For the inventory of MKS Mercurius as MSG's single container-crane vessel this results in a shift of the optimum from 55% to 65%, resulting in an increase in investment from €127,500 to €195,000. For the inventory of the MKS Mercurius, taking into account availability of the MKS Transferium in case of failure this results in a shift of the optimum from 35% to 45%, and the corresponding investment increases from €52,500 to €127,000.

### 8.3.3 Effect of Uncertainties (Component Life Expectancy)

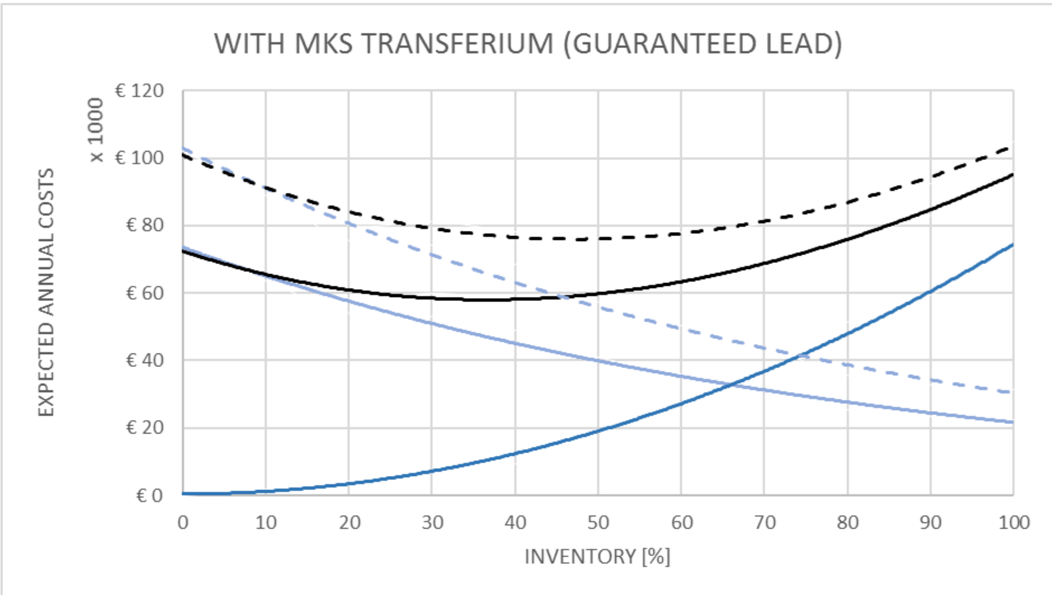
The average life expectancies of the components are estimations, based on expertise of the technical department and/or based on data from suppliers. The life expectancy influences the resulting failure probability of the component, and therefore affects the annual failure costs. An increase in life expectancy results in a decrease in failure probability and therefore leads to a reduction of annual failure costs. Vice versa, a decrease in life expectancy of the components thus leads to an increase of annual failure costs. Applying this to Figure 8.3 means with a 10% increase in life expectancy the optimum level of inventory decreases and less components should be stored in inventory. With a 10% decrease of life expectancy the optimum level of inventory increases and more components should be stored in inventory. In equivalent for a 10% increase in life expectancy the BCR of the component decreases, and with a 10% decrease of life expectancy the BCR of the component increases. Which is also reflected in the results shown in Appendix E. Furthermore the results show that the effect, meaning an increase from BCR<1 to BCR>1 or vice versa, due to a change in component life expectancy has some influence on the selection of inventory. For the MKS Mercurius, with a second container-crane vessel, the effect is limited to $\pm 1-3$ components. For MKS Mercurius as single vessel, the effect is limited to $\pm 2-5$ components.

### 8.3.4 Effect of Uncertainties (Failure Costs)

Various indications of prices are used to determine the total failure costs in case a component fails. These indications include: obtainable revenue, transfer rates, vessel hire rates, demurrage rate, etc. (see Chapter 6). A 10% increase (or decrease) in these indications results in an increase (or decrease) of failure costs. This increase has a similar result as discussed for an increase in lead time (Section 8.3.2), thus the increase in failure costs results in larger benefits in case components are stored in inventory. This means that the BCR's of the components increase, and as a result more components for which it becomes beneficial to store them in inventory. For a decrease of failure costs, this results in reduced benefits and a decrease of BCR's, which means a lower level of inventory is considered optimal (cost-effective).




(A) Sensitivity Guaranteed Lead Time (Only MKS Mercurius)




(B) Sensitivity Guaranteed Lead Time (With MKS Transferium)

FIGURE 8.4: Sensitivity Guaranteed Lead Time

*Note*: Own Composition

The effect of a 10% increase/decrease of failure costs on the inventory selection is shown in Appendix E. It shows that the effect of a 10% in- or decrease in failure costs has much less influence compared to the effect of guaranteed lead times, since the increase in failure costs with guaranteed lead times was much larger. The difference between a 10% increase in failure costs and a 10% decrease of failure costs is limited to $\pm 3-4$ components.

### 8.3.5 Effect of Uncertainties (Inventory Costs)

To determine the annual inventory costs of components, indications were required to determine interest costs, risk costs and warehousing costs. In contrast to lead time, life expectancy and failure costs, an increase or decrease of inventory costs has an effect on the annual costs of keeping inventory instead of the benefits of inventory. An increase in inventory costs, while maintaining identical expected annual failure costs, leads to an increase of the total annual costs. As a result the optimal level of inventory decreases, and less components have a BCR above one, which means less components should be stored in inventory. Vice versa a decrease in inventory costs results in an increase in optimal level of inventory, since more components have a BCR exceeding one and the list of inventory increases.

The effect of a 10% increase/decrease of inventory costs on the inventory selection is shown in Appendix E. It shows that the effect of a 10% in- or decrease of inventory costs has a limited effect on inventory selection. For a 10% increase in inventory costs the inventory selection is unchanged, compared to the default situation. For an 10% decrease of inventory costs the effect is limited to a shift of 1 – 2 components.

### 8.3.6 Conclusion Sensitivity Analysis

The BCR's of the various components showed a large spread. Due to this large spread the effect of various changes in parameters usually has a small effect on the ranking of components, which are based on their BCR's. Furthermore, for components with large BCR's (BCR>2) the effect of uncertainty is limited, because by increasing/decreasing several parameters the BCR's of large components will remain larger than 1. This means that for these components, the benefits will outweigh the costs independent on parameter changes. The largest effects are encountered in the region of components with BCR's between 0.5 - 2.0, because with these BCR's changes in parameters might result in a decrease in BCR below one (from BCR>1 to BCR<1) or an increase to above one. Meaning by adjusting some parameters the inventory selection is slightly altered.

The results of the sensitivity analysis are summarized within two tables, one for each scenario. Table 8.2 shows the list of components for MKS Mercurius as single-acting vessel, and Table 8.3 shows the list of components with availability of a second container-crane vessel (MKS Transferium). For all separate parameters the BCR's of the various components are determined. Table 8.2 and 8.3 show the minimum and maximum observed BCR for each component, observed in all separate sensitivity outcomes. In case a component has a BCR exceeding one for all parameter changes, the component is indicated in black. If the BCR of a component varies below and above one, meaning by adjusting some parameters it becomes cost-effective to store the component in inventory and for other adjustments it becomes unprofitable to store the component in inventory, the component is indicated in blue. At last, for components with BCR below one for all sensitivity outcomes the component is indicated in red. The outcome (BCR's) for each separate parameter, used in the sensitivity analysis, is provided in Appendix E.

TABLE 8.2: Inventory Selection Sensitivity (Only MKS Mercurius)

| Rank | Component | BCR Minimum | BCR Maximum | Cost of Component | Cumulative Costs | Rank | Component | BCR Minimum | BCR Maximum | Cost of Component | Cumulative Costs |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Expected Lead Time | | | | | | Guaranteed Lead Time | | | |
| 1 | Twistlock | 22.6 | 50.3 | 450 | 450 | 1 | Twistlock | 43.5 | 75.2 | 450 | 450 |
| 2 | Luffing Bearing (Cyl) | 8.3 | 16.3 | 3 500 | 3 950 | 2 | Control Module | 18.5.1 | 23 | 4 200 | 4 650 |
| 3 | Block Chain (Hook) | 8.8 | 15.8 | 2 100 | 6 050 | 3 | Block Chain (Hook) | 16.4 | 23.6 | 2 100 | 6 750 |
| 4 | Control Module | 6.3 | 11.4 | 4 200 | 10 250 | 4 | Luffing Bearing (Cyl) | 12.4 | 18.8 | 3 500 | 10 250 |
| 5 | Drive Unit Coupling | 6.3 | 10.6 | 1 800 | 12 050 | 5 | Cargo block | 13.5 | 19.0 | 2 100 | 12 350 |
| 6 | Rope Guard/Sheave | 5.5 | 9.9 | 3 400 | 15 450 | 6 | Safety/Pressure Valve | 10.9 | 16.1 | 3 600 | 15 950 |
| 7 | Oil Cooler Pump | 4.0 | 7.9 | 4 800 | 20 250 | 7 | Drive Unit Coupling | 12.3 | 15.8 | 1 800 | 17 750 |
| 8 | Safety/Pressure Valve | 3.8 | 7.9 | 3 600 | 23 850 | 8 | Rope Guard/Sheave | 11.6 | 14.8 | 3 400 | 21 150 |
| 9 | Cargo Block | 4.8 | 8.7 | 2 100 | 25 950 | 9 | Oil Cooler Pump | 9.3 | 11.8 | 4 800 | 25 950 |
| 10 | Check Valve/Hydr. (Cyl) | 3.6 | 6.6 | 2 200 | 28 150 | 10 | Check Valve/Hydr. | 7.1 | 10.2 | 2 200 | 28 150 |
| 11 | Force Measuring Strap | 2.9 | 5.4 | 2 200 | 30 350 | 11 | Guide Roller | 6.7 | 8.6 | 1 800 | 29 950 |
| 12 | Guide Roller | 2.4 | 4.7 | 1 800 | 32 150 | 12 | Cable Drum | 5.5 | 6.8 | 5 100 | 35 050 |
| 13 | V-Pump (Main Pump) | 2.4 | 4.5 | 8 400 | 40 550 | 13 | V-Pump (Main Pump) | 5.1 | 6.5 | 8 400 | 43 450 |
| 14 | Motor Swivel Gear | 1.9 | 3.4 | 8 200 | 48 750 | 14 | Force Measuring Strap | 5.1 | 7.2 | 2 200 | 45 650 |
| 15 | Cable Drum | 2.0 | 3.4 | 5 100 | 53 850 | 15 | Lifting Cable/Rope | 3.7 | 4.6 | 8 200 | 53 850 |
| 16 | Steel Strip | 1.6 | 3.0 | 180 | 54 030 | 16 | Steel Strip | 3.4 | 5.0 | 180 | 54 030 |
| 17 | Elec. Safety Sensor | 1.0 | 2.7 | 360 | 54 390 | 17 | Motor Swivel Gear | 2.9 | 3.8 | 8 200 | 62 230 |
| 18 | Lifting Cable/Rope | 1.2 | 3.3 | 8 200 | 62 590 | 18 | Hoisting Winch | 2.8 | 3.4 | 29 500 | 91 730 |
| 19 | Spreader | 1.2 | 2.1 | 18 000 | 80 590 | 19 | Oil Motor (Winch) | 2.6 | 3.2 | 17 000 | 108 730 |
| 20 | Cable Guide | 1.1 | 1.9 | 500 | 81 090 | 20 | Spreader | 2.4 | 3.0 | 18 000 | 126 730 |
| 21 | Hoisting Winch | 1.0 | 1.6 | 29 500 | 110 590 | 21 | Elec. Safety Sensor | 1.6 | 2.7 | 360 | 127 090 |
| 22 | Oil Motor (Winch) | 1.0 | 1.6 | 17 000 | 127 590 | 22 | Suction Pipe | 1.7 | 2.4 | 2 300 | 129 390 |
| 23 | Double Gear (Control) Pump | 0.7 | 1.3 | 4 100 | 131 690 | 23 | Double Gear (Control) Pump | 1.6 | 2.2 | 4 100 | 133 490 |
| 24 | Chain (CW) | 0.7 | 1.3 | 4 800 | 136 490 | 24 | Cable Guide | 1.3 | 1.9 | 500 | 133 990 |
| 25 | Slip Ring Unit | 0.6 | 1.1 | 34 000 | 170 490 | 25 | Height Adjustment Hydr. | 1.2 | 1.8 | 2 240 | 136 230 |
| 26 | Power Unit EL (Motor) | 0.6 | 1.0 | 21 000 | 191 490 | 26 | Slewing Gear | 1.3 | 1.7 | 5 100 | 141 330 |
| 27 | Height Adjustment Hydr. | 0.6 | 1.0 | 2 240 | 193 730 | 27 | Chain (CW) | 1.3 | 1.6 | 4 800 | 146 130 |
| 28 | Electric Motor (CW) | 0.6 | 1.0 | 4 500 | 198 230 | 28 | Power Unit EL (Motor) | 1.2 | 1.5 | 21 000 | 167 130 |
| 29 | Oil Cooler | 0.6 | 1.0 | 4 500 | 202 730 | 29 | Electric Motor (CW) | 1.2 | 1.5 | 4 500 | 171 630 |
| 30 | Luffing Cylinder | 0.5 | 0.9 | 60 000 | 262 730 | 30 | Double hook w. Suspension | 1.1 | 1.4 | 24 000 | 195 630 |
| 31 | Suction Pipe | 0.5 | 0.9 | 2 300 | 265 030 | 31 | Slip Ring Unit | 0.9 | 1.1 | 34 000 | 229 360 |
| 32 | Double Hook w. Suspension | 0.5 | 0.9 | 24 000 | 289 030 | 32 | Oil Cooler | 0.8 | 1.0 | 4 500 | 234 130 |
| 33 | Slewing Gear | 0.4 | 0.7 | 5 100 | 294 130 | 33 | Luffing Cylinder | 0.7 | 0.9 | 60 000 | 294 130 |
| 34 | Slew Ring Roller Bearing | 0.3 | 0.5 | 98 000 | 392 130 | 34 | Slew Ring Roller Bearing | 0.4 | 0.5 | 98 000 | 392 130 |

*Note*: Own Composition

TABLE 8.3: Inventory Selection Sensitivity (With MKS Transferium)

| Rank | Component | BCR Minimum | BCR Maximum | Cost of Component | Cumulative Costs | Rank | Component | BCR Minimum | BCR Maximum | Cost of Component | Cumulative Costs |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Expected Lead Time | | | | | | Guaranteed Lead Time | | | |
| 1 | Twistlock | 10.7 | 18.3 | 450 | 450 | 1 | Twistlock | 20.3 | 34.4 | 450 | 450 |
| 2 | Luffing Bearing (Cyl) | 4.4 | 6.6 | 3 500 | 3 950 | 2 | Control Module | 11.9 | 14.7 | 4 200 | 4 650 |
| 3 | Block Chain (Hook) | 4.1 | 5.8 | 2 100 | 6 050 | 3 | Cargo Block | 8.8 | 12.2 | 2 100 | 6 750 |
| 4 | Control Module | 3.7 | 4.7 | 4 200 | 10 250 | 4 | Safety/Pressure Valve | 6.9 | 10.2 | 3 600 | 10 350 |
| 5 | Drive Unit Coupling | 3.4 | 4.3 | 1 800 | 12 050 | 5 | Block Chain (Hook) | 7.7 | 10.8 | 2 100 | 12 450 |
| 6 | Rope Guard/Sheave | 3.2 | 4.0 | 3 400 | 15 450 | 6 | Drive Unit Coupling | 6.8 | 8.6 | 1 800 | 14 250 |
| 7 | Oil Cooler Pump | 2.6 | 3.2 | 4 800 | 20 250 | 7 | Luffing Bearing (Cyl) | 5.6 | 8.3 | 3 500 | 17 750 |
| 8 | Safety/Pressure Valve | 2.2 | 3.2 | 3 600 | 23 850 | 8 | Rope Guard/Sheave | 6.4 | 8.0 | 3 400 | 21 150 |
| 9 | Cargo Block | 2.6 | 3.6 | 2 100 | 25 950 | 9 | Oil Cooler Pump | 5.1 | 6.4 | 4 800 | 25 950 |
| 10 | Check Valve/Hydr. (Cyl) | 1.7 | 2.4 | 2 200 | 28 150 | 10 | Cable Drum | 3.6 | 4.5 | 5 100 | 31 050 |
| 11 | V-Pump (Main Pump) | 1.5 | 1.9 | 8 400 | 36 550 | 11 | Check Valve/Hydr. | 3.6 | 5.0 | 2 200 | 33 250 |
| 12 | Motor Swivel Gear | 1.2 | 1.5 | 8 200 | 44 750 | 12 | V-Pump (Main Pump) | 2.8 | 3.5 | 8 400 | 41 650 |
| 13 | Cable Drum | 1.2 | 1.5 | 5 100 | 49 850 | 13 | Guide Roller | 2.6 | 3.4 | 1 800 | 43 450 |
| 14 | Force Measuring Strap | 0.9 | 1.4 | 2 200 | 52 050 | 14 | Lifting Cable/Rope | 2.5 | 3.1 | 8 200 | 51 650 |
| 15 | Elec. Safety Sensor | 0.7 | 1.1 | 360 | 52 410 | 15 | Hoisting Winch | 2.0 | 2.5 | 29 500 | 81 150 |
| 16 | Guide Roller | 0.8 | 1.1 | 1 800 | 54 210 | 16 | Oil Motor (Hoisting) | 1.8 | 2.2 | 17 000 | 98 150 |
| 17 | Lifting Cable/Rope | 0.8 | 1.0 | 8 200 | 62 410 | 17 | Motor Swivel Gear | 1.5 | 1.8 | 8 200 | 106 350 |
| 18 | Steel Strip | 0.7 | 1.1 | 180 | 62 590 | 18 | Spreader | 1.3 | 1.7 | 18 000 | 124 350 |
| 19 | Slip Ring Unit | 0.8 | 0.9 | 34 000 | 96 590 | 19 | Force Measuring Strap | 1.3 | 1.8 | 2 200 | 126 550 |
| 20 | Hoisting Winch | 0.7 | 0.9 | 29 500 | 126 090 | 20 | Elec. Safety Sensor | 0.7 | 1.1 | 360 | 126 910 |
| 21 | Spreader | 0.7 | 0.9 | 18 000 | 144 090 | 21 | Steel Strip | 0.7 | 1.1 | 180 | 127 090 |
| 22 | Cable Guide | 0.6 | 0.9 | 500 | 144 590 | 22 | Power Unit EL (Motor) | 0.8 | 1.0 | 21 000 | 148 090 |
| 23 | Luffing Cylinder | 0.6 | 0.8 | 60 000 | 204 590 | 23 | Slip Ring Unit | 0.8 | 0.9 | 34 000 | 182 090 |
| 24 | Oil Motor (Winch) | 0.6 | 0.8 | 17 000 | 221 590 | 24 | Double Hook w. Suspension | 0.7 | 0.9 | 24 000 | 206 090 |
| 25 | Power Unit EL (Motor) | 0.5 | 0.6 | 21 000 | 242 590 | 25 | Cable Guide | 0.6 | 0.9 | 500 | 206 590 |
| 26 | Slew Ring Roller Bearing | 0.4 | 0.5 | 98 000 | 340 590 | 26 | Luffing Cylinder | 0.7 | 0.8 | 60 000 | 266 590 |
| 27 | Oil Cooler | 0.3 | 0.4 | 4 500 | 345 090 | 27 | Electric Motor (CW) | 0.4 | 0.6 | 4 500 | 271 090 |
| 28 | Double Gear (Control) Pump | 0.3 | 0.5 | 4 100 | 349 190 | 28 | Slew Ring Roller Bearing | 0.4 | 0.5 | 98 000 | 369 090 |
| 29 | Double Hook w. Suspension | 0.3 | 0.4 | 24 000 | 373 190 | 29 | Chain (CW) | 0.3 | 0.4 | 4 800 | 373 890 |
| 30 | Height Adjustment Hydr. | 0.3 | 0.4 | 2 240 | 375 430 | 30 | Oil Cooler | 0.3 | 0.4 | 4 500 | 378 390 |

*Note*: Own Composition

Although the effect of uncertainty is limited to a portion of the components, the effect on the required investment can be substantial. With availability of MKS Mercurius, based on expected lead time, the minimum inventory should consist of 13 components. Which combined result in an investment of ≈ €50,000. The effect of an increase in lead time, to guaranteed lead times, would result in an increase of inventory to 19 components, which would result in an investment of ≈ €125,000. Changes in component life expectancy, failure costs and inventory costs show a limited effect on inventory selection. In case one of the container-crane vessels is sold, relocated etc., which would lead to MKS Mercurius as single-acting vessels, the optimal inventory expands to 22 - 30 components. This would result in an investment of €127,500 – €202,500. In overall a business decision should be made to decide to keep a limited inventory for minimal investment or to increase the inventory (and reliability) resulting in larger costs.

## 8.4 Recommended/Optimized Spare-Part Inventory

This section addresses the recommended spare-part inventory for MSG's container-crane vessel MKS Mercurius. Due to large differences in failure impact and resulting inventory selection, with availability of a second container-crane vessel, an inventory is recommended for both: (1) MKS Mercurius, taking into account availability of MKS Transferium in case of failure; and (2) MKS Mercurius as MSG's single container-crane vessel.

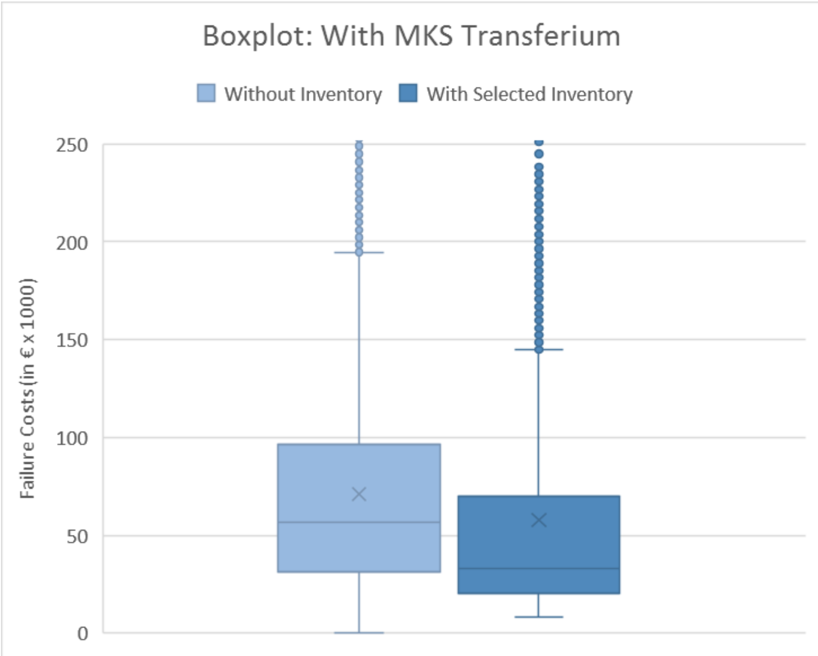
### 8.4.1 Recommended Spare-Part Inventory (With MKS Transferium)

The MKS Mercurius and MKS Transferium both operate in the Port of Rotterdam are, which means, in case of failure of the MKS Mercurius, lifting activities scheduled to be executed by the MKS Mercurius can be taken over by the MKS Transferium. Therefore the scenario related to failure of the MKS Mercurius with availability of a second container-crane vessel is currently most relevant for MSG. For this scenario the effect of failure is partially mitigated by the presence of a second container-crane vessel. For this reason, compared to the scenario with MKS Mercurius as MSG's single container-crane vessel, vessel availability is considered less crucial. Combined with the fact that expected lead times are viewed as the most likely outcome, the inventory selection for this scenario is based on the outcome with expected lead times. Based on the outcome of the sensitivity analysis the inventory includes 13 components, which have a BCR exceeding one for all sensitivity outcomes.

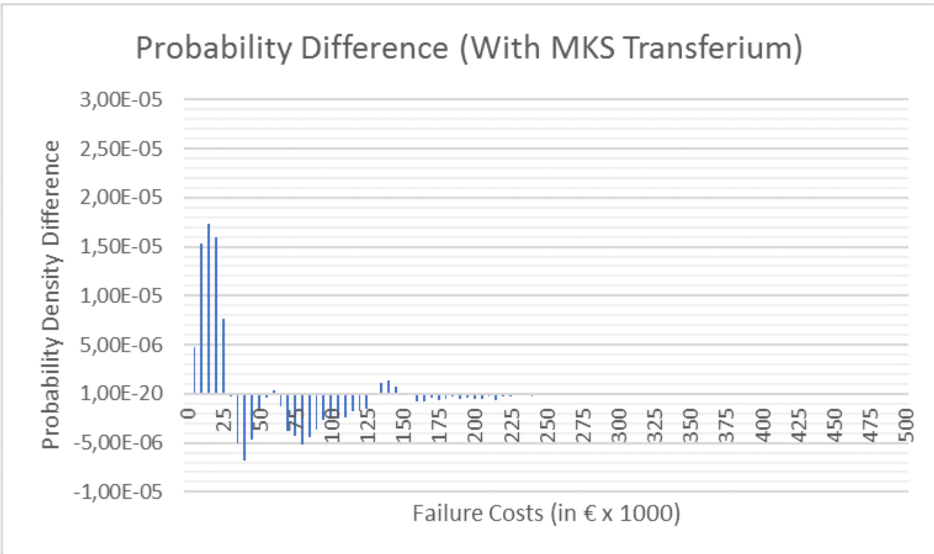
Figure 8.5a shows the comparison of expected annual costs with and without the selected inventory with box plots. Figure 8.5b shows the difference in probability density for this scenario with and without inventory.

From Figure 8.5a it can be seen that with the recommended inventory the spread of expected annual costs decreases. This decrease in annual costs is the result of the decreased annual failure costs, due to direct availability of the spare-parts stored in inventory. Furthermore from Figure 8.5b it can be seen that the probability of low annual failure costs (< €50,000) increases and therefore also the probability of larger failure costs decreases.

The inventory (Table 8.4) requires an initial investment of ≈ €50,000. With the inventory a reduction of expected annual failure costs can be achieved of €22,000. Which with €8,500 annual inventory costs results in an expected annual net benefit of €13,000. As a result the inventory requires a payback period of approximately 4 years. With a larger inventory the probability of a failure resulting in severe consequences and large failure costs decreases,




(A) Distribution Annual Costs (With MKS Transferium)




(B) Density Histogram Comparison with/without Inventory (With MKS Transferium)

FIGURE 8.5: Impact Selected Inventory (With MKS Transferium)

*Note*: Own Composition

TABLE 8.4: Recommended Inventory Selection (With MKS Transferium)

| **Component** | **Cost of Component** |
|---|---|
| Twistlock | 450 |
| Luffing Bearing (Cyl) | 3 500 |
| Block Chain (Hook) | 2 100 |
| Control Module | 4 200 |
| Drive Unit Coupling | 1 800 |
| Rope Guard/Sheave | 3 400 |
| Oil Cooler Pump | 4 800 |
| Safety/Pressure Valve | 3 600 |
| Cargo Block | 2 100 |
| Check Valve/Hydr. (Cyl) | 2 200 |
| V-Pump (Main Pump) | 8 400 |
| Motor Swivel Gear | 8 200 |
| Cable Drum | 5 100 |

*Note*: Own Composition

this would result in a reduced spread in possible annual costs (Fig. 8.5a). On the contrary, a larger inventory would require a substantially larger investment, due to the increased annual inventory costs the annual net benefit decreases and a longer period is required for the investment to be recouped. Although this thus results in an increase in vessel availability (reduced downtime), this is not cost-minimizing and therefore, in accordance with the interests of the client, considered a sub-optimal inventory.

### 8.4.2 Recommended Spare-Part Inventory (Only MKS Mercuirus)

When MSG decides to relocate (or sell etc.) one of the container-crane vessels the effect of direct availability of spare-parts increases, because the financial impact of failure is significantly larger due to the absence of a second crane vessel, able to execute lifting activities. This means for the scenario with MKS Mercurius as MSG's only container-crane vessel inventory becomes more crucial, in order to ensure minimal downtime of the vessel and minimize annual costs. Therefore, when the decision is made to relocate (or sell) the MKS Transferium, MSG should expand MKS Mercurius' spare-part inventory. Since for this scenario more value has to be attached to vessel availability and reliability, to avoid failures with severe financial consequences, the inventory selection consists of: all components with minimum BCR exceeding one in case of expected lead times, including all components below €10,000 with BCR exceeding one for guaranteed lead times see Table 8.2. The spreader is excluded from inventory, since a spreader can be rented in case of failure. As a result, the inventory includes 28 components (Table 8.5).

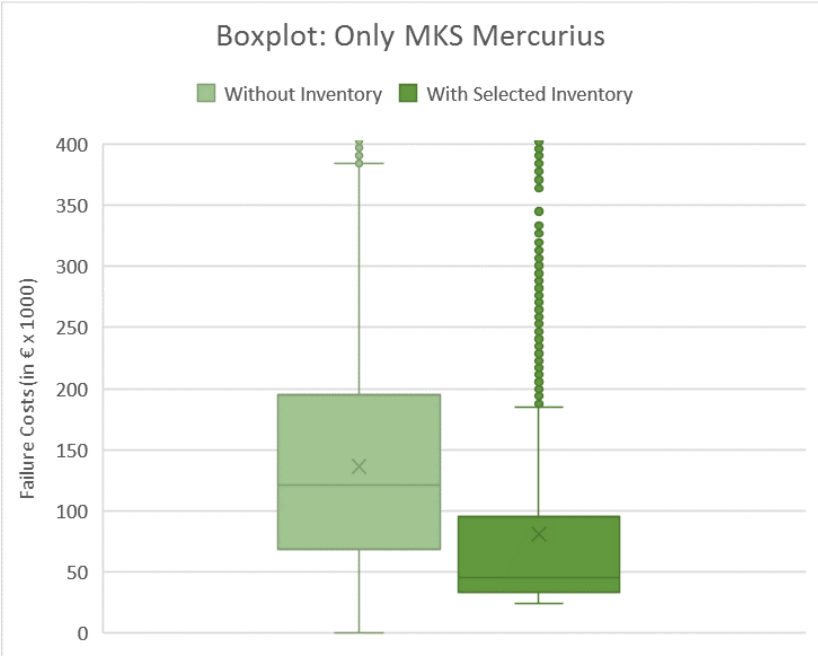
Figure 8.6a shows the comparison of expected annual costs with and without the selected inventory with box plots. Figure 8.6b shows the density histograms and compares probability density for this scenario with and without inventory.

The inventory (Table 8.5) requires an initial investment of $\approx$ €137,000. With the inventory a reduction of expected annual failure costs can be achieved of €79,000. Which with €24,000 annual inventory costs results in an expected annual net benefit of €55,000. This shows that for the scenario with MKS Mercurius as MSG's single container-crane vessel

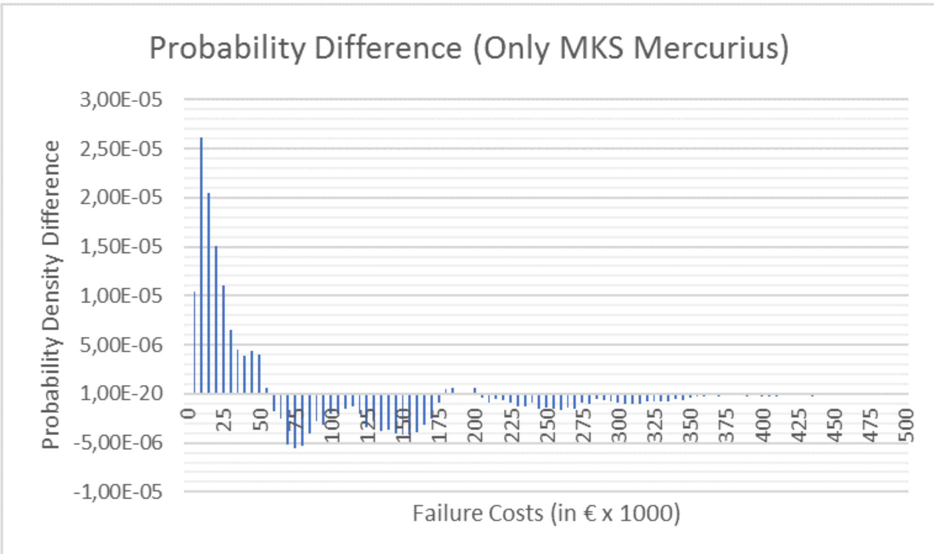
TABLE 8.5: Recommended Inventory Selection (Only MKS Mercurius)

| **Component** | **Cost of Component** |
|---|---|
| Twistlock | 450 |
| Luffing Bearing (Cyl) | 3 500 |
| Block Chain (Hook) | 2 100 |
| Control Module | 4 200 |
| Drive Unit Coupling | 1 800 |
| Rope Guard/Sheave | 3 400 |
| Oil Cooler Pump | 4 800 |
| Safety/Pressure Valve | 3 600 |
| Cargo Block | 2 100 |
| Check Valve/Hydr. (Cyl) | 2 200 |
| V-Pump (Main Pump) | 8 400 |
| Motor Swivel Gear | 8 200 |
| Cable Drum | 5 100 |
| Guide Roller | 1 800 |
| Force Measuring Strap | 2 200 |
| Lifting Cable/Rope | 8 200 |
| Steel Strip | 180 |
| Hoisting Winch | 29 500 |
| Oil Motor (Winch) | 17 000 |
| Elec. Safety Sensor | 360 |
| Suction Pipe | 2 300 |
| Double Gear (Control) Pump | 4 100 |
| Cable Guide | 500 |
| Height Adjustment Hydr. (Cabin) | 2 240 |
| Slewing Gear | 5 100 |
| Chain (CW) | 4 800 |
| Electric Motor (CW) | 4 500 |
| Oil Cooler | 4 500 |

*Note*: Own Composition




(A) Distribution Annual Costs (Only MKS Mercurius)




(B) Density Histogram Comparison with/without Inventory (Only MKS Mercurius)

FIGURE 8.6: Impact Selected Inventory (Only MKS Mercurius)

*Note*: Own Composition

the reduced failure impact with (large) inventory results in significant improvement to the vessels financial performance. The optimal level of inventory for MKS Mercurius as single container-crane vessel is approximately 55% (see Section 8.2.3), but with larger inventory the annual costs remain to provide a reduction compared to the annual costs without inventory. Therefore an inventory requiring an even larger initial investment (for example €200,000 – €250,000 with a net benefit of ≈ €50,000) can still be recouped within 4 – 5 years. A more expensive inventory would therefore still yield satisfactory results, regarding cost minimization, and provide a large increase in vessel availability, due to a decrease in downtime.

## 8.5 Conclusion

This section addressed the inventory selection and optimization for MSG's container-crane vessel MKS Mercurius and addressed the sensitivity, regarding uncertainties of the research, on the inventory selection. As a result this chapter addressed the answer to both SQ8 and SQ9.

8. *For which components/parts is it, from a long-term financial perspective, cost-effective to store them in inventory?*

For the cost-effectiveness of keeping a component in inventory a comparison is proposed based on the expected net benefit and/or benefit/cost ratios (BCR) for each component. The results showed that a different optimal/recommended inventory is obtained for both scenarios: (1) MKS Mercurius, taking into account availability of MKS Transferium in case of failure; and (2) MKS Mercurius as MSG's single container-crane vessel.

For the inventory of the MKS Mercurius, considering the current situation with two container-crane vessels, the optimal level of inventory is ≈35%, which includes the 35% of components with the largest BCR's. The selection of spare-parts for this inventory is shown in Table 8.6. This inventory requires an initial investment of approximately €50,000, and includes a total of €8,500 of annual inventory costs. This inventory leads to a reduction of expected annual failure costs of €22,000, which means the annual net benefit is equal to €13,500. The investment therefore has a return of 26% and requires a payback period of approximately 4 years.

In case MSG decides to relocate (or sell etc.) one of the container-crane vessels the benefit of keeping a spare-part inventory significantly increases. For the inventory of the MKS Mercurius, as MSG's single container-crane vessel, the optimal level of inventory is ≈55%. Due to the increased importance of vessel availability, and to decrease the probability of occurrence of failures with severe financial consequences, the selected inventory is increased to 28 components (Table 8.6). This inventory requires an initial investment of €137,000 and leads to a decrease of expected annual failure costs equal to €79,000. Which with €24,000 of annual inventory costs results in an annual net benefit of €55,000. The investment therefore has a return of 43% and requires an expected payback period of less than 3 years.

Essentially a consideration must be made between a cost-minimizing inventory, or a larger inventory which increases vessel availability. The effect of direct availability of spare-parts, on vessel availability and the reduction in probability of severe financial consequences this leads to, is considered more important in the scenario with MKS Mercurius as MSG's single container-crane vessel. As a result, for this scenario, a more extensive inventory for the MKS Mercurius is recommended.

TABLE 8.6: Recommended Inventory

| Component | Cost of Component | Component | Cost of Component |
|---|---|---|---|
| **With MKS Transferium** | | **Only MKS Mercurius** | |
| Twistlock | 450 | Twistlock | 450 |
| Luffing Bearing (Cyl) | 3 500 | Luffing Bearing (Cyl) | 3 500 |
| Block Chain (Hook) | 2 100 | Block Chain (Hook) | 2 100 |
| Control Module | 4 200 | Control Module | 4 200 |
| Drive Unit Coupling | 1 800 | Drive Unit Coupling | 1 800 |
| Rope Guard/Sheave | 3 400 | Rope Guard/Sheave | 3 400 |
| Oil Cooler Pump | 4 800 | Oil Cooler Pump | 4 800 |
| Safety/Pressure Valve | 3 600 | Safety/Pressure Valve | 3 600 |
| Cargo Block | 2 100 | Cargo Block | 2 100 |
| Check Valve/Hydr. (Cyl) | 2 200 | Check Valve/Hydr. (Cyl) | 2 200 |
| V-Pump (Main Pump) | 8 400 | V-Pump (Main Pump) | 8 400 |
| Motor Swivel Gear | 8 200 | Motor Swivel Gear | 8 200 |
| Cable Drum | 5 100 | Cable Drum | 5 100 |
| | | Guide Roller | 1 800 |
| | | Force Measuring Strap | 2 200 |
| | | Lifting Cable/Rope | 8 200 |
| | | Steel Strip | 180 |
| | | Hoisting Winch | 29 500 |
| | | Oil Motor (Winch) | 17 000 |
| | | Elec. Safety Sensor | 360 |
| | | Suction Pipe | 2 300 |
| | | Double Gear (Control) Pump | 4 100 |
| | | Cable Guide | 500 |
| | | Height Adjustment Hydr. (Cabin) | 2 240 |
| | | Slewing Gear | 5 100 |
| | | Chain (CW) | 4 800 |
| | | Electric Motor (CW) | 4 500 |
| | | Oil Cooler | 4 500 |

*Note*: Own Composition

9. *How do uncertainties in the assumptions made in this research affect the proposed inventory strategy? And how sensitive are the results regarding these uncertainties?*

From the uncertainties of assumptions made in the research it can be concluded that uncertainties mainly affect: failure probabilities of the components, failure durations in case of failure, failure costs, and annual inventory costs. Therefore the sensitivity analysis showed that changes in lead time, component life expectancy, failure costs, and inventory costs had the largest effect on the inventory selection.

The results showed that due to the fact that there is a large spread in benefit/cost ratios the effect of uncertainties are limited to component with BCR in the range of 0.5 – 2.0. For the scenario MKS Mercurius with availability of a second container-crane vessel the effect of uncertainty was limited to 6 components, which affected the inventory selection from a minimum of 13 components to a maximum of 19 component. This additional inventory requires additional investment costs of €57,500. For the inventory of MKS Mercurius as single container-crane vessel the effect of uncertainty was limited to 8 components, which affected the inventory selection from a minimum of 22 components to a maximum of 30 components. This additional inventory requires additional investment costs of €77,500.

For the scenario with MKS Mercurius as single container-crane vessel there is added need for vessel availability. As a result inventory selection is based on components with BCR exceeding one for expected lead times, including components with BCR's exceeding one for guaranteed lead times when costs below €10,000. This adds 6 components (to the minimum of 22 componetns), and increases investment by €22,500.

# Chapter 9

# Conclusions & Recommendations

This research is intended to increase the reliability of MSG's container-crane vessel MKS Mercurius by proposing an optimized spare-part inventory. The spare-part inventory should reduce the total costs of operating and maintaining the vessel and ensure profit maximization for MSG. The following main research question was formulated: *"For which crane components/parts will keeping a spare-part inventory result in a cost-effective improvement of the reliability for the container-crane vessel MKS Mercurius?"*. To answer this question quantitative research has been conducted to determine the reduction in failure impact/costs (risk), due to direct availability of spare-parts stored in inventory, compared to the resulting inventory costs this entails.

The quantified benefits of keeping a spare-part inventory showed that direct availability of spare-parts mainly has an effect on: failure durations; repair costs; operational consequences; and financial consequences, including downtime related costs. This effect is translated to resulting failure costs after failure, which includes: opportunity cost (revenue loss), container removal costs, additional planning costs, business recovery costs, and repair costs. Depending on the failure event the total failure costs can be between €4,000 – €190,000. Direct availability of spare-parts can reduce these failure costs up to €85,000 depending on the component and severity of consequences (after failure) to the operability of the crane.

Furthermore the operational and resulting financial consequences after failure showed that availability of a second container-crane vessel (MKS Transferium), in case of failure of the MKS Mercurius, results in a large decrease in failure costs (failure impact). With availability of a second container-crane vessel, without any inventory, a reduction in failure costs can be achieved between €2,000 – €40,000 depending on the type of component and the severity of operational consequences after failure. Which is mainly due to the fact that this second container-crane vessel is able to taken-on MKS Mercurius' lifting activities in case of failure of the vessels cargo handling gear. In order to do, at the moment of failure of one of the container-crane vessels, the other vessel (in this case MKS Transferium) will free-up capacity to execute lifting operations, by removing regular container activities to other barges. This means that containers which are planned to be handled by MKS Transferium and not require crane operations are taken over by other barges. For this reason, for the inventory selection and optimization, a distinction is made in two scenarios. This results in an optimized spare-parts inventory for: (1) MKS Mercurius, taking into account availability of the MKS Transferium in case of failure; and (2) MKS Mercurius as MSG's single container-crane vessel.

Besides the benefit of keeping a spare-part inventory, owning and managing a spare-part inventory also involves costs. These costs can be based on the component stored in inventory and include: interest costs, risk costs, and warehousing costs. Depending on the type of component these annual inventory costs vary between €300 - €11,000.

To compare the benefit of keeping a spare-part inventory to the annual inventory costs, the benefits are translated to an annual expected benefit, by multiplying the quantified benefit by the annual failure probability (between 4% - 20%) of the component. Since this is equal to probability times impact, ultimately a consideration is made between the risk of failure without having a spare-part directly available compared to the annual costs of having this part in inventory.

Currently MSG is equipped with two container-crane vessels. For the inventory of the MKS Mercurius, taking into account availability of the MKS Transferium in case of failure, the optimal level of inventory is ≈35%. As a result the optimal inventory includes 13 components, which are selected based on their benefit/cost ratio. This inventory requires an initial investment of €50,000, includes €8,500 annual inventory costs, and leads to a reduction of expected annual failure costs of €22,000, which means the annual net benefit is equal to €13,500. As a result the investment is expected to be recouped within a period of approximately 4 years. A larger inventory would require a larger investment and all-though this would lead to a further decrease of failure costs this effect is countered by the increasing annual inventory costs, resulting in an increase in total cost and a smaller net benefit. The increase in inventory would lead to an increase in vessel availability, but since this results in larger costs it is considered a sub-optimal inventory.

In case MSG decides to relocate (or sell etc.) one of the container-crane vessels the benefit of keeping a spare-part inventory significantly increases. Expected annual failure costs, without inventory, in this scenario are €136,000. This scenario therefore contains an increased importance to vessel availability, in order to avoid failures with severe financial consequences. For this reason a more extensive inventory is recommended, including 28 components. This inventory slightly exceeds the optimal (minimizing expected annual costs) level of inventory (55%, 23 components), in order to reduce the probability of outliers regarding annual failure costs and increase reliability. This inventory requires an initial investment of €137,000, includes €24,000 annual inventory costs, and leads to a reduction of expected annual failure costs of €79,000, which means the annual net benefit is equal to €55,000. As a result the investment is expected to be recouped in less than 3 years.

Essentially, the amount of components to store in inventory and the corresponding initial investment made is a managerial decision for MSG. This requires a consideration for either a cost-minimizing inventory, or a larger inventory for which the probability of outliers regarding annual failure costs decreases. Based on the analysis in this study it is recommended, for the current situation with two container-crane vessels, to invest in a set of 13 components. This is likely to result in expected annual savings of €13,000 and requires a relatively short payback period of 4 years. Furthermore, direct availability of these spare-parts will lead to an improvement to the reliability of the vessel. In case MSG decides to relocate (or sell) one of the container-crane vessels a spare-part inventory for the MKS Mercurius is regarded to lead to a vital improvement to vessel availability and the vessels operational result. In this case, MSG should make a substantial investment ( €137,000) on an extensive inventory.

Recommendations for future research include: identify which components can be used on both vessels and determine how this affects the selection of inventory; determine a further disassembly for (expensive) components and identify benefit of including these items in inventory; identify the possibility and potential benefit of developing and implementing a preventive maintenance strategy; and explore options to outsource inventory management.

If components can be used on both vessels this means the possible benefit of keeping this component in inventory increases, while the annual inventory costs remain the same. Identifying for which components this applies can result in a further optimized inventory. Secondly, in the current selection of inventory, several components, which are critical to the functioning of the crane, are not included in inventory. For these components it could be beneficial to disassemble these components in smaller items and to determine the benefit of storing these items in inventory. Furthermore, a preventive maintenance strategy can provide more data on condition and residual life expectancy of the components and could lead to earlier notification of deteriorating components. In addition this could result in acquisitioning of spare-parts closer to the moment they are required, possibly reducing the need for extensive inventory. At last, for certain components the financial benefit which can be achieved by direct availability of a spare in case of failure is outweighed by its annual inventory costs. Outsourcing inventory management could lead to a reduction in annual inventory costs and in a more extensive inventory, it may be possible to combine this with several crane owners. Exploring these options could be advantages for MSG.

# Bibliography


Anthony, M. et al. (2012). “Reliability Analysis for power to fire pump using Fault Tree and RBD”. In: *IEEE Industrial & Commercial Power Systems Conference*. Vol. 48. Louisville: IEEE.

Antony, G.G. (2008). *How to Determine the MTBF of Gearboxed*. Tech. rep. Virginia: American Gear Manufacturers Association.

Blauwens, G., P. De Baere, and E.M. Van De Voorde (2016). *Transport Economics*. sixth. Berchem: De Boeck.

Brocken, E.M. (2016). “Improving the Reliability of Ship Machinery: A Step Towards Unmanned Shipping”. MA thesis. Technical University of Delft.

Cacuci, D.G., M. Ionescu-Bujor, and I.M. Navon (2005). *Sensitivity and Uncertainty Analysis: Applications to Large-Scale Systems*. 2. Boca Raton, FL, USA: Taylor & Francis.

CCPS (2000). *Guidelines for Chemical Process Quantitative Risk Analysis*. 2nd ed. American Institute of Chemical Engineers. New York.

CRgraph (2014). *Fault Tree Analysis*. URL: http://weibull.de/COM/Fault_Tree_Analysis.pdf (visited on 12/04/2017).

Dekking, F.M. et al. (2005). *A Modern Introduction to Probability and Statistics; Understanding Why and How.* London: Springer.

Donders, J. and T. Lejeune (2015). “Wanneer een voorraad meer kost dan het opbrengt; Waardering, Voorziening en Afschrijven van Spare Parts op Voorraad”. In: *Service Magazine* 2.

Durlinger, P. (2013). “Voorraad- en bestelkosten: de oplossing?!” In: *IT Logistiek* 3.

Goossens, A.J.M. and R.J.I. Basten (2015). “Exploring maintenance policy selection using the Analytic Hierarchy Process; An application for naval ships”. MA thesis. Enschede: University of Twente.

Grimmelius, H. (2003). *Module 9 – Marine Systems Performance & Maintenance*. Delft: Delft University of Technology.

Hmida, J. Ben, G. Regan, and J. Lee (2013). “Inventory Management and Maintenance in Offshore Vessel Industry”. In: *Journal of Industrial Engineering* 2013, p. 7.

Laskowski, R. (2015). “Fault Tree Analysis as a tool for modelling the marine main engine reliability structure”. In: *Scientific Journal of the Maritime University of Szczecin* 41.113, pp. 71–77.

MCT (2017). *Freight Operator Mercurius Container Transport Lucassen*. URL: http://mct-lucassen.nl/het-bedrijf (visited on 12/04/2017).

Mercurius (2017). *Mercurius Shipping Group*. URL: http://www.mercurius-group.nl/over-ons/ (visited on 12/04/2017).

Morello, M.G., K. L. Cavalca, and Z. Silveira (2008). “Development and reduction of a fault tree for gearboxes of heavy commercial vehicles based on identification of critical components”. In: *Quality and Reliability Engineering International* 24.2, pp. 183–198.

NEVI (2014). *Voorraadkosten*. 1.1. Kennisbank NEVI. Zoetermeer.

Pannell, D. (1997). “Sensitivity analysis of normative economic models: theoretical framework and practical strategies”. In: *Agricultural Economics* 16.2, pp. 139–152.

Peeters, J.F.W., R.J.I. Basten, and T. Tinga (2017). "Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner". In: *BETA publicatie: working papers*. Vol. 528. Eindhoven: Technische Universiteit Eindhoven.

Pintelon, L. and A. Parodi-Herz (2008). "Maintenance: An Evolutionary Perspective". In: *Complex System Maintenance Handbook*. Springer Series in Reliability Engineering. Springer, pp. 21–48.

Poppe, J. et al. (2017). "Numerical study of inventory management under various maintenance policies". In: *Reliabiltiy Engineering & System Safety* 169.

Saltelli, A., K. Chan, and E. Scott (2008). *Sensitivity Analysis*. Vol. 134. New Yersey: John Wiley & Sons, Inc.

Saltelli, A. et al. (2004). *Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models*. New York, NY, USA: Halsted Press.

Shurgard (2017). *Shurgard - Self Storage Units*. URL: https://www.shurgard.nl/available-units?searchLocation=zwijndrecht&type=new.

Sinnamon, R.M. and J.D. Andrews (1997). "Improved Accuracy in Quantitative Fault Tree Analysis". In: *Quality and Reliability Engineering International*. Vol. 13. Loughborough: Loughborough University of Technology, pp. 285–292.

Smith, D.J. (2017). *Reliability, Maintainability and Risk: Practical Methods for Engineers*. ninth. Oxford: Butterworth-Heinemann.

Tinga, T. (2010). "Application of physical failure models to enable usage and load based maintenance." MA thesis. Den Helder: Netherlands Defence Academy.

Turan, O. et al. (2011). "Investigating the Reliability and Criticality of the Maintenance Characteristics of a Diving Support Vessel". In: *Quality and Reliability Engineering International* 27, pp. 931–946.

Van Dorsser, J.C.M. (2013). *Back-up opties bij uitval Kraanschepen*. In-House Research. Mercurius Shipping Group.

# Appendix A

# Component Tree

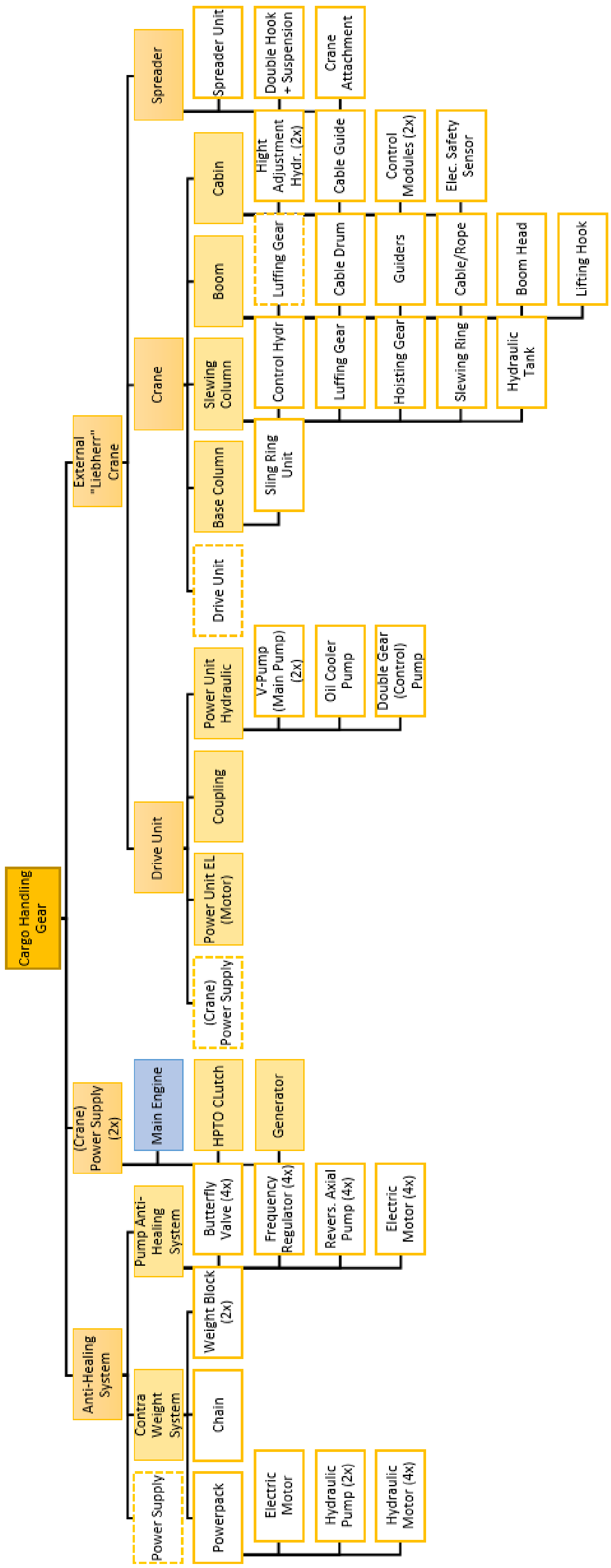



FIGURE A.1: System & Component Breakdown Cargo Handling Gear MKS Mercurius

# Appendix B

# Fault Tree Analysis

The fault tree for the container-crane vessel MKS Mercurius is presented in this section. Failure of one or more components may lead to one of the six different vessel states or conditions, which are discussed in Chapter 6. These vessel states are included in the fault tree to show failure of which component(s) would result in the aforementioned conditions. For reviewing and presenting purposes the decision is made to present the fault tree in multiple branches instead of the entire tree as a whole. The fault tree includes numbers at which new branches of the tree (presented in different figures) should be attached. The fault tree includes components related to propulsion of the vessel, this includes power supply, manoeuvring gear and the bow thruster. This section is included for completeness (and since some of the components are also required to use the crane), but are not used in further analysis.

Figure B.1 shows the top of the fault tree. A division is made in systems and components needed for propulsion of the vessel and a section with components related to the cargo handling gear. In Figure B.1 the main component groups are shown, more elaborate breakdown schematics of these groups are shown in Figures B.2 till B.11. The dotted line indicates failure of the bow thruster. While this is part of the propulsion, failure of the bow thruster does not immediately result in loss of propulsion and therefore a separate condition is indicated.

The fault tree of the power supply for propulsion of the vessel is shown in Figure B.2. The part of the drive shaft responsible for propulsion consists of two identical shafts (port-side and starboard side). Both of these shafts consist of the main engine connected to a gearbox with flexible clutches in-between and a propeller shaft which rotates the propeller. The propeller is part of the manoeuvring gear shown in Figure B.3, but is also a necessity for propulsion and is therefore indicated with a box framed with a dotted line. The fault tree for the manoeuvring gear of the vessel is shown in Figure B.3. The manoeuvring gear consists of a twin rudder system, with both rudders connected by a rod. This system is driven by a PTO located on the gearbox, which is driven by the main engine. The position of the rudders are adjusted by two cylinder which are attached to the rudders. The manoeuvring gear consists of a hydraulic power pack, steering gear and propellers. The vessel is able to manoeuvre with a single propeller, and is unable to manoeuvre when one or both rudders fail, the connecting rod fails, the hydraulic power pack fails or one or both cylinders fail. Figure B.4 shows components related to the bow thruster. The thruster is driven by an auxiliary engine, which drives a prop shaft and through transmission drives a propeller shaft which rotates the horizontal propeller.

The Power Supply for the cargo handling gear (Fig. B.5) is delivered by the rear side of the drive shaft, which is also identical for both the port-side and the starboard side shaft. In normal operation only the port-side shaft is used to drive the crane. Both of the shafts consist of the main engine, a HPTO clutch and a generator. When a component on one of

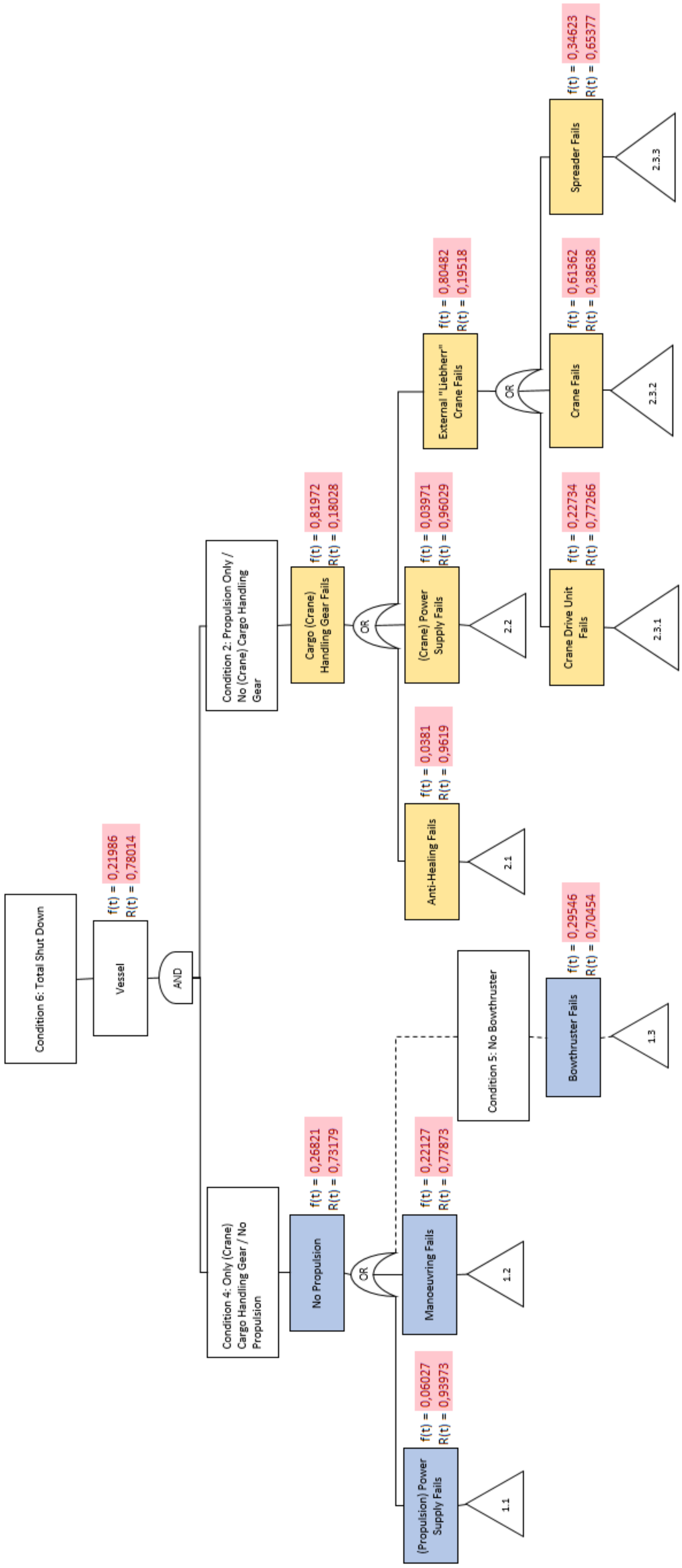



FIGURE B.1: Fault Tree: Top

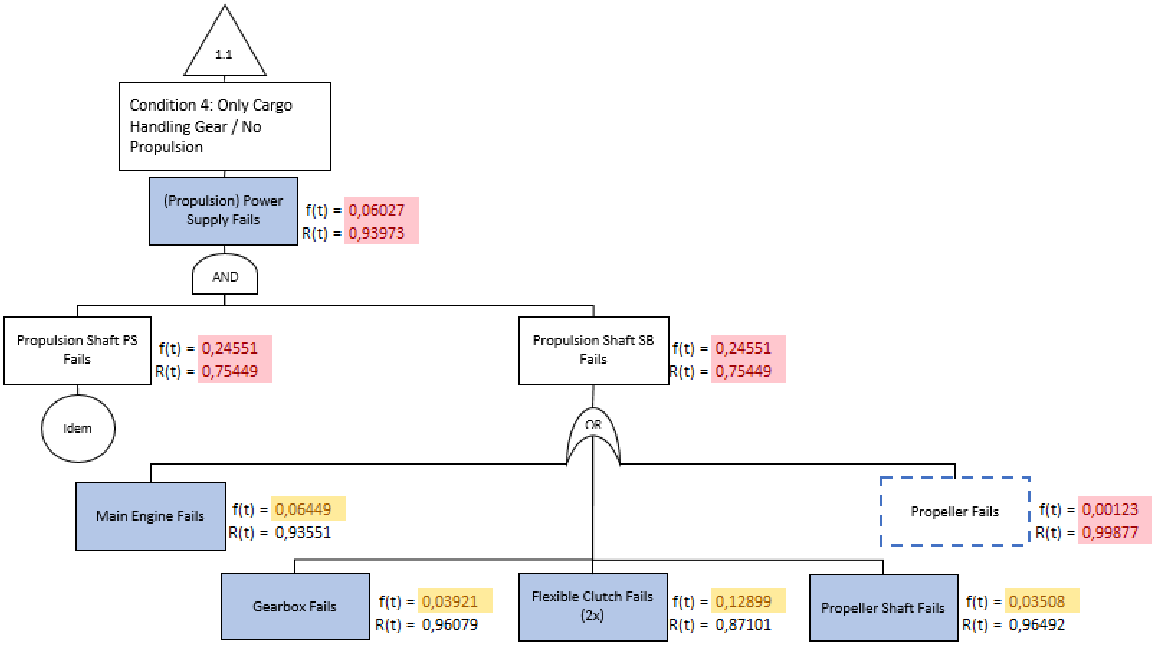



FIGURE B.2: Fault Tree: (Propulsion) Power Supply

these shafts fail the other shaft can still be used to supply power to the crane. This means in order for the (crane) power supply to fail (a component on) both shafts must fail.

For vessel stability during lifting an Anti-Heeling system (Fig. B.6) is incorporated in the design. This Anti-Heeling system consists of a Contra-Weight system and a Pump Anti-Heeling system. When the Anti-Heeling system fails the vessel is unable to use the crane. This already applies to failure of the Pump Anti-Heeling System, since this system has the largest impact and provides the larges countering momentum. When the Contra-Weight system fails the vessel is still able to load empty containers and/or load containers at limited speed. The (crane) power supply is needed to provide power to these systems. The Contra-Weight system is driven by a power pack, which consists of an electric motor, two hydraulic pumps and four hydraulic motors. Both hydraulic pumps drive two hydraulic motors which force movement of the weight blocks connected with a chain. The pump anti-healing system is divided in a front and back section each with two reversible axial pumps connected to the ballast tanks. For anti-healing during lifting operations only the back two pumps and tanks are used. If one of these pumps fails the whole back part of the pump system fails, in other words only one of the two pumps must fail in order for the section to fail. This same principle holds for the front pumps and tanks. The butterfly valves are used to regulate the flow to the tanks. The frequency regulator sends a signal to the valves and pumps when the lifting equipment is used.

The cranes drive unit (Fig. B.7) provides power for the cranes basic functions, luffing, lifting and slewing. The drive unit consists of an electric motor, a coupling and a hydraulic unit consisting of two main pumps, a control pump and an oil cooler pump. Failure of either one of the main pumps would result in inability to use the crane. The fault tree for the 'Liebherr' crane itself is shown in Figure B.8. The focus of the research is with components of the cargo handling gear, therefore the fault tree for the crane is largest and is further decomposed in Figures B.9 and B.10. The crane is divided in the base column, the slewing column, the crane boom and the operator cabin. The spreader is a separate unit attached to the crane, which enables the crane to lift containers (Fig. B.11). The slewing column (Figure B.9) consists

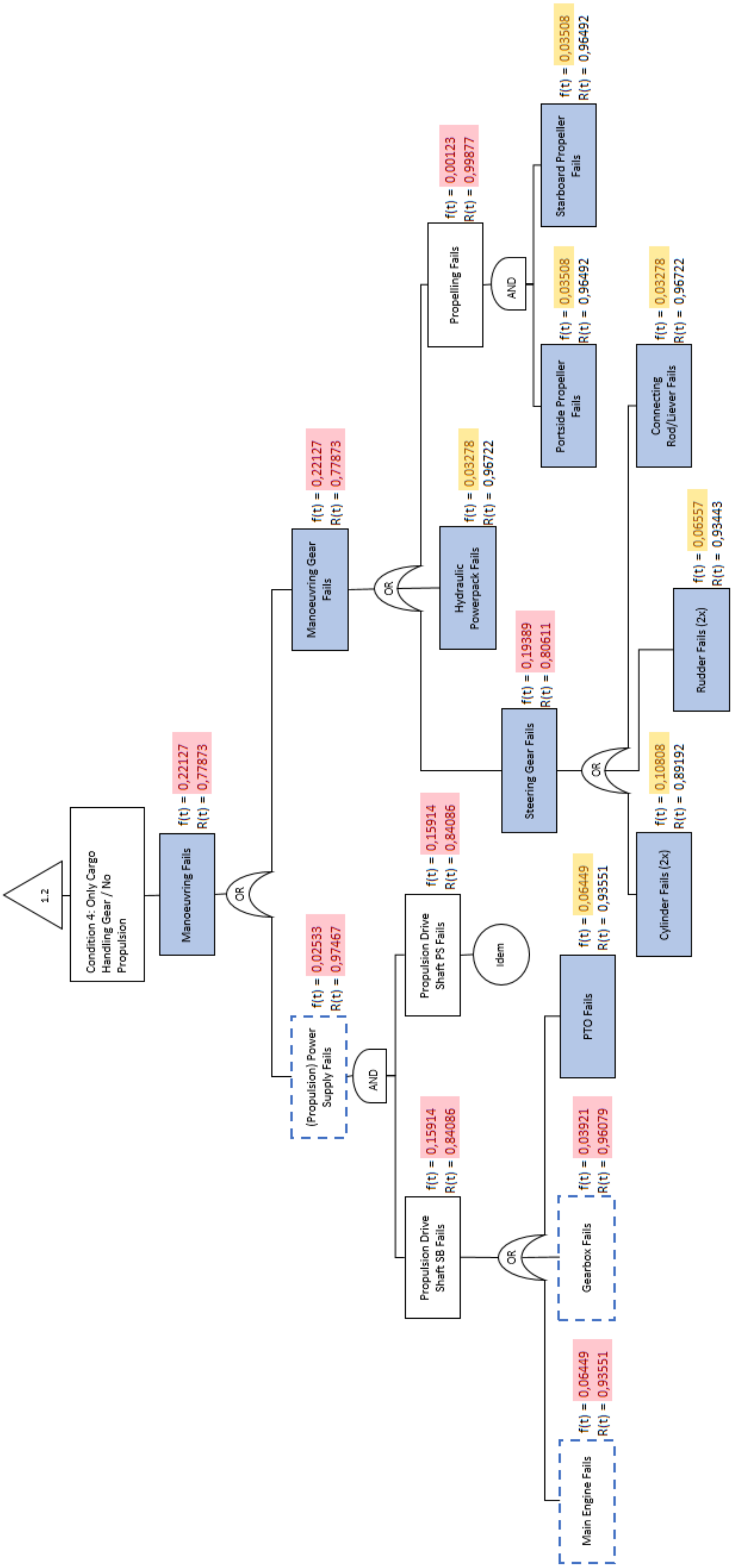



FIGURE B.3: Fault Tree: Manoeuvring Gear

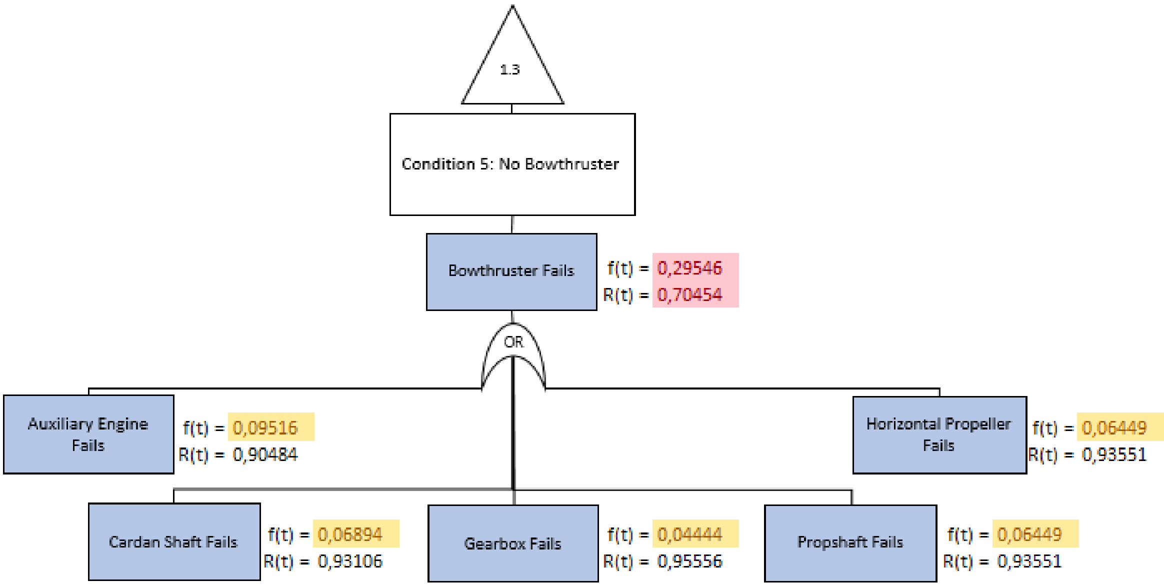



FIGURE B.4: Fault Tree: Bow Thruster

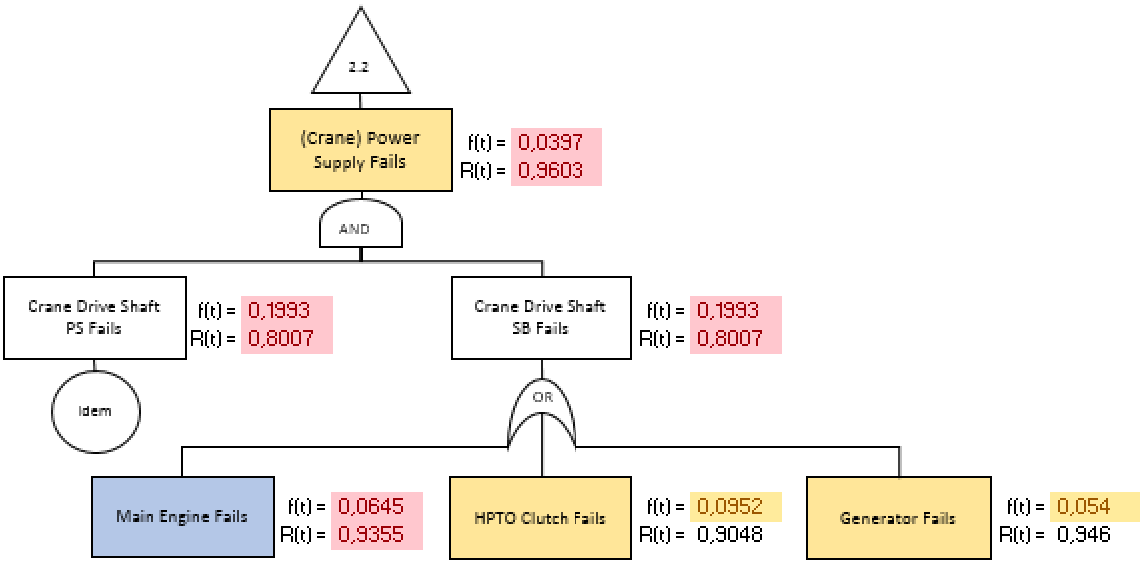



FIGURE B.5: Fault Tree: (Crane) Power Supply

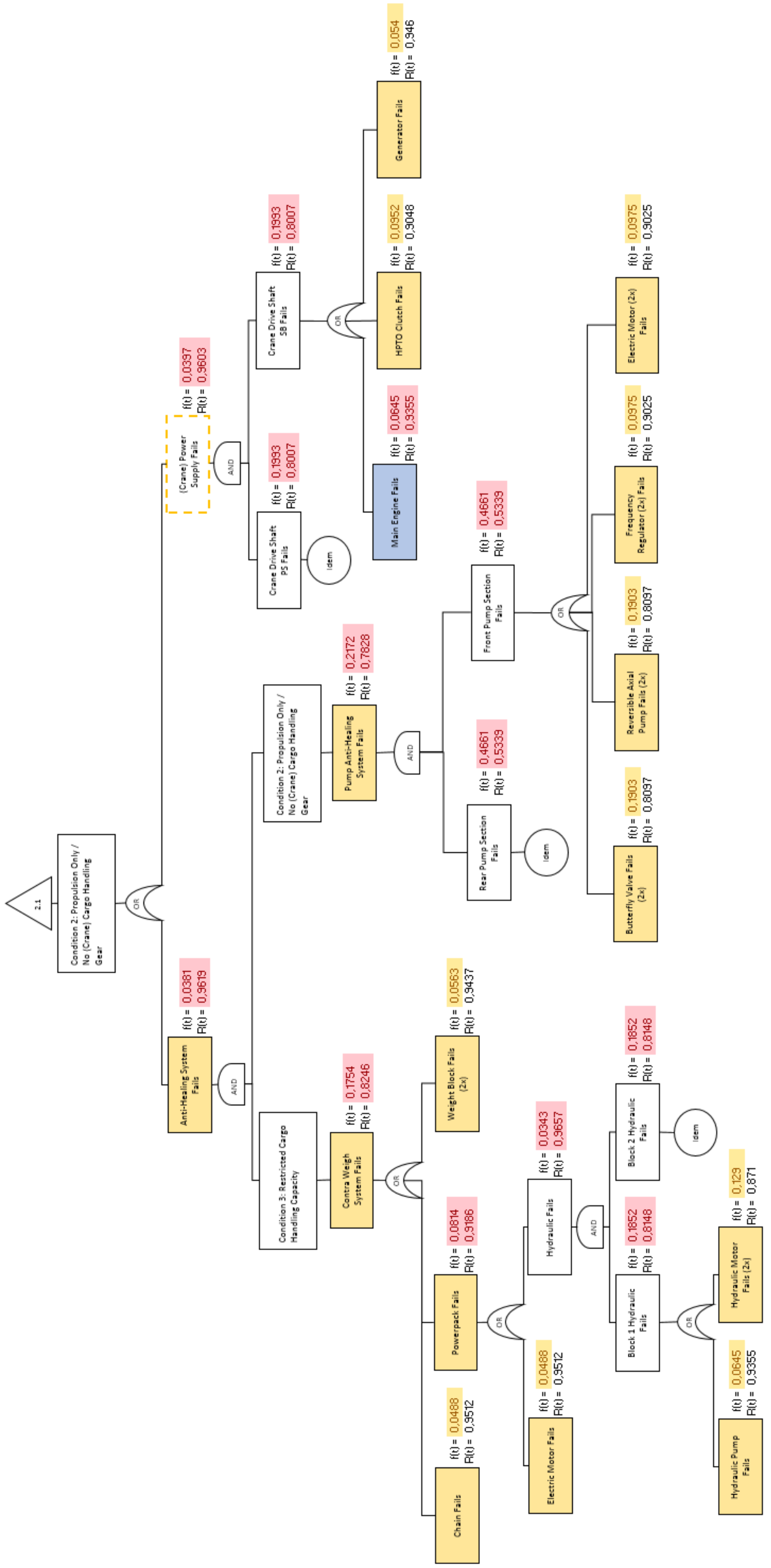



FIGURE B.6: Fault Tree: Anti-Heeling

of main component groups such as the slewing ring, where the roller bearing and slewing gears are located, the luffing gear, the housing gear, the hoisting gear and the hydraulic tank. These component groups are further broken down in different items. The fault tree for the crane boom is shown in Figure B.10. the luffing gear is attached to the slewing column and is essential to move the boom. Further components are the lifting cable/rope, the cable drum, boom head and the lifting hook.

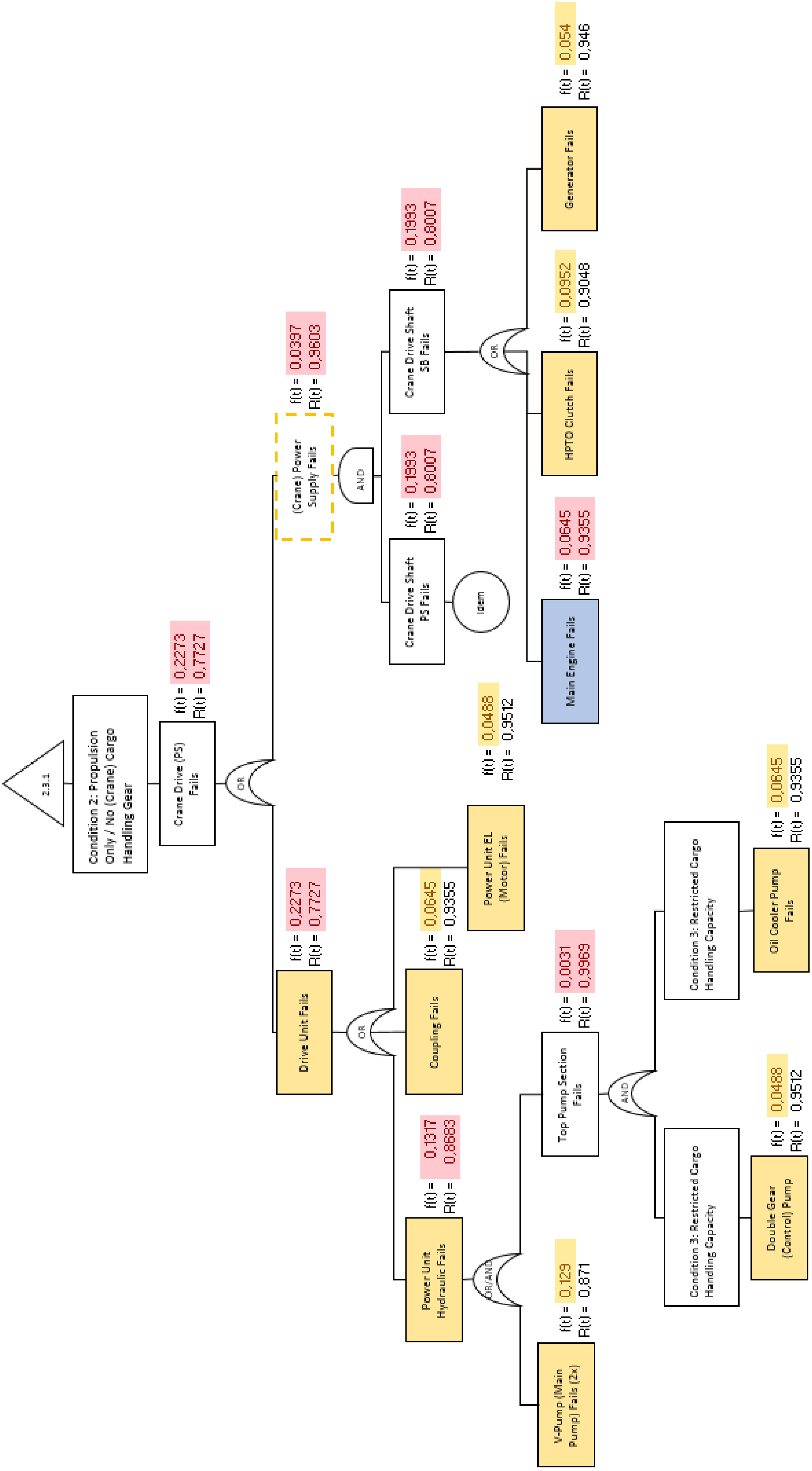



FIGURE B.7: Fault Tree: Crane Drive Unit

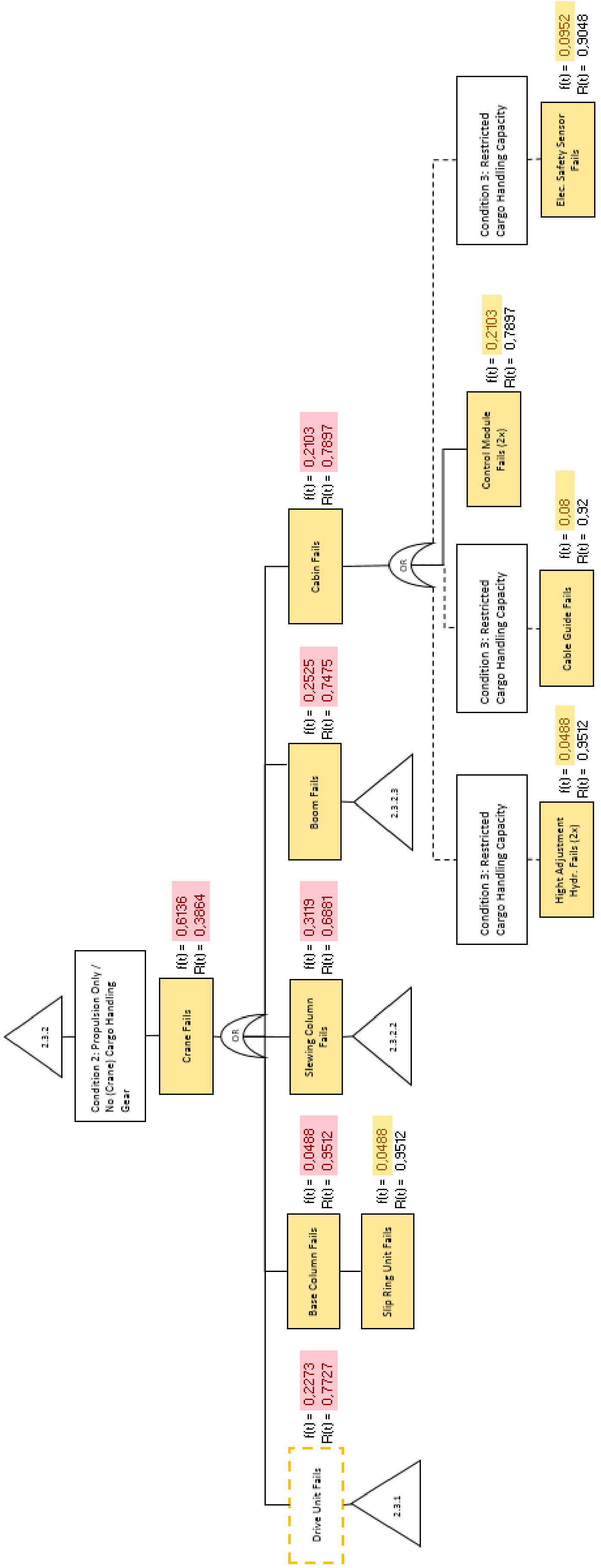



FIGURE B.8: Fault Tree: Crane

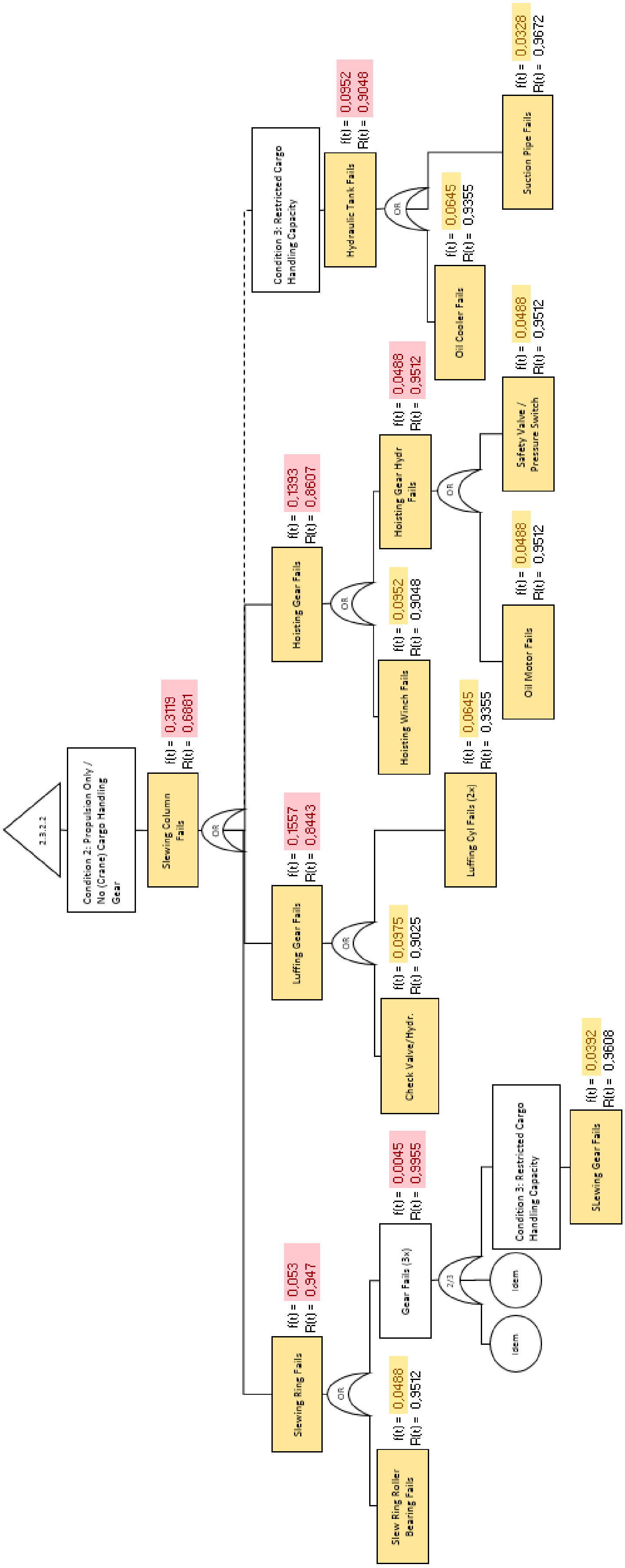



FIGURE B.9: Fault Tree: Slewing Column

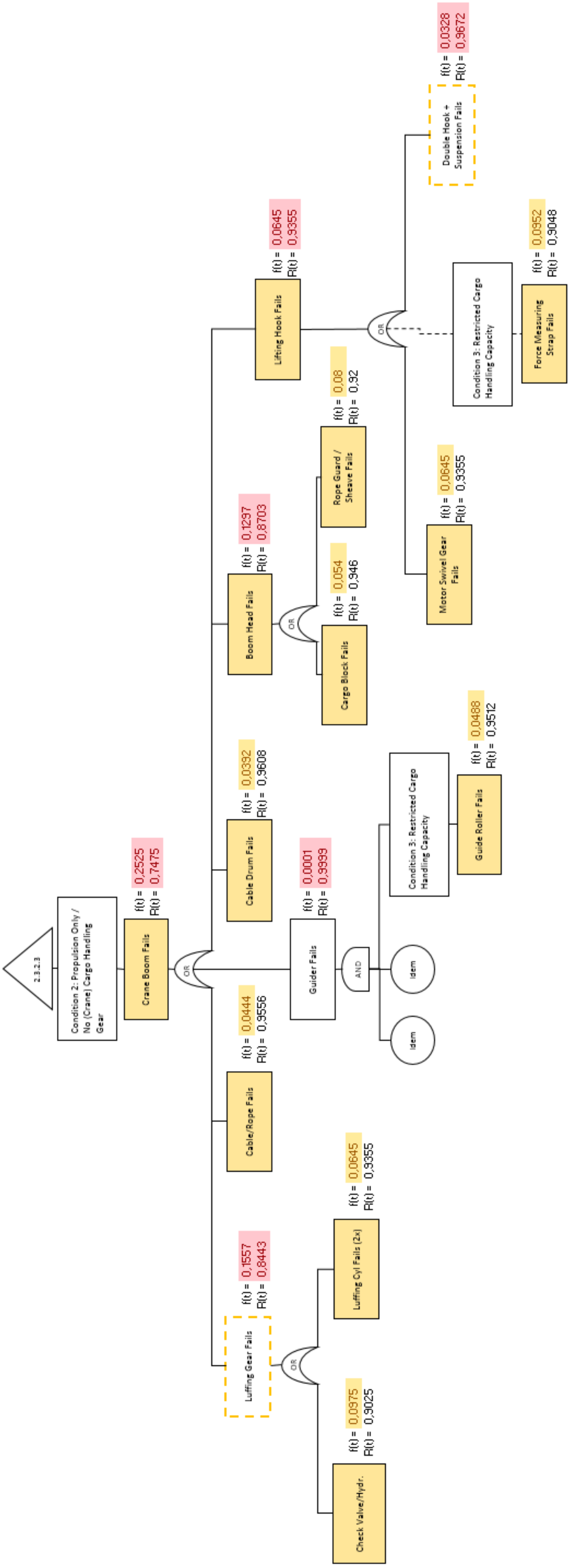



FIGURE B.10: Fault Tree: Crane Boom

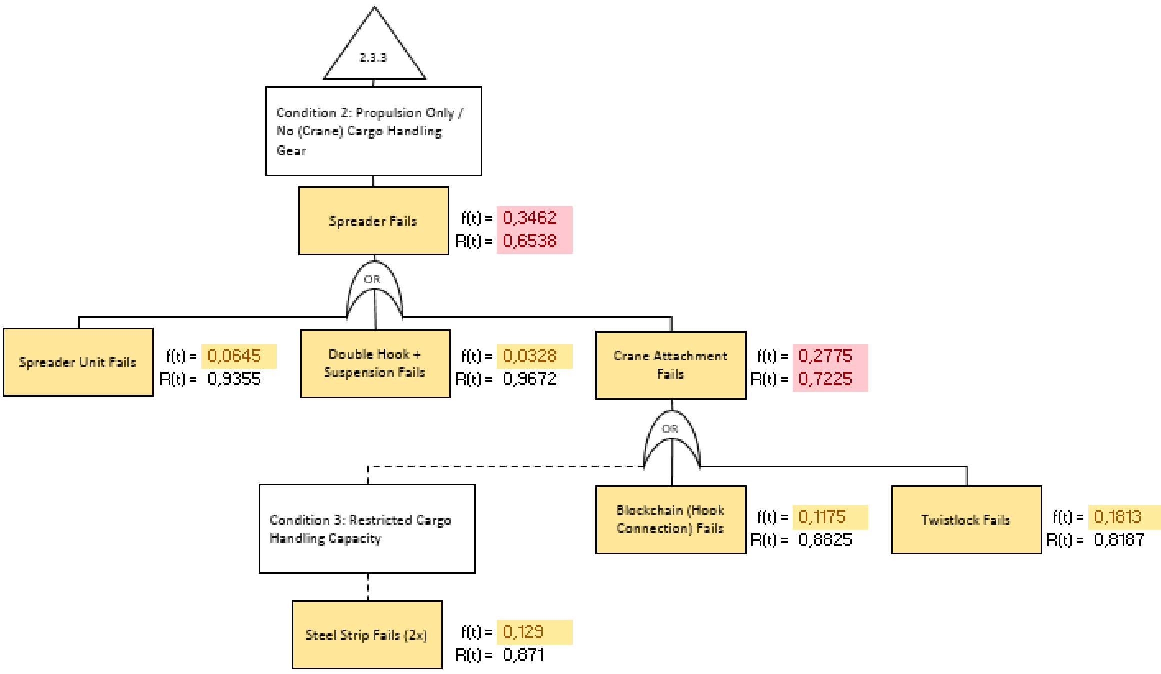


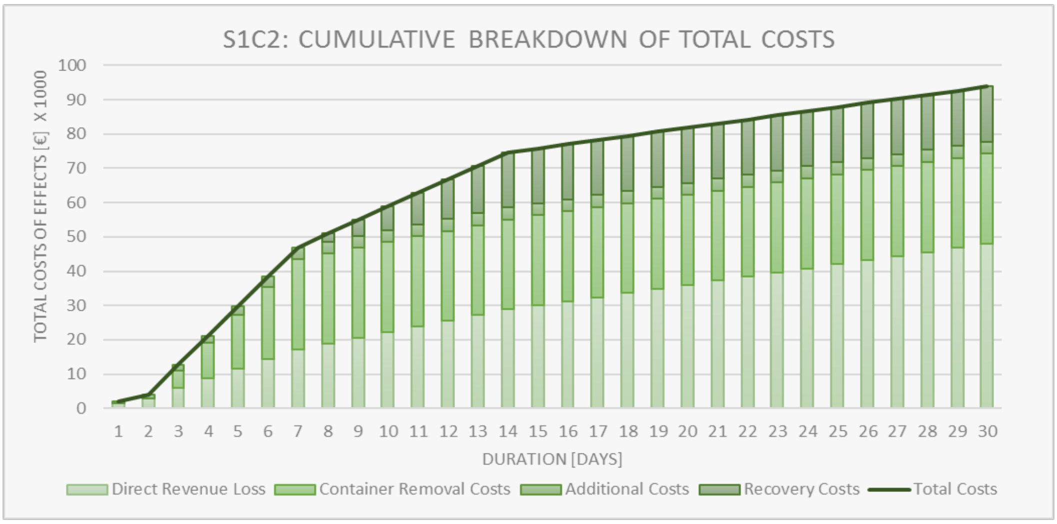

FIGURE B.11: Fault Tree: Spreader

# Appendix C

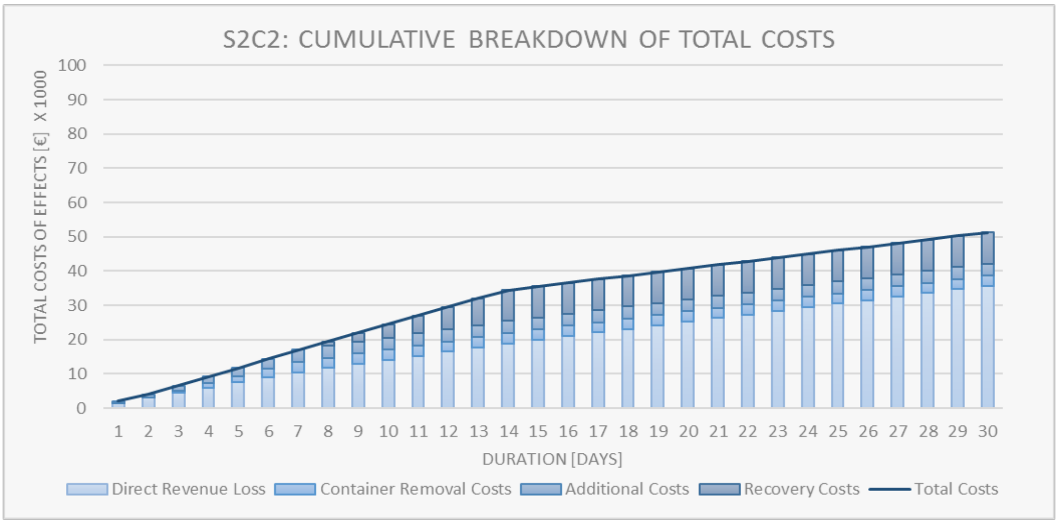
# Failure Costs

TABLE C.1: Parameters Revenue Loss & Long-term Damages

| **Parameter** | **Unit** | **Duration (Days)** | | | |
|---|---|---|---|---|---|
| | | **0 - 2 Days** | **2 - 7 Days** | **7 - 14 Days** | **>14 Days** |
| ***Condition 2: Crane Defect*** | | | | | |
| ***Scenario 1: Only MKS Mercurius*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 50 | 100 | 100 | 100 |
| Revenue Loss Regular Work ($\alpha$) | % | 0 | 0 | -200 | -300 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 50 | 0 |
| ***Scenario 2: With MKS Transferium*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 50 | 50 | 40 | 35 |
| Revenue Loss Regular Work ($\alpha$) | % | 50 | 50 | 40 | 35 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 35 | 0 |
| ***Condition 3.1: Weight Restriction (Only Empty Containers)*** | | | | | |
| ***Scenario 1: Only MKS Mercurius*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 30 | 30 | 15 | 15 |
| Revenue Loss Regular Work ($\alpha$) | % | 0 | 0 | 0 | 0 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 30 | 0 |
| ***Scenario 2: With MKS Transferium*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 0 | 0 | 0 | 0 |
| Revenue Loss Regular Work ($\alpha$) | % | 50 | 50 | 50 | 50 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 0 | 0 |
| ***Condition 3.2: Speed Restriction*** | | | | | |
| ***Scenario 1: Only MKS Mercurius*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 0 | 0 | 0 | 0 |
| Revenue Loss Regular Work ($\alpha$) | % | 75 | 75 | 50 | 50 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 0 | 0 |
| ***Scenario 2: With MKS Transferium*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 0 | 0 | 0 | 0 |
| Revenue Loss Regular Work ($\alpha$) | % | 0 | 0 | 0 | 0 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 0 | 0 |
| ***Condition 6: Crane Total Shutdown*** | | | | | |
| ***Scenario 1: Only MKS Mercurius*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 100 | 100 | 100 | 100 |
| Revenue Loss Regular Work ($\alpha$) | % | 100 | 100 | 100 | 100 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 50 | 0 |
| ***Scenario 2: With MKS Transferium*** | | | | | |
| Revenue Loss Crane Work ($\alpha$) | % | 0 | 100 | 70 | 50 |
| Revenue Loss Regular Work ($\alpha$) | % | 0 | 100 | 70 | 50 |
| Recovery (Loss Week after Failure) | % | 0 | 0 | 50 | 0 |

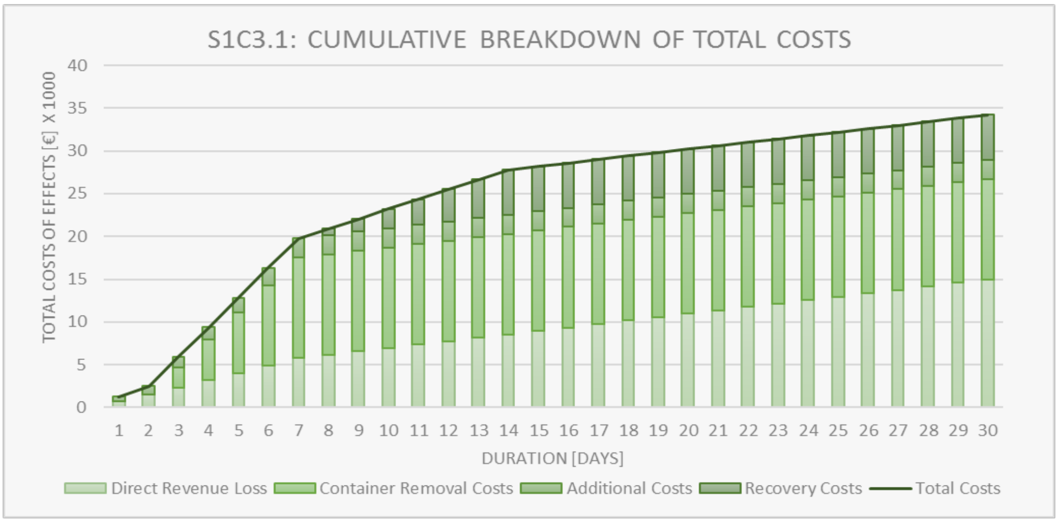



(A) Cumulative Breakdown of Failure Costs in case of Crane Defect (Only MKS Mercurius)

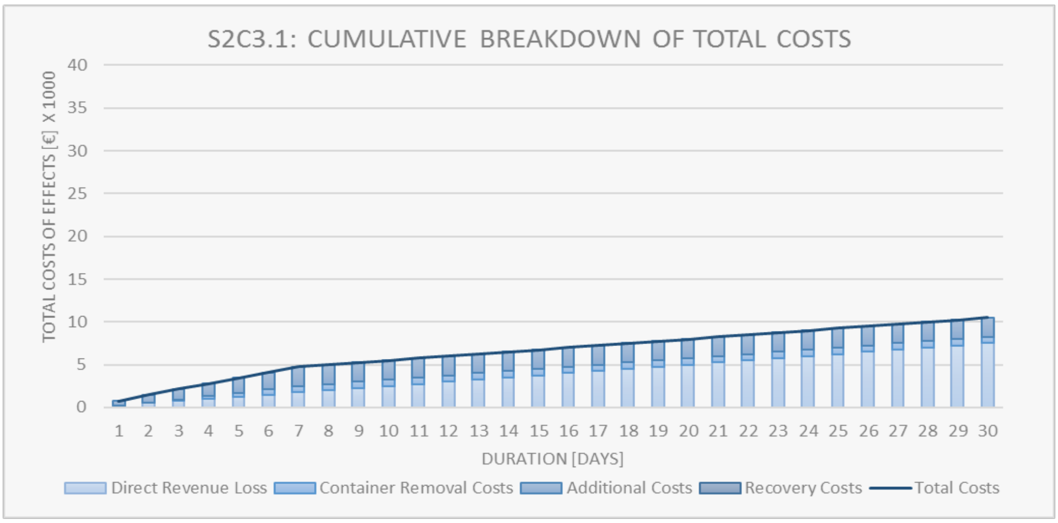



(B) Cumulative Breakdown of Failure Costs in case of Crane Defect (With MKS Transferium)

FIGURE C.1: Development of Failure Costs for Crane Defect (Condition 2)

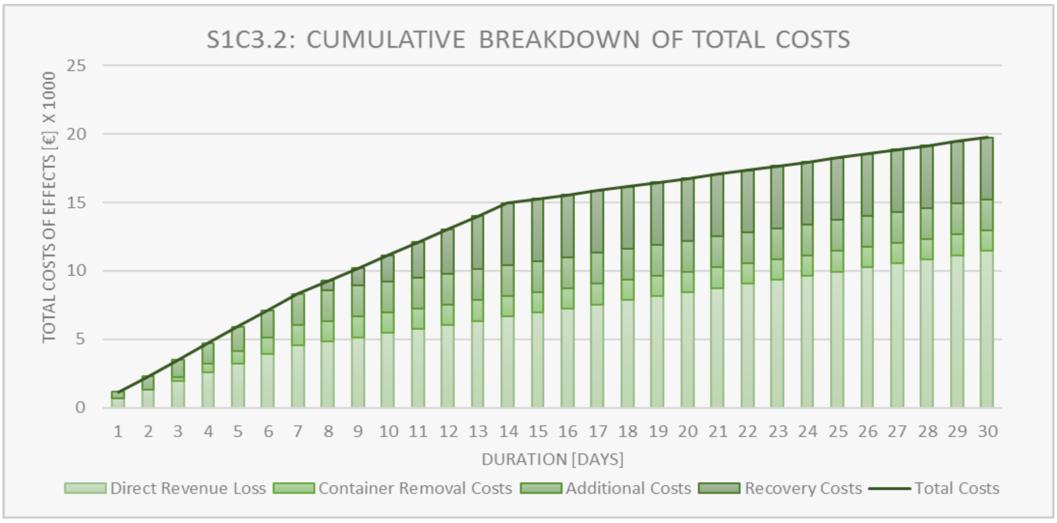



(A) Cumulative Breakdown of Failure Costs in case of Weight Restriction (Only MKS Mercurius)

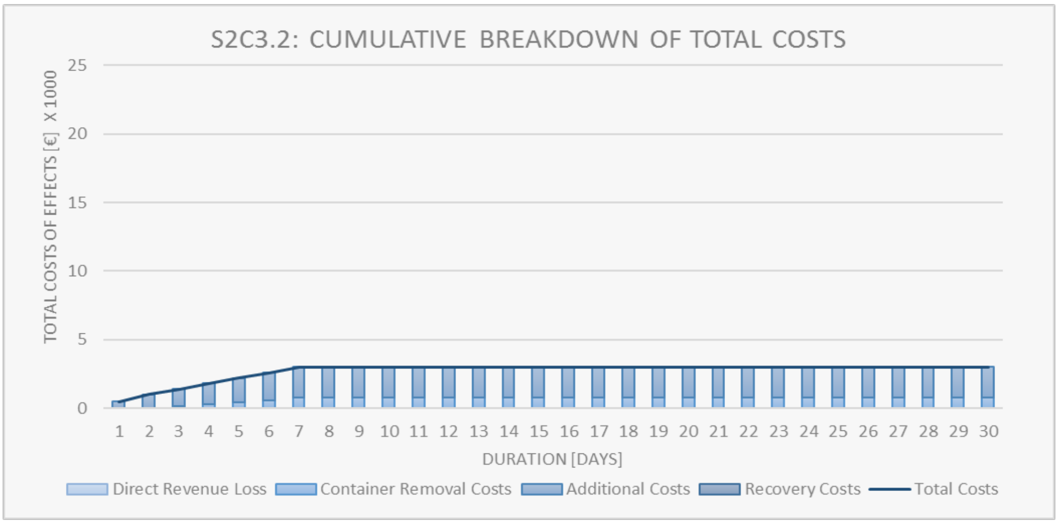



(B) Cumulative Breakdown of Failure Costs in case of Weight Restriction (With MKS Transferium)

FIGURE C.2: Development of Failure Costs for Weight Restriction (Condition 3.1)

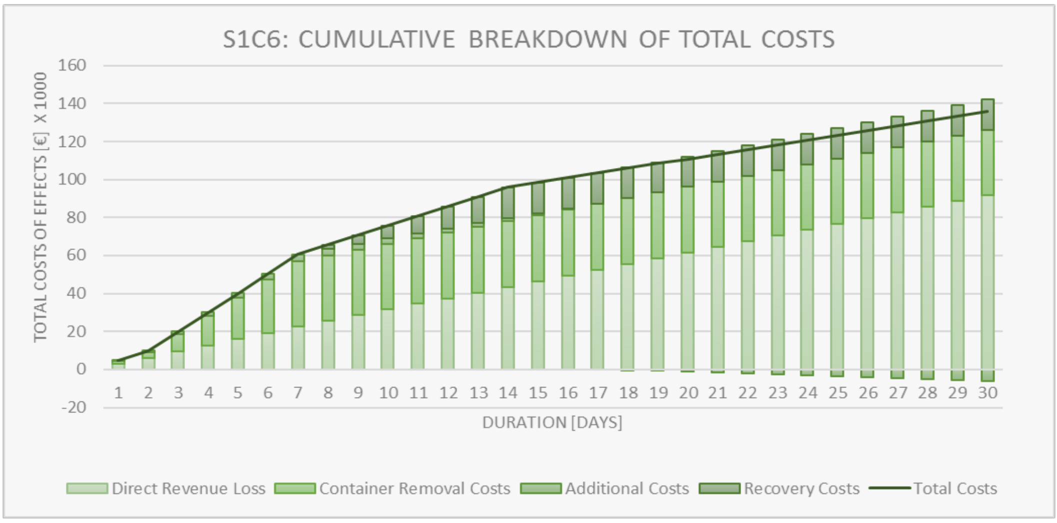



(A) Cumulative Breakdown of Failure Costs in case of Speed Restriction (Only MKS Mercurius)

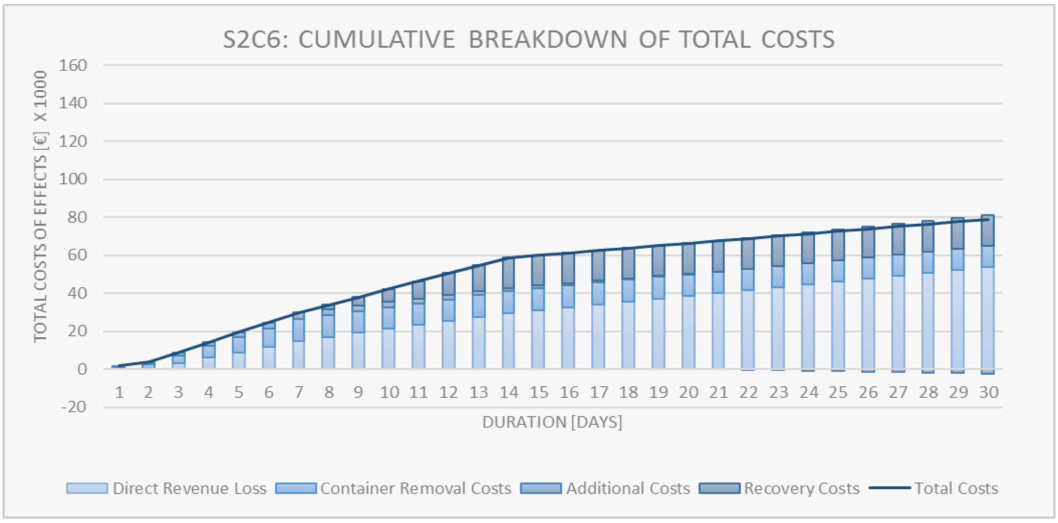



(B) Cumulative Breakdown of Failure Costs in case of Speed Restriction (With MKS Transferium)

FIGURE C.3: Development of Failure Costs for Speed Restriction (Condition 3.2)




(A) Cumulative Breakdown of Failure Costs in case of Total Shutdown (Only MKS Mercurius)




(B) Cumulative Breakdown of Failure Costs in case of Total Shutdown (With MKS Transferium)

FIGURE C.4: Development of Failure Costs for Total Shutdown (Condition 6)

Appendix D

# Benefit/Cost Ratios of Crane Components

TABLE D.1: Total Overview of Benefit/Cost Ratios of Crane Components (Only MKS Mercurius)

| # | Component | Annual Failure Probability | Failure Impact Reduction (in €) | Expected Annual Benefit | Costs | Net Benefit | BCR |
|---|---|---|---|---|---|---|---|
| | | | **Only MKS Mercurius** | | | | |
| 1 | Twistlock | 0.200 | 49 800 | 9 960 | 300 | 9 660 | 33.2 |
| 2 | Luffing Bearing (Cyl) | 0.100 | 63 850 | 6 385 | 450 | 5 935 | 14.2 |
| 3 | Block Chain (Hook Connection) | 0.125 | 50 050 | 6 256 | 500 | 5 756 | 12.5 |
| 4 | Control Module (2x) | 0.111 | 62 300 | 6 922 | 700 | 6 222 | 9.9 |
| 5 | Coupling | 0.067 | 61 900 | 4 127 | 450 | 3 677 | 9.2 |
| 6 | Rope Guard / Sheave | 0.083 | 62 150 | 5 179 | 600 | 4 579 | 8.6 |
| 7 | Oil Cooler Pump | 0.067 | 62 100 | 4 140 | 600 | 3 540 | 6.9 |
| 8 | Safety Valve / Pressure Switch | 0.050 | 61 950 | 3 097 | 450 | 2 647 | 6.9 |
| 9 | Cargo Block | 0.056 | 61 950 | 3 442 | 500 | 2 942 | 6.9 |
| 10 | Check Valve/Hydr. | 0.050 | 52 100 | 2 605 | 500 | 2 105 | 5.2 |
| 11 | Force Measuring Strap | 0.100 | 20 900 | 2 090 | 500 | 1 590 | 4.2 |
| 12 | Guide Roller (3x) | 0.050 | 23 950 | 1 197 | 300 | 897 | 4.0 |
| 13 | V-Pump (Main Pump) (2x) | 0.067 | 64 800 | 4 320 | 1 100 | 3 220 | 3.9 |
| 14 | Motor Swivel Gear | 0.067 | 60 350 | 4 023 | 1 350 | 2 673 | 3.0 |
| 15 | Cable Drum | 0.040 | 59 600 | 2 384 | 800 | 1 584 | 3.0 |
| 16 | Steel Strip (2x) | 0.067 | 9 000 | 600 | 250 | 350 | 2.4 |
| 17 | Elec. Safety Sensor | 0.100 | 2 400 | 240 | 100 | 140 | 2.4 |
| 18 | Cable/Rope | 0.050 | 60 350 | 2 743 | 1 350 | 1 393 | 2.0 |
| 19 | Spreader Unit | 0.067 | 64 600 | 4 307 | 2 400 | 1 907 | 1.8 |
| 20 | Cable Guide | 0.083 | 5 650 | 471 | 300 | 171 | 1.6 |
| 21 | Hoisting Winch | 0.100 | 51 450 | 5 145 | 3 600 | 1 545 | 1.4 |
| 22 | Oil Motor (Hoisting) | 0.050 | 56 800 | 2 840 | 2 050 | 790 | 1.4 |
| 23 | Double Gear (Control) Pump | 0.050 | 12 100 | 605 | 550 | 55 | 1.1 |
| 24 | Chain | 0.050 | 21 400 | 1 070 | 1 000 | 70 | 1.1 |
| 25 | Slip Ring Unit | 0.050 | 78 100 | 3 905 | 4 100 | -195 | 1.0 |
| 26 | Power Unit EL (Motor) | 0.050 | 50 150 | 2 507 | 2 700 | -193 | 0.9 |
| 27 | Hight Adjustment Hydr. | 0.050 | 9 100 | 455 | 500 | -45 | 0.9 |
| 28 | Electric Motor | 0.050 | 17 100 | 855 | 950 | -95 | 0.9 |
| 29 | Oil Cooler | 0.067 | 9 450 | 630 | 700 | -70 | 0.9 |
| 30 | Luffing Gear Hydr. (Cyl) | 0.067 | 82 000 | 5 467 | 6 800 | -1333 | 0.8 |
| 31 | Suction Pipe | 0.033 | 12 000 | 400 | 500 | -100 | 0.8 |
| 32 | Double Hook + Suspension | 0.033 | 67 400 | 2 247 | 3 050 | -803 | 0.7 |
| 33 | Slewing Gear (3x) | 0.040 | 12 400 | 496 | 800 | -304 | 0.6 |
| 34 | Slew Ring Roller Bearing | 0.050 | 99 700 | 4 985 | 10 800 | -5 815 | 0.5 |
| 35 | Butterfly Valve (2x) | 0.100 | 1 250 | 125 | 600 | -475 | 0.2 |
| 36 | Reversible Axial Pump (2x) | 0.100 | 1 850 | 185 | 1 100 | -915 | 0.2 |
| 37 | HPTO Clutch | 0.100 | 2 100 | 210 | 1 250 | -1 040 | 0.2 |
| 38 | Hydraulic Motor (2x) | 0.067 | 1 100 | 73 | 500 | -427 | 0.1 |
| 39 | Electric Motor (2x) | 0.050 | 1 200 | 60 | 500 | -440 | 0.1 |
| 40 | Weight Block (2x) | 0.029 | 18 700 | 534 | 4 500 | -3 966 | 0.1 |
| 41 | Frequency Regulator (2x) | 0.050 | 1 050 | 52 | 450 | -398 | 0.1 |
| 42 | Hydraulic Pump | 0.067 | 2 200 | 147 | 1 300 | -1 153 | 0.1 |
| 43 | Generator | 0.056 | 4 600 | 256 | 3 050 | -2 794 | 0.1 |

*Note:* Based on Expected Lead Times (Own Composition)

TABLE D.2: Total Overview of Benefit/Cost Ratios of Crane Components (With MKS Transferium)

| # | Component | Annual Failure Probability | Failure Impact Reduction (in €) | Expected Annual Benefit | Costs | Net Benefit | BCR |
|---|---|---|---|---|---|---|---|
| | | | With MKS Transferium | | | | |
| 1 | Twistlock | 0.200 | 18 300 | 3 660 | 300 | 3 360 | 12.2 |
| 2 | Luffing Bearing (Cyl) | 0.100 | 26 550 | 2 655 | 450 | 2 205 | 5.9 |
| 3 | Block Chain (Hook Connection) | 0.125 | 18 550 | 2 319 | 500 | 1 819 | 4.6 |
| 4 | Control Module (2x) | 0.111 | 26 400 | 2 933 | 700 | 2 233 | 4.2 |
| 5 | Coupling | 0.067 | 26 000 | 1 733 | 450 | 1 283 | 3.9 |
| 6 | Rope Guard / Sheave | 0.083 | 26 250 | 2 187 | 600 | 1 587 | 3.6 |
| 7 | Oil Cooler Pump | 0.067 | 26 200 | 1 747 | 600 | 1 147 | 2.9 |
| 8 | Safety Valve / Pressure Switch | 0.050 | 26 050 | 1 302 | 450 | 852 | 2.9 |
| 9 | Cargo Block | 0.056 | 26 050 | 1 447 | 500 | 947 | 2.9 |
| 10 | Check Valve/Hydr. | 0.050 | 19 100 | 955 | 500 | 455 | 1.9 |
| 11 | V-Pump (Main Pump) (2x) | 0.067 | 27 500 | 1 833 | 1 100 | 733 | 1.7 |
| 12 | Motor Swivel Gear | 0.067 | 27 650 | 1 843 | 1 350 | 493 | 1.4 |
| 13 | Cable Drum | 0.040 | 26 900 | 1 076 | 800 | 276 | 1.3 |
| 14 | Force Measuring Strap | 0.100 | 5 400 | 540 | 500 | 40 | 1.1 |
| 15 | Elec. Safety Sensor | 0.100 | 1 000 | 100 | 100 | 0 | 1.0 |
| 16 | Guide Roller (3x) | 0.050 | 5 850 | 292 | 300 | -8 | 1.0 |
| 17 | Cable/Rope | 0.050 | 27 650 | 1 257 | 1 350 | -93 | 0.9 |
| 18 | Steel Strip (2x) | 0.067 | 3 400 | 227 | 250 | -23 | 0.9 |
| 19 | Slip Ring Unit | 0.050 | 69 100 | 3 455 | 4 100 | -645 | 0.8 |
| 20 | Hoisting Winch | 0.100 | 29 250 | 2 925 | 3 600 | -675 | 0.8 |
| 21 | Spreader Unit | 0.067 | 28 700 | 1 913 | 2 400 | -487 | 0.8 |
| 22 | Cable Guide | 0.083 | 2 650 | 221 | 300 | -79 | 0.7 |
| 23 | Luffing Gear Hydr. (Cyl) | 0.067 | 73 000 | 4 867 | 6 800 | -1 933 | 0.7 |
| 24 | Oil Motor (Hoisting) | 0.050 | 28 600 | 1 430 | 2 050 | -620 | 0.7 |
| 25 | Power Unit EL (Motor) | 0.050 | 27 950 | 1 397 | 2 700 | -1 303 | 0.5 |
| 26 | Slew Ring Roller Bearing | 0.050 | 89 200 | 4 460 | 10 800 | -6 340 | 0.4 |
| 27 | Oil Cooler | 0.067 | 3 550 | 237 | 700 | -463 | 0.3 |
| 28 | Double Gear (Control) Pump | 0.050 | 3 700 | 185 | 550 | -365 | 0.3 |
| 29 | Double Hook + Suspension | 0.033 | 30 100 | 1 003 | 3 050 | -2 047 | 0.3 |
| 30 | Hight Adjustment Hydr. | 0.050 | 3 200 | 160 | 500 | -340 | 0.3 |
| 31 | Chain (CW) | 0.050 | 5 600 | 280 | 1 000 | -720 | 0.3 |
| 32 | Electric Motor (CW) | 0.050 | 5 000 | 250 | 950 | -700 | 0.3 |
| 33 | Suction Pipe | 0.033 | 3 200 | 107 | 500 | -393 | 0.2 |
| 34 | Butterfly Valve (AH) | 0.100 | 1 250 | 125 | 600 | -475 | 0.2 |
| 35 | Slewing Gear | 0.040 | 3 600 | 144 | 800 | -656 | 0.2 |
| 36 | Reversible Axial Pump | 0.100 | 1 850 | 185 | 1 100 | -915 | 0.2 |
| 37 | HPTO Clutch | 0.100 | 2 100 | 210 | 1 250 | -1 040 | 0.2 |
| 38 | Hydraulic Motor (AH) | 0.067 | 1 100 | 73 | 500 | -427 | 0.1 |
| 39 | Electric Motor (AH) | 0.050 | 1 200 | 60 | 500 | -440 | 0.1 |
| 40 | Frequency Regulator (AH) | 0.050 | 1 050 | 52 | 450 | -398 | 0.1 |
| 41 | Hydraulic Pump (AH) | 0.067 | 2 200 | 147 | 1 300 | -1 153 | 0.1 |
| 42 | Weight Block (CW) | 0.029 | 14 200 | 406 | 4 500 | -4 094 | 0.1 |
| 43 | Generator | 0.056 | 4 600 | 256 | 3 050 | -2 794 | 0.1 |

*Note:* Based on Expected Lead Times (Own Composition)

# Appendix E

# Sensitivity Analysis

## E.1 MKS Mercurius as MSG's single container-crane vessel

BCR of each component and for each sensitivity outcome shown in Table E.1.

## E.2 MKS Mercurius with Availability MKS Transferium

BCR of each component and for each sensitivity outcome shown in Table E.2.

TABLE E.1: Sensitivity Analysis (Only MKS Mercurius)

| | | | BCR's Expected Lead Time | | | | | | | BCR's Guaranteed Lead Time | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RANK | COMPONENT | COMPONENT PRICE | Default | +10%Life | -10%Life | +10%Failure | -10%Failure | +10%inv | -10%inv | Default | +10%Life | -10%Life | +10%Failure | -10%Failure | +10%inv | -10%inv |
| 1 | Twistlock | 450 | 33.2 | 22.6 | 36.9 | 38.7 | 28.6 | 33.5 | 50.3 | 49.8 | 45.3 | 55.3 | 56.8 | 43.5 | 50.1 | 75.2 |
| 2 | Luffing Bearing (Cyl) | 3 500 | 14.2 | 8.3 | 15.8 | 16.3 | 12.3 | 10.7 | 14.3 | 16.5 | 15 | 18.3 | 18.8 | 14.4 | 12.4 | 16.6 |
| 3 | Block Chain (Hook) | 2 100 | 12.5 | 8.7 | 13.9 | 14.6 | 10.8 | 12.6 | 15.8 | 18.7 | 17 | 20.8 | 21.4 | 16.4 | 18.9 | 23.6 |
| 4 | Cabin Control Module | 4 200 | 9.9 | 6.3 | 11.0 | 11.4 | 8.6 | 9.3 | 10.7 | 20.7 | 18.8 | 23.0 | 23.1 | 18.5 | 19.4 | 22.4 |
| 5 | Drive Unit Coupling | 1 800 | 9.2 | 6.3 | 10.2 | 10.5 | 8.0 | 9.2 | 10.4 | 13.9 | 12.7 | 15.5 | 15.7 | 12.3 | 14.0 | 15.8 |
| 6 | Rope Guard/Sheave | 3 400 | 8.6 | 5.5 | 9.6 | 9.9 | 7.5 | 8.7 | 9.5 | 13.1 | 11.9 | 14.6 | 14.8 | 11.6 | 13.2 | 14.4 |
| 7 | Oil Cooler Pump | 4 800 | 6.9 | 4.0 | 7.7 | 7.9 | 6.0 | 6.4 | 7.0 | 10.5 | 9.5 | 11.6 | 11.8 | 9.3 | 9.7 | 10.5 |
| 8 | Safety/Pressure Valve | 3 600 | 6.9 | 3.8 | 7.6 | 7.9 | 6.0 | 5.2 | 6.9 | 14.5 | 13.1 | 16.1 | 16.1 | 12.9 | 10.9 | 14.5 |
| 9 | Cargo Block | 2 100 | 6.9 | 4.8 | 7.6 | 7.9 | 6.0 | 6.9 | 8.7 | 15.1 | 13.8 | 16.8 | 16.9 | 13.5 | 15.2 | 19.0 |
| 10 | Check Valve/Hydr. | 2 200 | 5.2 | 3.6 | 5.8 | 6.1 | 4.5 | 5.3 | 6.6 | 8.1 | 7.4 | 9.0 | 9.2 | 7.1 | 8.2 | 10.2 |
| 11 | Force Measuring Strap | 2 200 | 4.2 | 2.9 | 4.6 | 5.0 | 3.9 | 4.3 | 5.3 | 5.6 | 5.1 | 6.3 | 6.5 | 5.2 | 5.7 | 7.2 |
| 12 | Guide Roller | 1 800 | 4.0 | 2.4 | 4.4 | 4.7 | 3.7 | 3.5 | 4.1 | 7.7 | 7.0 | 8.6 | 8.5 | 7.0 | 6.7 | 7.8 |
| 13 | V-Pump (Main Pump) | 8 400 | 3.9 | 2.5 | 4.4 | 4.5 | 3.4 | 3.6 | 4.1 | 5.7 | 5.2 | 6.4 | 6.5 | 5.0 | 5.3 | 6.0 |
| 14 | Motor Swivel Gear | 8 200 | 3.0 | 1.9 | 3.3 | 3.4 | 2.6 | 2.7 | 3.1 | 3.4 | 3.0 | 3.7 | 3.8 | 2.9 | 3.0 | 3.5 |
| 15 | Cable Drum | 5 100 | 3.0 | 2.0 | 3.3 | 3.4 | 2.6 | 3.0 | 3.2 | 6.1 | 5.6 | 6.8 | 6.8 | 5.5 | 6.1 | 6.5 |
| 16 | Steel Strip | 180 | 2.4 | 1.6 | 2.7 | 2.7 | 2.0 | 2.4 | 3.0 | 4.0 | 3.6 | 4.4 | 4.5 | 3.4 | 4.0 | 5.0 |
| 17 | Elec. Safety Sensor | 360 | 2.4 | 0.9 | 2.7 | 2.7 | 2.1 | 1.6 | 2.4 | 2.4 | 2.2 | 2.7 | 2.7 | 2.1 | 1.6 | 2.4 |
| 18 | Lifting Cable/Rope | 8 200 | 2.0 | 1.3 | 2.3 | 2.3 | 1.8 | 1.8 | 2.1 | 4.1 | 3.8 | 4.6 | 4.6 | 3.7 | 3.7 | 4.3 |
| 19 | Spreader | 18 000 | 1.8 | 1.2 | 2.0 | 2.1 | 1.6 | 1.7 | 2.0 | 2.7 | 2.4 | 3.0 | 3.0 | 2.4 | 2.5 | 2.9 |
| 20 | Cable Guide | 500 | 1.6 | 1.1 | 1.7 | 1.8 | 1.3 | 1.6 | 1.9 | 1.6 | 1.4 | 1.7 | 1.8 | 1.3 | 1.6 | 1.9 |
| 21 | Hoisting Winch | 29 500 | 1.4 | 0.9 | 1.6 | 1.6 | 1.3 | 1.4 | 1.5 | 3.1 | 2.8 | 3.4 | 3.4 | 2.8 | 2.9 | 3.3 |
| 22 | Oil Motor (Hoisting) | 17 000 | 1.4 | 0.9 | 1.5 | 1.6 | 1.2 | 1.4 | 1.5 | 2.8 | 2.6 | 3.2 | 3.2 | 2.6 | 2.8 | 3.2 |
| 23 | Double Gear (Control) Pump | 4 100 | 1.1 | 0.7 | 1.2 | 1.2 | 0.9 | 1.0 | 1.3 | 1.8 | 1.7 | 2.0 | 2.1 | 1.6 | 1.7 | 2.2 |
| 24 | Chain (CW) | 4 800 | 1.1 | 0.7 | 1.2 | 1.3 | 1.0 | 1.0 | 1.2 | 1.4 | 1.3 | 1.6 | 1.6 | 1.3 | 1.4 | 1.5 |
| 25 | Slip Ring Unit | 34 000 | 1.0 | 0.6 | 1.1 | 1.0 | 0.9 | 0.9 | 1.0 | 1.0 | 0.9 | 1.1 | 1.0 | 0.9 | 0.9 | 1.0 |
| 26 | Power Unit EL (Motor) | 21 000 | 0.9 | 0.6 | 1.0 | 1.0 | 0.8 | 0.9 | 1.0 | 1.4 | 1.2 | 1.5 | 1.5 | 1.2 | 1.3 | 1.4 |
| 27 | Height Adjustment Hydr. | 2 240 | 0.9 | 0.6 | 1.0 | 1.0 | 0.8 | 0.9 | 1.1 | 1.4 | 1.3 | 1.6 | 1.6 | 1.2 | 1.4 | 1.8 |
| 28 | Electric Motor (CW) | 4 500 | 0.9 | 0.6 | 1.0 | 1.0 | 0.8 | 0.8 | 1.0 | 1.3 | 1.2 | 1.5 | 1.4 | 1.2 | 1.2 | 1.4 |
| 29 | Oil Cooler | 4 500 | 0.9 | 0.5 | 1.0 | 1.0 | 0.7 | 0.8 | 1.0 | 0.9 | 0.8 | 1.0 | 1.0 | 0.7 | 0.8 | 1.0 |
| 30 | Luffing Cylinder | 60 000 | 0.8 | 0.5 | 0.9 | 0.9 | 0.7 | 0.8 | 0.8 | 0.8 | 0.7 | 0.9 | 0.9 | 0.7 | 0.8 | 0.8 |
| 31 | Suction Pipe | 2 300 | 0.8 | 0.5 | 0.9 | 0.9 | 0.7 | 0.8 | 1.0 | 1.9 | 1.7 | 2.1 | 2.2 | 1.7 | 1.9 | 2.4 |
| 32 | Double Hook + Suspension | 24 000 | 0.7 | 0.5 | 0.8 | 0.8 | 0.6 | 0.7 | 0.8 | 1.3 | 1.1 | 1.4 | 1.4 | 1.1 | 1.2 | 1.3 |
| 33 | Slewing Gear | 5 100 | 0.6 | 0.4 | 0.7 | 0.7 | 0.5 | 0.6 | 0.7 | 1.4 | 1.3 | 1.6 | 1.6 | 1.3 | 1.4 | 1.5 |
| 34 | Slew Ring Roller Bearing | 98 000 | 0.5 | 0.3 | 0.5 | 0.5 | 0.4 | 0.4 | 0.5 | 0.5 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.5 |
| 35 | Butterfly Valve (AH) | 3 200 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 36 | Reversible Axial Pump (AH) | 5 500 | 0.2 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 |
| 37 | HPTO Clutch | 9 000 | 0.2 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 |
| 38 | Hydraulic Motor (AH) | 2 477 | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.2 |

*Note*: Own Composition

TABLE E.2: Sensitivity Analysis (With MKS Transferium)

| | | | BCR's Expected Lead Time | | | | | | | BCR's Guaranteed Lead Time | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RANK | COMPONENT | COMPONENT PRICE | Default | +10%Life | -10%Life | +10%Failure | -10%Failure | +10%inv | -10%inv | Default | +10%Life | -10%Life | +10%Failure | -10%Failure | +10%inv | -10%inv |
| 1 | Twistlock | 450 | 12.2 | 11.1 | 13.6 | 13.6 | 10.7 | 12.2 | 18.3 | 22.9 | 20.8 | 25.5 | 25.2 | 20.3 | 22.9 | 34.4 |
| 2 | Cabin Control Module | 4 200 | 4.2 | 3.8 | 4.7 | 4.6 | 3.7 | 3.9 | 4.5 | 13.2 | 12 | 14.7 | 14.5 | 11.9 | 12.3 | 14.2 |
| 3 | Cargo Block | 2 100 | 2.9 | 2.6 | 3.2 | 3.2 | 2.6 | 2.9 | 3.6 | 9.8 | 8.9 | 10.9 | 10.7 | 8.8 | 9.8 | 12.2 |
| 4 | Safety/Pressure Valve | 3 600 | 2.9 | 2.6 | 3.2 | 3.2 | 2.6 | 2.2 | 2.9 | 9.2 | 8.4 | 10.2 | 10.1 | 8.3 | 6.9 | 9.2 |
| 5 | Block Chain (Hook) | 2 100 | 4.6 | 4.2 | 5.2 | 5.2 | 4.1 | 4.6 | 5.8 | 8.7 | 7.9 | 9.6 | 9.5 | 7.7 | 8.7 | 10.8 |
| 6 | Drive Unit Coupling | 1 800 | 3.9 | 3.5 | 4.3 | 4.3 | 3.4 | 3.9 | 4.3 | 7.6 | 6.9 | 8.5 | 8.4 | 6.8 | 7.6 | 8.6 |
| 7 | Luffing Bearing (Cyl) | 3 500 | 5.9 | 5.4 | 6.6 | 6.5 | 5.2 | 4.4 | 5.9 | 7.5 | 6.8 | 8.3 | 8.3 | 6.6 | 5.6 | 7.5 |
| 8 | Rope Guard/Sheave | 3 400 | 3.6 | 3.3 | 4.1 | 4.0 | 3.2 | 3.6 | 4.0 | 7.2 | 6.5 | 8.0 | 7.9 | 6.4 | 7.2 | 7.8 |
| 9 | Oil Cooler Pump | 4 800 | 2.9 | 2.6 | 3.2 | 3.2 | 2.6 | 2.7 | 2.9 | 5.7 | 5.2 | 6.4 | 6.3 | 5.1 | 5.3 | 5.7 |
| 10 | Cable Drum | 5 100 | 1.3 | 1.2 | 1.5 | 1.5 | 1.2 | 1.3 | 1.4 | 4.0 | 3.7 | 4.5 | 4.4 | 3.6 | 4.0 | 4.3 |
| 11 | Check Valve/Hydr. | 2 200 | 1.9 | 1.7 | 2.1 | 2.1 | 1.7 | 1.9 | 2.4 | 4.0 | 3.6 | 4.4 | 4.4 | 3.6 | 4.0 | 5.0 |
| 12 | V-Pump (Main Pump) | 8 400 | 1.7 | 1.5 | 1.9 | 1.8 | 1.5 | 1.5 | 1.7 | 3.1 | 2.8 | 3.5 | 3.4 | 2.8 | 2.9 | 3.3 |
| 13 | Guide Roller | 1 800 | 1.0 | 0.9 | 1.1 | 1.1 | 0.9 | 0.8 | 1.0 | 3.1 | 2.8 | 3.4 | 3.2 | 2.5 | 2.6 | 3.1 |
| 14 | Lifting Cable/Rope | 8 200 | 0.9 | 0.8 | 1.0 | 1.0 | 0.8 | 0.8 | 1.0 | 2.7 | 2.5 | 3.1 | 3.0 | 2.5 | 2.5 | 2.9 |
| 15 | Hoisting Winch | 29 500 | 0.8 | 0.7 | 0.9 | 0.9 | 0.7 | 0.8 | 0.9 | 2.3 | 2.1 | 2.5 | 2.5 | 2.0 | 2.2 | 2.4 |
| 16 | Oil Motor (Winch) | 17 000 | 0.7 | 0.6 | 0.8 | 0.8 | 0.6 | 0.7 | 0.8 | 2.0 | 1.8 | 2.2 | 2.2 | 1.8 | 1.9 | 2.2 |
| 17 | Motor Swivel Gear | 8 200 | 1.4 | 1.2 | 1.5 | 1.5 | 1.2 | 1.2 | 1.4 | 1.6 | 1.5 | 1.8 | 1.8 | 1.5 | 1.5 | 1.7 |
| 18 | Spreader | 18 000 | 0.8 | 0.7 | 0.9 | 0.9 | 0.7 | 0.8 | 0.9 | 1.5 | 1.4 | 1.7 | 1.6 | 1.3 | 1.4 | 1.6 |
| 19 | Force Measuring Strap | 2 200 | 1.1 | 1.0 | 1.2 | 1.2 | 1.0 | 1.1 | 1.3 | 1.4 | 1.3 | 1.6 | 1.5 | 1.3 | 1.4 | 1.8 |
| 20 | Elec. Safety Sensor | 360 | 1.0 | 0.9 | 1.1 | 1.1 | 0.9 | 0.7 | 1.0 | 1.0 | 0.9 | 1.1 | 1.1 | 0.9 | 0.7 | 1.0 |
| 21 | Steel Strip | 180 | 0.9 | 0.8 | 1.0 | 1.1 | 0.7 | 0.9 | 1.1 | 0.9 | 0.8 | 1.0 | 1.1 | 0.7 | 0.9 | 1.1 |
| 22 | Power Unit EL (Motor) | 21 000 | 0.5 | 0.5 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.9 | 0.8 | 1.0 | 1.0 | 0.8 | 0.9 | 0.9 |
| 23 | Slip Ring Unit | 34 000 | 0.8 | 0.8 | 0.9 | 0.9 | 0.8 | 0.8 | 0.9 | 0.8 | 0.8 | 0.9 | 0.9 | 0.8 | 0.8 | 0.9 |
| 24 | Double Hook + Suspension | 24 000 | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 | 0.3 | 0.4 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.7 | 0.8 |
| 25 | Cable Guide | 500 | 0.7 | 0.7 | 0.8 | 0.9 | 0.6 | 0.7 | 0.9 | 0.7 | 0.7 | 0.8 | 0.9 | 0.6 | 0.7 | 0.9 |
| 26 | Luffing Cylinder | 60 000 | 0.7 | 0.7 | 0.8 | 0.8 | 0.6 | 0.7 | 0.8 | 0.7 | 0.7 | 0.8 | 0.8 | 0.6 | 0.7 | 0.8 |
| 27 | Electric Motor (CW) | 4 500 | 0.3 | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.3 | 0.5 | 0.5 | 0.6 | 0.5 | 0.4 | 0.5 | 0.6 |
| 28 | Slew Ring Roller Bearing | 98 000 | 0.4 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 |
| 29 | Chain (CW) | 4 800 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.3 | 0.4 | 0.4 | 0.3 | 0.3 | 0.4 |
| 30 | Oil Cooler | 4 500 | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 | 0.3 | 0.4 | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 | 0.3 | 0.4 |

*Note*: Own Composition