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Maintenance and spare parts inventory optimization at container terminals: the case of ECT

by

Asteris Plousios

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Abstract

One of the biggest issues in every industry, either in production or in service providing as terminals are, is the optimization of the maintenance policy. The share of maintenance costs in the total costs of every industry is very big and minimizing them has been a research objective since the beginning of mechanization in production. As the equipment got more complex and expensive, the need for effective maintenance appeared, and this can be shown in the three different stages in the evolution of maintenance concepts. The most modern concepts optimize age replacement times by taking into account several different failure distributions of equipment. Moreover, modern maintenance concepts like RCM and TPM have appeared and emphasize in the qualitative improvement. The innovation they propose is the involvement of all the levels and departments of a company and as they showed their effectiveness they are being adopted by an increasing number of companies nowadays.

Furthermore, an important part of having effective maintenance is the synchronization of maintenance needs with the spare parts inventory. The inventory costs, another big cost center in many industries, compromise in a big part from holding costs for spare parts inventory. The optimal spares inventory management can relief a company from over-stocking and also minimize downtime due to shortage of a specific part. It is apparent thus, that cooperation with the maintenance department is of utmost importance in order for both departments to benefit.

This thesis addresses the above issues in the terminal industry, where little research on maintenance has been made and tries to connect optimal maintenance policies with the spare parts inventory management. The real-life application on Europe's largest container terminal, ECT in Rotterdam, gives important results on the importance of data input, organization and company mentality in the overall effectiveness of the proposed methods.

Relationship between Thesis Objectives and Report Structure								
Thesis objectives	Chapter 1	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7	Chapter 8
Maintenance	○	○	●	●			●	○
Spare parts	○	○			●		●	○
Criticality Classification	○					●		○

●= strong relationship; ○= weaker relationship

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List of Abbreviations

AGV	Automated Guided Vehicle
CM	Corrective Maintenance
DSS	Decision Support System
ECT	Europe Container Terminals
FEU	Forty-foot Equivalent Unit
FMECA	Failure Mode Effect and Criticality Analysis
HSE	Health Environment Safety
METRIC	Multi-Echelon Technique for Recoverable Item Control
MRP	Materials Requirement Planning
PoR	Port of Rotterdam
PM	Preventive Maintenance
QC	Quay Crane
RCM	Reliability Centered Maintenance
SC	Straddle Carrier
TPM	Total Productive Maintenance
TEU	Twenty-foot Equivalent Unit
ULCV	Ultra-Large Container Vessel
ZPMC	Zhenhua Port Machinery Co. Ltd.

1. Introduction and research design

The uninterrupted work of port handling equipment is of great importance to a container terminal operator, as downtime costs can reach thousands of Euros per hour. Since the terminal is a very important part of a supply chain, with many parties involved, it is very important to avoid being the bottleneck but rather eliminate unplanned stops and maximize efficiency. Moreover, as theory supports, the maintenance schedule of all the equipment on the terminal should be fully integrated with the terminal operations, so that maximum efficiency can be achieved. An optimum maintenance policy targets therefore to the minimization of the total cost consisting of the spare parts inventory costs, the costs of inspections and downtime costs.

As any company trying to optimize maintenance, a container terminal is expected to use a modern approach like preventive or predictive maintenance in order to avoid breakdown maintenance and also make sure that the spare parts inventory is performing well, connected to the maintenance schedule. However, is this really the case in practice? To find out, we shall study the actual situation at ECT, the largest container terminal in Europe, situated in Rotterdam. ECT has spent millions in being one of the first automated terminals of the world and still competes with high performance numbers through automated operations. Nonetheless, is it also using state of the art policies in other departments, like maintenance-and how can it be improved? In particular we will study the following the following research question:

- *How can we optimally connect the maintenance schedule with the spare parts inventory on a container terminal?*

In order to answer this question, we must investigate the following sub-questions which will give us further insight on the problem:

- *What is a container terminal and how does ECT operate?*
  A detailed description of a container terminal and the analysis of operations on ECT are essential in order to help the reader understand the context of the problem.

- *What is maintenance and its importance in a container terminal?*
  The introduction to maintenance and its modern concepts that are used in the industry will provide us with ideas of the proposed managerial decisions about the maintenance concept that should be adopted.

- *Can we economically prevent equipment failures?*
  The main task of every maintenance policy is to reduce downtime by preventing unexpected failures, but always in a way that is cost-effective for the company.

- *How can we manage a spare parts inventory?*
  A vital part of every industry, the spare parts inventory needs to be carefully studied and optimized in order for the maintenance policy to be effective.

- *How can we collect reliable data, expert judgment and how can we apply that to our research objectives?*
  The data collection problem is almost always present in quantitative research and the problems that often accompany it need to be overtaken with alternative reliable sources of information.

- *Why and how can we classify the spare parts on criticality?*
  Since the number of spare parts is very big in every company, a decision has to be made as to on which products we focus first.

- *Can we lower overall maintenance and inventory costs in ECT with further actions?*
  Although some steps towards more cost-effective maintenance management can be made with the current research, there are many more problems to be addressed and that could improve the overall performance of the maintenance and inventory departments.

1.1 Research motivation

In the terminal business, customer service and satisfaction is everything. During the last 5 years, with the shipping industry reaching new record highs, liner shipping companies competed fiercely with each other in the booming Far east-Europe and America trades, where the demand for transportation was phenomenal. In order to stay competitive, each liner tried to be the best in terms of frequency and speed. One of the most important links in this whole supply chain is the container terminal, were transhipment or change of modality is made. The liner companies were willing to choose the most expensive but efficient terminal, if it would allow them to minimize their port call time, so that they could maximize the frequency of their services. So the main objective for terminals was to be able to provide their service whenever needed, without interruption.

Nowadays with the economic downturn, liner companies struggle with the reduced demand and thus terminals compete fiercely in order to provide the best rate to the container carriers. The focus has changed, towards cost-control and the reduction of unnecessary expenses.

In the first case, the availability of the terminal equipment was of vital importance, as the downtime costs were destructive for the terminals. Responsible for the availability was the maintenance department, which should ensure that unexpected downtime caused from breakdowns was minimized and that any maintenance should be carefully planned to fit in the tight schedule of operations. However, even now, although availability is not the main concern, maintenance plays a very important role, as discussed later, since the costs connected with it are very big.

The specific equipment under study, the three quay crane of the same type were chosen because, first of all, the quay crane is the sea to land connection of the supply chain and of the most importance in a terminal. Furthermore, the enormous capital cost needed for investment on quay cranes, requires careful study of its life cycle costs a major part of which are maintenance costs.

1.2 Research objectives

This Master thesis was created during a 4 month period of internship at Europe Container Terminals B.V. There were two objectives during this internship. The first was to study and evaluate the maintenance policies and organization of

ECT as well as the spare parts inventory policies. The second and main objective was to propose a modern maintenance concept that could be implemented in the organization and to integrate it with the spare parts management, so that total costs could be minimized. The research was made for a specific type of quay cranes, as the study of all the equipment on the terminal would take years and is out of the scope of a master thesis. However, the purpose of the thesis is that it can be used as a generic tool, so that similar studies can be easily made on the rest of the terminal equipment.

In order to achieve those objectives, a reasonable amount of time was spent on understanding the processes of the terminal and the major role that maintenance has in it. The conflict with operations for availability of the crane and the conflict with the warehouse for the availability of the spare parts were carefully examined. The insight of the operations of all departments was acquired with lengthy interviews and discussions with employees of all levels.

1.3 Research Design

Research is classified into basic and applied research. Since this thesis is carried out to study a specific problem, it can be classified under the applied research area. It uses fundamental knowledge to provide a solution to the specific problem of maintenance concept and spare parts optimization for ECT.

1.3.1 Approach

The approach used to carry out the research can be classified into quantitative and qualitative (Neuman, 2003). In this thesis mostly quantitative methods were used in order to address the research question. Statistical methods were used in processing the data and operations research models were applied in maintenance and inventory optimization. Furthermore, economic analysis was carried out in order to estimate costs and all the above were integrated into creating a large model for the whole research objective.

1.3.2 Data collection

The techniques used to collect the data necessary for the research are classified according to Neuman (2003) into quantitative and qualitative. Quantitative collection is in the form of numbers and qualitative in the form of words.

In this study, data was collected through interviews with the technicians, technical specialists, foremen and maintenance engineers, who gave estimates for the information needed. Also, data was collected from the company's DSS which has been used since 2004, however is not implemented correctly, as discussed later (Chapter 5) and data is partially entered. For this reason, attention was given on the interviews and the few data from the DSS were used to verify some of the interview findings.

1.4 Contents

In chapter 2, an introduction and description of the equipment and operations on the most important container terminal in Europe, ECT, is made. Also in chapter 2, the conditions of the case study in ECT and the specific equipment under study are presented.

Further on, in chapter 3, the reader can find an introduction in maintenance and the evolution of its concepts. Preventive maintenance is presented in chapter 4, along with the mathematical model that optimizes the costs of preventive age replacement. The theory and literature review of spare parts inventory management are described in chapter 5, and the situation in ECT's spare part warehouse is analyzed. The available data and its usage in the research objective are presented in chapter 6, along with the method of criticality classification for spare parts.

In chapter 7 the results of the data analysis and the application of the mathematical models on maintenance and spares inventory management are described. Finally, in chapter 8, the conclusions of the research, the possible implementation in ECT and points for further research are discussed.

1.5 Chapter Summary

A container terminal is nowadays on of the most important parts of global supply chains. The uninterrupted operation of the terminal is critical to its survival in the competitive environment of providing service, especially in an area like North Europe.

The present research focuses on terminal maintenance, which ensures the availability and well being of the equipment on a terminal. Specifically, a case study on maintenance optimization of quay cranes on the ECT container terminal in Rotterdam is presented. Furthermore, the maintenance schedule is linked to the spare parts inventory, in order to optimize the costs of the whole supply chain of costs in a terminal.

Since the research is a case study, it is applied and the approach used is quantitative and less qualitative. The data used is collected through interviews, information systems and personal observations during operations.

2. Europe Container Terminals

In order to better understand the context of the problem in the terminal industry and the company that the study took place, some information about ECT is presented in this chapter, along with specifics about the maintenance operations on Delta Terminal in Rotterdam. The source used for company information was ECT website and for equipment information, the data available to the maintenance department.

2.1 Company description

In 1966, the container made its debut in the port of Rotterdam. The introduction of this new phenomenon spurred some port companies to set up a special company focusing on the handling of containers: ECT. The stevedore acquired an own terminal in the Eemhaven (where the Home Terminal is presently located). In August 1967, the first official container ship moored here alongside the quay. It was the 'Atlantic Span', owned by shipping company ACL.

Initially just a small company, ECT already handled as many as 160,000 containers in 1970. In 1975, ECT handled almost 500,000 containers; in 1983 volumes had risen to more than a million. In the meantime, during 1984, a new ECT terminal was constructed at the Maasvlakte, the Delta Terminal. In 1988, ECT entered into a contract with Sea-Land for the establishment of a dedicated terminal for this shipping company at the Maasvlakte. This first ever robotized container terminal caught the attention of the whole world. Most of the operations were - and still are - fully automated. Automated Guided Vehicles (AGVs) take care of the transport between quay crane and stack. In the stack, all the work is carried out by Automated Stacking Cranes (ASCs). The Delta/Sea-Land terminal officially opened its doors in June of 1993.

Following the take-over of Sea-Land by Maersk in 1999, ECT itself has been managing the Delta/Sea-Land Terminal under the name Delta Dedicated North Terminal for new customers. Since early 2002, ECT has been part of the Hong Kong-based Hutchinson Port Holdings Group (HPH). In December of 2004, consensus was reached about the construction of the Euromaxx Terminal on the northern side of the Maasvlakte and operation started in the beginning of 2008. The continuous growth of container traffic can be seen in Figure 2.1.

2.1.1 Competitive Position

ECT owns several other terminals in Netherlands (Venlo) but also in Germany (Duisburg) and Belgium (Willebroek). However its core business takes place in the Delta terminal which is situated almost directly on the North Sea. Almost all of the major container shipping lines have included Rotterdam in their sailing schedules. Large vessels even dock at the Delta Terminal twice in a single journey, making the Maasvlakte their first and last European port of call.

However, it is not only the unrivalled accessibility from the North Sea that truly makes the Delta Terminal the container gateway to Europe. Highly efficient corridors connect the Delta Terminal to various destinations all over Europe. Around 40 per cent of the containers destined for the European market are carried by barge. Furthermore, more than 100 container rail shuttles a week arrive at and depart from the Rail Service Center at the Maasvlakte, while the Delta Terminal handles more than 16,000 trucks a week. Last but not least, the Delta Terminal constitutes the focal point for high frequency feeder services to 110 ports throughout the whole of Europe (Source: ECT).

Directly opposite the ECT terminals, the Port of Rotterdam has developed various large- scale distribution centers. These so-called Distriparks offer every possibility for additional logistics services. The Distripark Eemhaven (35 hectares) is close to the ECT City Terminal. The Distripark Maasvlakte (86 hectares) is just across the road from the ECT Delta Terminal. Flyovers offer a direct link between the Distriparks and the terminals. There is an internal track between the Distripark Maasvlakte and the ECT Delta Terminal which allows for the fast delivery and dispatch of containers from ship to warehouse and vice versa.

Rotterdam has a market share of 30% of the total container volume in northwest Europe. Rotterdam is the largest container port in Europe and fourth in the world. The ports of Antwerp and Hamburg with 20% with 22% market share respectively are ECT's largest competitors in the same geographical area. The ports of Zeebrugge and Le Havre with rates of approximately 16% have the greatest growth rates in the area. In the port of Rotterdam ECT has a market share of 73%, divided in 54% for Delta Container Division and 19% for the Home Terminal. However the crane productivity reaches an average of 25 containers per hour which leaves ECT behind the competition including Antwerp average of about 35 containers per hour. (Source: ECT)

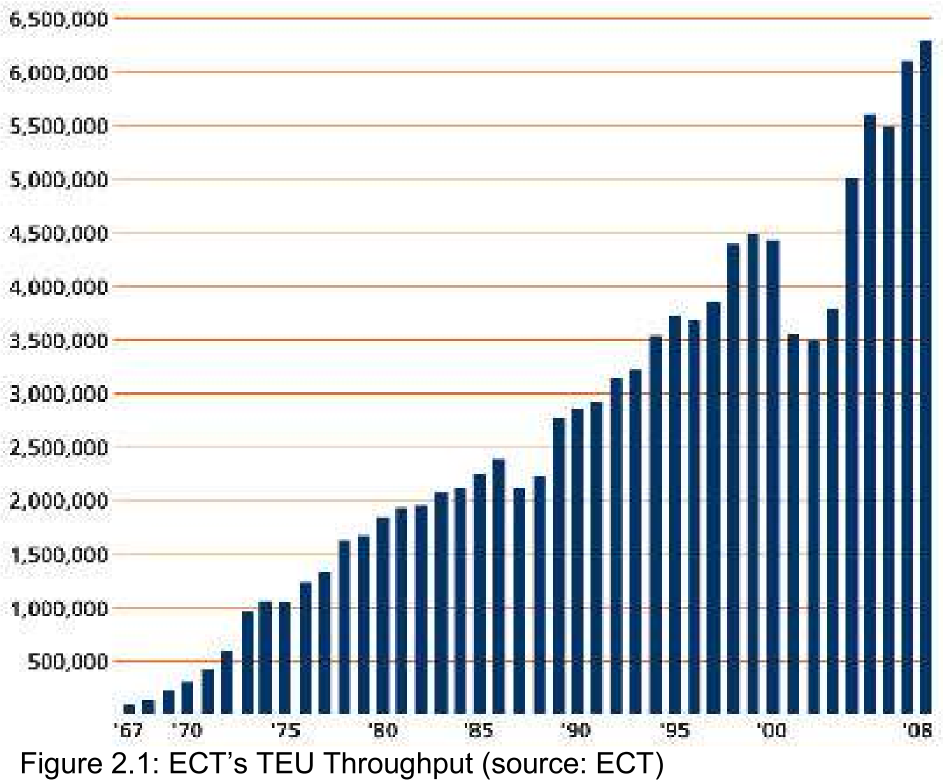


Figure 2.1: ECT's TEU Throughput (source: ECT)

2.1.2 Automation and equipment

The Delta Terminal is divided in several areas - shown in Figure 2.2, depending on the modality served and the location:

- Delta Barge Feeder (DBF) which replaced an older barge terminal and has the newest and most advanced quay cranes (3) on the terminal

- Delta Dedicated North, East and West – (DDN, DDW, DDE) which are intended mostly for serving deep-sea vessels and have a total of 38 quay cranes.
- There are also two rail terminals with 4 cranes

When built Delta Terminal was the first automated terminal in the world and still remains one of the most efficient, with state of the art equipment and customized software which ensures the smooth operation. Specifically, the operations between the quay and the yard are totally automated, as Automated Guided Vehicles (AGV) move the containers to the stack and the Automated Stacking Cranes (ASC) place the containers automatically to the predefined place in the stack. The total capital value of the assets, quay and stacking cranes, spreaders and vehicles, is more than €500mln (Table 2.1).

Table 2.1: DELTA Terminal information (source: ECT)

Total area		265 ha
Quay length		3,6 km
Depth		Max. 16,6 m
Inland shipping	Available area	7,2 ha
	Quay length	0,37 km
Rail	Available area	18 ha
	No. of cranes	4
Container quay cranes	38	
Straddle carriers	39	
Automated guided vehicles (AGV)	265	
Automated stacking cranes (ASC)	137	

Figure 2.2: Delta Container Terminal (source: ECT)

2.1.3 Operations Description

The primary operation is the transhipment of containers. Containers can be loaded on or unloaded from trains, trucks, barges, feeders or deepsea vessels in the areas described in 2.1.1. Figure 2.3 shows schematically the flow of containers in Delta Terminal.

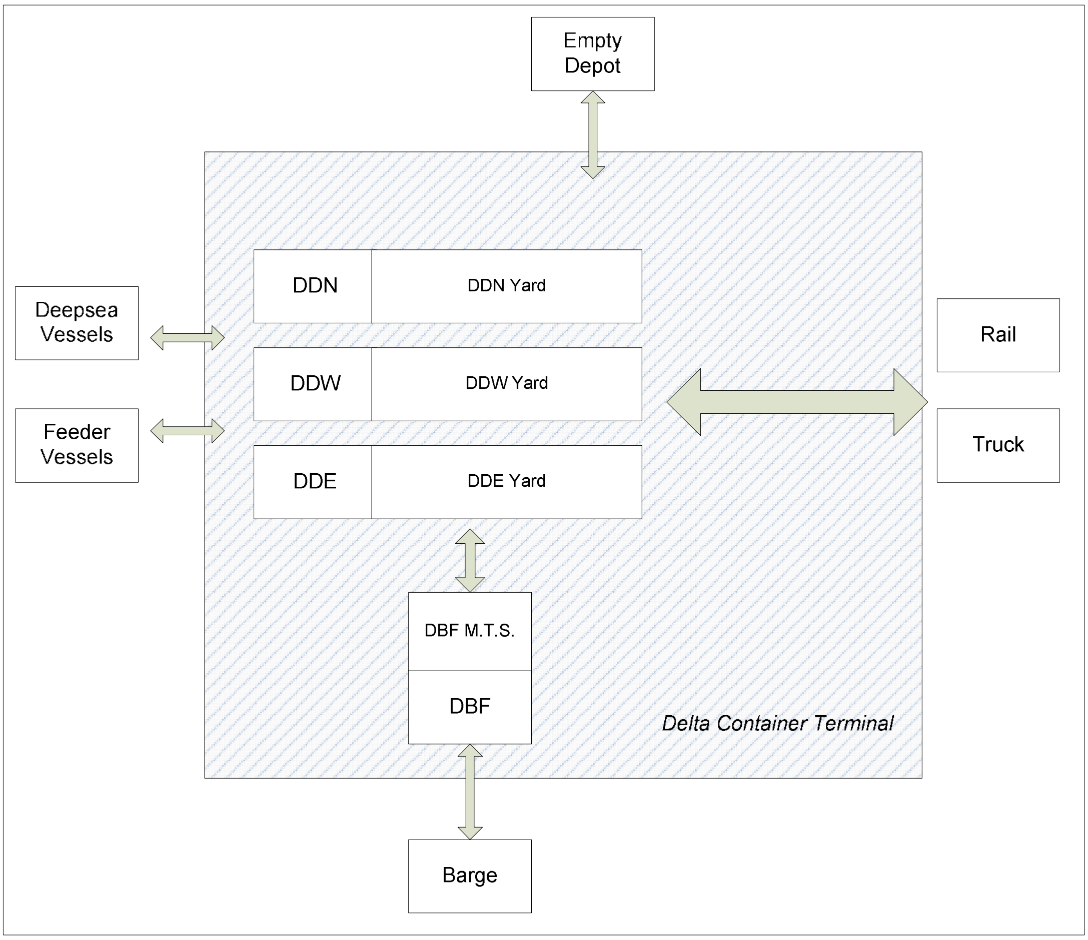


Figure 2.3: Container Movement on ECT Delta Terminal (source: author)

On the seaside, containers are handled with quay cranes, which vary on size and reach and are able to serve even the biggest of containers vessels today. In DDN, DDW and DDE, the containers are moved between the quay and the stack with AGVs whereas in DBF they are placed onto Multi Trailer Systems (MTS) and are moved to and from the stack with straddle carriers (SC). Also containers loaded/unloaded from the trains are placed on MTS and are stacked by SCs. Between the stack and the truck chassis, containers are moved with SCs. There are several Empty Depots on the Delta terminal but also on other sites in the Maasvlackte area, where MTS move the empty or damaged containers.

2.1.4 Information Technology Systems

In ECT, an Enterprise Resource Planning system is used, provided by Oracle Software. This system compromises of several systems to support all the aspects of ECT's activities. It has among others, Customer Relationship Management, Warehouse Management and Maintenance Management Systems.

Before the takeover from HPH, until 2004, the company was using the SAP software and was forced to change as HPH uses globally the Oracle software, on a server based on its Hong Kong headquarters. This transition however, was made very fast, and the little compatibility between the two different systems caused a lot of historical data to be lost. Furthermore, the users needed some transitional time to get used to the new software which even today after 5 years is not working to its full potential for the benefit of the company.

2.1.5 Organization

The research was conducted in the Technical and Maintenance Department (Technische & Onderhouds Dienst, TOD) of ECT's Delta Terminal. The TOD is under the Technical & Engineering department of ECT and has under its responsibility the maintenance of the equipment and buildings (BTOD) on Delta Terminal. There is a distinction within the equipment department between vehicle and crane maintenance. There are four separate maintenance departments in ECT, covering the main assets: Cranes (quay and stacking), Spreaders, Vehicles and Buildings. The research took place in the TOD management support department, cooperating with the crane department, as the subject of the study was a specific type of quay crane. Below in Figure 2.4 the breakdown of the TOD organization is shown. The total number of workers in the TOD department is 180 which makes it the biggest department within ECT which employs almost 2000 people, after of course the operations department which is the main activity of the terminal and represents about 85% of the personnel. The approximate 10% share over the total number of employees shows the significance that is given on maintenance and the need for optimization in order to make it more than a cost center.

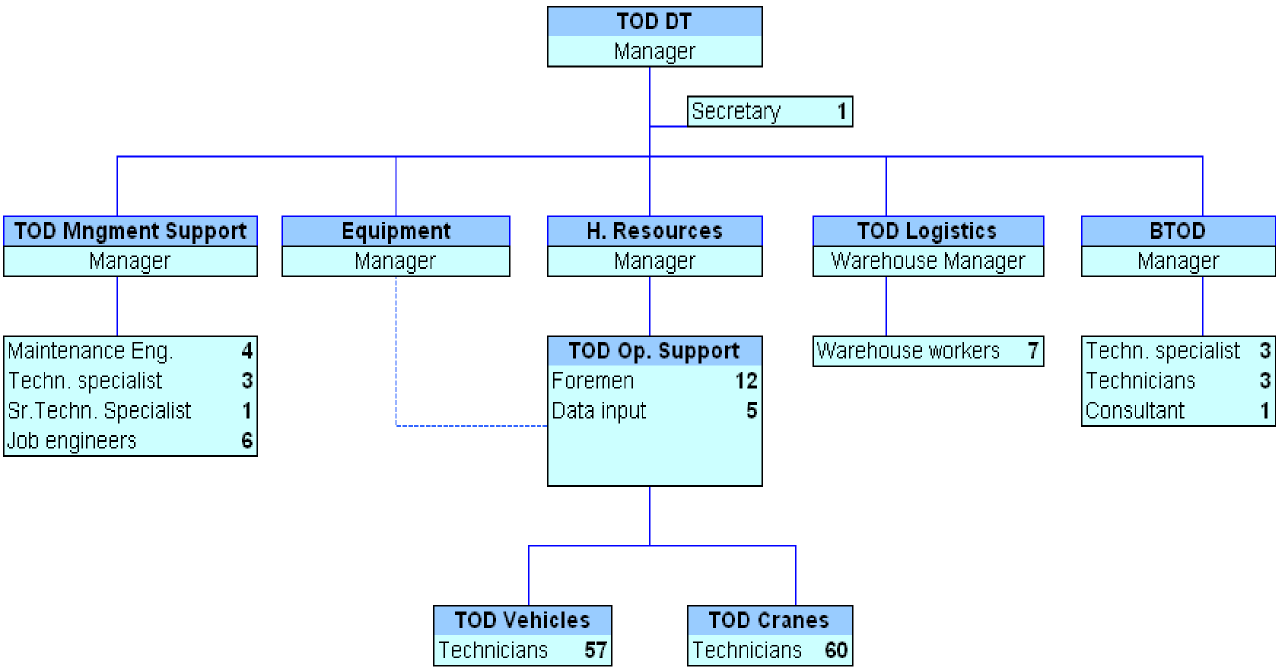


Figure 2.4: ECT's Maintenance department organization (source: ECT)

2.2 Case study in ECT

The scope of this thesis will be narrowed down to one specific type of quay cranes, the ZPMC ZP1 cranes, after recommendation from the ECT management which has great interest in this study. These specific cranes are on the DDE quay wall area and along with adjacent cranes, are in the part of the quay which Evergreen ships are handled. ECT has a contract with Evergreen, promising the full availability of this quay area any time an Evergreen ship wants to berth in ECT. This means that the availability of the ZP1 cranes is of great importance, as the consequences of a breakdown can be greater than any other crane which is not dedicated to a shipping line by contract. The Taiwanese company recently became a minority shareholder in ECT, by acquiring stocks from HPH (source PoR). Furthermore, the cost of these quay cranes which reach €6.000.000, show the importance of this equipment for the terminal-probably the most important every container terminal makes - and stresses the need for the minimization of their life cycle costs, which can be achieved through carefully planned maintenance.

The ZP1 cranes were also chosen as they have enough historical data – although not reliable – about failures (from 2005) and during the busy 2008, their performance was among the worst of the terminal, with a very low MMBF. That is the reason why ECT management wanted to study and optimize the maintenance schedule of these cranes as also the results of this thesis could be used as a generic guide to be applied to other equipment. Technical information about the cranes can be found in Table 2.2 and the schematics of the crane are shown in figure 2.5.

Some interesting details and facts about the specific problems of quay cranes concerning operations, life cycle and reliability study follow. These subjects were chosen as they are important for the reader to comprehend the peculiarities of quay cranes and they are mentioned often later on in the thesis.

Table 2.2: ZPMC ZP1 cranes (source: ZPMC)

Manufacturer		Shanghai Zhenhua Port Machinery Co. Ltd.
Description		Post-Panamax quay cranes with twin-lift capability
Reach	Horizontal	65m – 22 TEU wide
	Vertical	57.5m height to lift – 40m over rail, 17.5m below rail
Weight Capacity		70 tons
Operating speed	Lift full load	75 m/min
	Lift empty	150 m/min
	Lowering	150 m/min
	Trolley	240 m/min
	Gantry	45 m/min

2.2.1 Crane life-cycle, fatigue

The ZP1 ZPMC cranes have a guaranteed by the manufacturer structure durability of 2 million moves, as most quay cranes. When this number of moves is exceeded, there is a detailed inspection for signs of fatigue done by outsourced experts and the crane needs to stay out of operations for a few days. Even if dangerous fatigue signs are found, there is the possibility of reinforcing the structure and using the crane for a certain number of moves more.

2.2.2 MMBF

Instead of the commonly used MTBF, Mean Time Between Failures, for the assessment of the effectiveness of the maintenance program of cranes, Mean Moves Between Failures (MMBF) is used. As failure is considered any malfunction of the equipment that slows down or stops completely the operation of the crane. Reports are created for every week for each type of crane and also for each asset type, with a moving average of 6 weeks, so that the management can see the progress of the equipment failure rate. In Figure 2.6 the MMBF is shown for the past year, as recorded by ECT. The MMBF shows great variance weekly so, it is not such a good measure for indicating performance, in contrast to the moving average index which should be used by the management in order to evaluate the effectiveness of the maintenance department. From the MMBF data that we have about the crane, we can calculate a reliable approximation of MTBF that can be used for reliability studies. After we calculate the average moves that a crane makes over a year, we can divide the MMBF with that number and get the MTBF number in years.

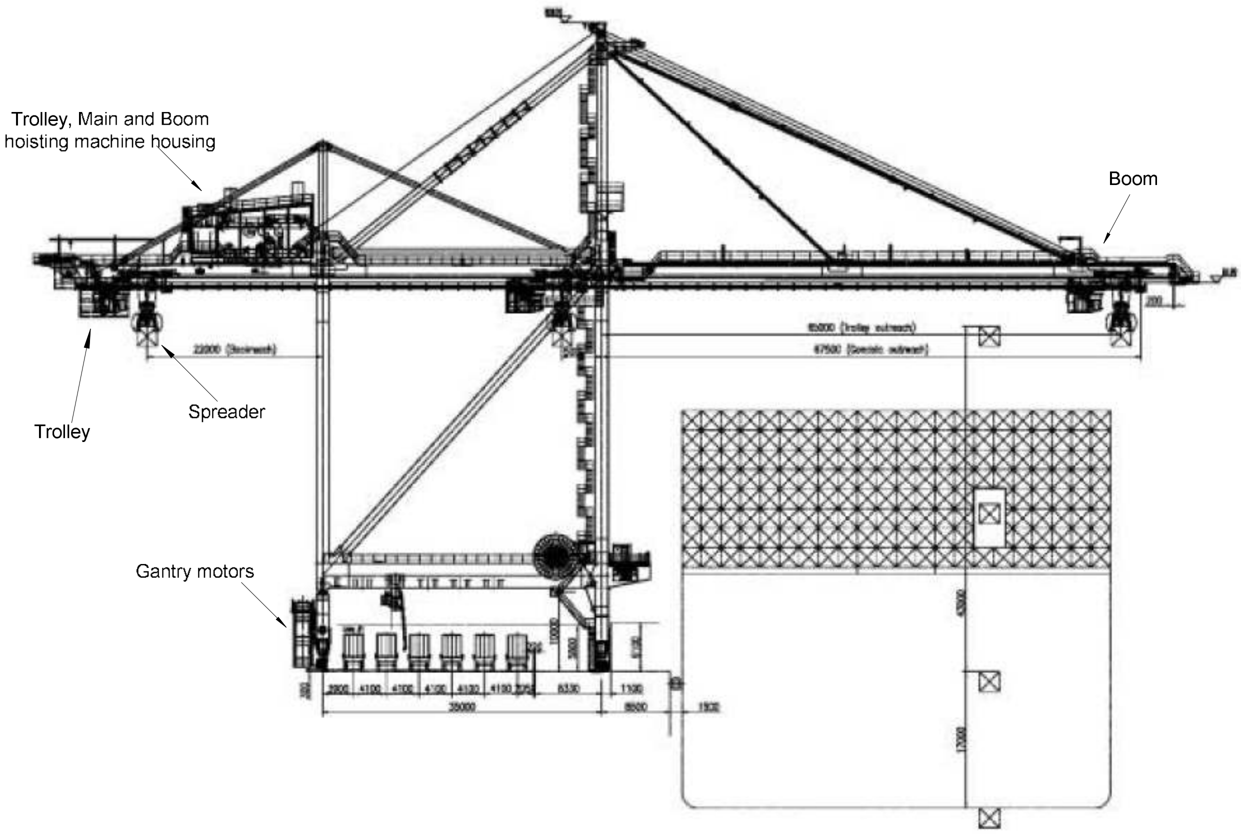
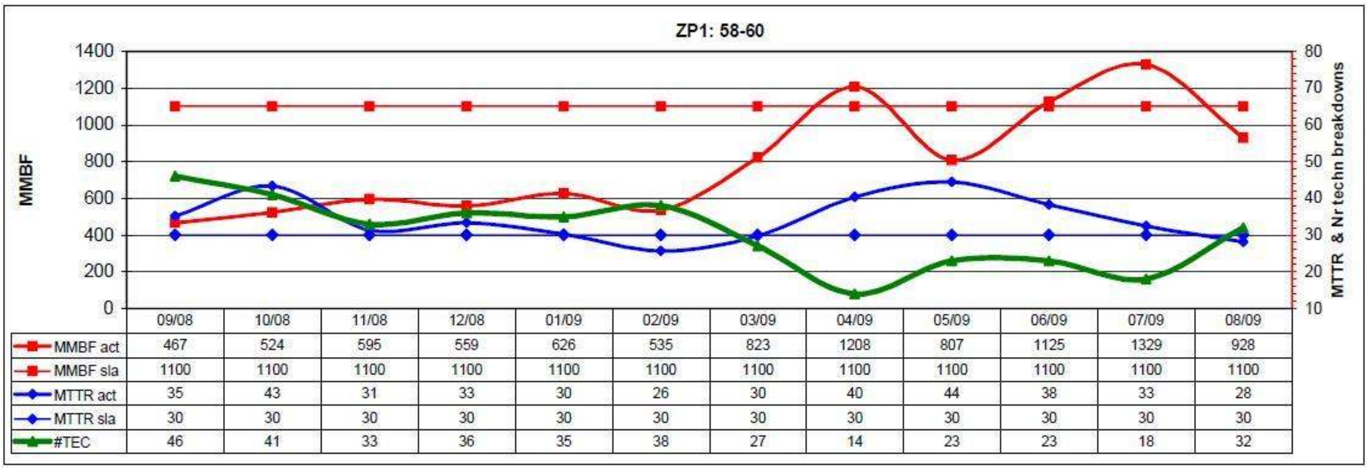


Figure 2.5: ZP1 Structure (source: ZMPC)



	09/08	10/08	11/08	12/08	01/09	02/09	03/09	04/09	05/09	06/09	07/09	08/09
MMBF act	467	524	595	559	626	535	823	1208	807	1125	1329	928
MMBF sla	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100
MTTR act	35	43	31	33	30	26	30	40	44	38	33	28
MTTR sla	30	30	30	30	30	30	30	30	30	30	30	30
#TEC	46	41	33	36	35	38	27	14	23	23	18	32

Figure 2.6: ZP1 MMBF and MTTR diagram over a year's time (Source: ECT)

2.2.3 Technical personnel

The technicians and blue collar workers create a problem in the smooth and optimized operation of maintenance, as most don't see the benefits of the modern maintenance concepts. The biggest problem appears in the preventive maintenance scheduling, where the technicians ignore the instructions and refuse to change a component that is still working correctly, sticking to the traditional way of thinking for maintenance. They cannot understand that potential breakdown time would cost much more to the company than a replacement of a working component.

2.5.4 Quay operations-Maintenance conflict

Quay operations want the cranes available all the time in order to plan the berth allocation and crane split, whereas the maintenance department wants to be able to perform the preventive maintenance and inspections according to the schedule. In case of a breakdown during operations, the maintenance and corrections needed are carried out by the terminal's "breakdown" team, which is responsible for all the equipment on the terminal rushes to the crane and most often performs incomplete maintenance. They fix temporarily the problem and create a new work order for the specialized crane maintenance crew which then tries to restore perfectly the crane's condition, in a time slot between operations.

Every Monday, the maintenance scheduler meets with the quay operations scheduler and they try to fit the planned maintenance of quay cranes between the quay operations. The same happens with the ASCs where a meeting with the yard operations takes place and the free time slots for their planned maintenance are determined. For the last 3 months a new concept has been applied, where inspections take place regularly during the operation of the cranes, so that the technicians can spot deteriorating equipment from vibrations and sound irregularities which could not be discovered otherwise. This idea has proven very useful as the recent increase in MMBF have been partly attributed to that.

2.5.5 Inspection Schedule - Inspection list

The failure finding schedule is set on certain time intervals and it is not based on the number of moves made by the crane. The schedule is shown in Table 2.3. Since the majority of failures are connected to the number of moves of the crane, the optimal would be to inspect the crane after a certain number of moves, based on the MMBF. One other problem that exists is that while the maintenance manual of the crane, supplied by ZMPC gives detailed instructions about inspections, time intervals and lubrication, they are not followed. ECT uses the same inspection list as older crane types. The technical specialists try together with the maintenance engineers to create a list that applies to each different crane's characteristics.

Table 2.3: Crane inspection policy (source: ECT)

Interval	Duration of crane unavailability
Every 2 weeks	Half hour during operation
Every month	2 days
Every 2 months	2 days (bigger list)
Twice a year	Lubrication for zpmc cranes

Figure 2.7: ULCV served by ECT's ZP1 cranes (source: ECT)

2.6 Spreaders

An important part on the crane that needs special mentioning is the spreader, which is the apparatus which grabs the containers with twist locks and is connected to the crane with the main hoisting system. The spreader, although it is handled by the crane operator and is a vital part of the loading and unloading procedure, is not studied in the present thesis, as it part of a totally different department in ECT and is considered a different asset. The main reason for this distinction is that the cost and complexity of the spreader favours the careful study of their maintenance through a different department. Since the spreaders are interchangeable between most cranes of any type, the spreader maintenance department ensures that there are available spreaders at any time and it has to handle the very big number of failures, due to mishandling from the operator mostly, but also due to the low reliability they have.

2.7 Chapter Summary

ECT is the largest container terminal in Europe, and one of the most important worldwide, helping Rotterdam to be one of the top ports in the world. The competitive position of ECT makes the minimization of downtime mandatory, so that the service level can remain the best in the area. Maintenance plays the most important role in keeping a high service level, and the organization of ECT's maintenance department and cost figures proves the value given on it by the management.

The case study in ECT will narrow down its scope on the maintenance optimization of quay cranes, which considered a separate department in the organization, showing the importance of this equipment for the smooth operation of the terminal. A spreader is a vital part of the operation of the quay crane, however it will not be studied, as in ECT it is considered a separate department by itself.

3. Maintenance

Maintenance is a process that is activated and can be defined as the combination of all the technical and associated administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function (International Electrotechnical Vocabulary [IEV] 191-07-01).

Maintenance objectives can be summarized under four headings: ensuring the system function (availability, efficiency and product quality); ensuring the system life (asset management); ensuring safety; and ensuring human well-being (Dekker, 1996). For production equipment, ensuring the system function should be the prime maintenance objective. Here, maintenance has to provide the right (but not the maximum) reliability, availability, efficiency and capability (i.e. producing at the right quality) of production systems, in accordance with the need for these characteristics.

Maintenance concepts changed rapidly over the second half of the 20th century. Because of the increasingly more complex installations and equipment used as the industrialization conquered the western world, new views on maintenance organization and responsibilities were needed. Although at first developed for manufacturing processes, maintenance concepts were recognized as being of great importance in all aspects of our life and of course in service providing, such as terminals.

Consideration of maintenance should start in the design phase of systems. However, the maintenance concept or strategy describes what events (e.g. failure, passing of time) trigger what type of maintenance (inspection, repair, replacement), and it can be determined both after the design phase and in the operations phase (Dekker, 1996). In general, maintenance management attempts to optimize the maintenance tasks, and minimizing the repair time is an issue of maintenance optimization that comprises the availability of spare parts when required.

3.1 The three generations in maintenance evolution

Three stages in the evolution of management concepts can be traced from the early 1900s up to the 21st century. In the period up to WWII, due to the low mechanization, downtime and thus prevention of failures did not matter that much. During the second period, wartime forced engineers to mechanize production and accept less downtime. The concept of preventive maintenance was created, which in the 60s consisted mainly of equipment overhauls at fixed intervals. Furthermore, as the capital tied up in fixed assets rose sharply, emphasis was given on prolonging asset life with careful maintenance planning.

Since the mid-seventies, the process of change in industry has gathered even greater momentum. The changes can be classified under the headings of new expectations, new research and new techniques. Downtime affects the productive capability of physical assets by reducing output, increasing operating costs and affecting customer service. By the 1960's and 1970's, this was already a major concern in the manufacturing, mining and transport sectors. The effects of downtime are being aggravated by the worldwide move towards just-in-time systems, where reduced stocks of materials throughout the supply chain mean that quite small equipment failures are now increasingly likely to interfere with the operation of an entire facility. In recent times, the growth of mechanization and automation bas meant that reliability and availability are now also key issues in sectors as diverse as health care, data processing, telecommunications and building management.

More and more failures have serious safety or environmental consequences, at a time when standards in these areas are rising rapidly. In some parts of the world, the point is approaching where organizations either conform to society's safety and environmental expectations, or they cease to operate. This emphasizes even more the significance of maintenance and focus goes beyond cost and becomes a simple matter of organizational survival.

At the same time as our dependence on physical assets is growing, so too is their cost - to operate and to own. To secure the maximum return on the investment that they represent, they must be kept working efficiently for as long as we want them to. Finally, the cost of maintenance itself is still rising, in absolute terms and as a proportion of total expenditure. As a result, in only thirty years it has moved from almost nowhere to the top of the league as a cost control priority

New research is also changing many of our basic beliefs about age and failure. In particular, it is apparent that there is less and less connection between the operating age of most assets and how likely they are to fail. (Figure 3.1)

However, 3rd Generation research has revealed that not one or two but *six* failure patterns actually occur in practice, As discussed in more detail later in this chapter, one of the most important conclusions to emerge from this research is a growing realization that although they may be done exactly as planned, a great many traditionally-derived maintenance tasks achieve nothing, while some are actively counterproductive and even dangerous. This is especially true of many tasks done in the name of preventive maintenance. On the other hand, many more maintenance tasks that are essential to the safe operation of modern, complex industrial systems do not appear in the associated maintenance programs.

After the mid 70s, automation appeared in manufacturing and also because of the increased competition, the expectations changed. Customer satisfaction, service level, product quality, and cost effectiveness were the objectives of transport and manufacturing sectors and reliability and availability of equipment played a major role in achieving these goals. The modern perception on failure rates have move on from the well-known “bathtub” curve and the following six type of failure distributions are considered nowadays and are shown in Figure 3.1:

A: bathtub curve – infant mortality, steady probability period, wear out period
B: constant probability, then wear out zone
C: slowly increasing probability – no wear out
D: low probability when new, then constant
E: constant
F: high infant mortality, then constant

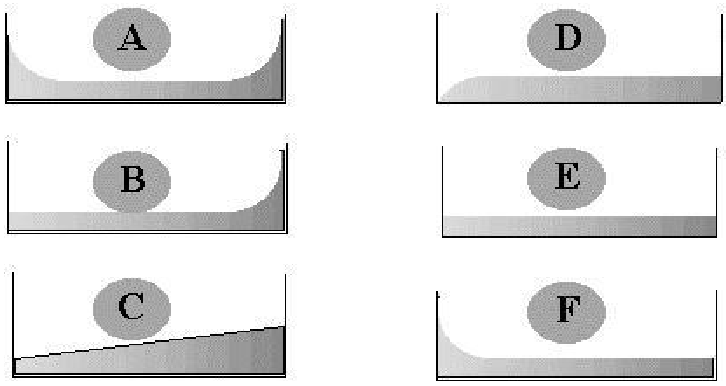


Figure 3.1: Failure distribution patterns (source: Moubray)

3.2 Literature review

Maintenance research has been made mostly for production plants, warranty issues. Mostly focus was given on quality of product, minimal downtime of production, reduction of accidents. A container terminal offers service, so the biggest concern would be the uninterrupted availability of equipment, so that the maximum desired level of service is achieved.

Spare parts inventory management can be improved greatly by taking into account the failure distribution of the equipment requiring the parts. Data that is simply based on historical usage may not be as useful. Integrated inventory and maintenance models have been developed in the past; however, more research is needed (Duffuaa et al. 1998). In particular, proposed models should be more realistic, so that they can be used to improve spare parts management and at the same time reduce costs. Also, this will lead to improvements in equipment availability.

3.3 Methods and maintenance concepts

There has been immense growth in new maintenance concepts and techniques, as seen in Table 3.1. Many have been developed over the past twenty years, and more are emerging every week.

Table 3.1: The three Generations in Maintenance evolution (source: Moubray)

1st generation	Maintenance after breakdown
2nd generation	Systems for planning and controlling work
	Scheduled overhauls
	Introduction of computing power
3rd generation	Condition monitoring
	Design for reliability and maintainability
	Hazard studies
	Small, fast computers
	Failure modes and effects analyses (FMEA)
	Expert Systems
	Multi-skilling and teamwork

The new developments include (Moubray, 1997):

- decision support tools, such as hazard studies, failure modes and effects analyses and expert systems
- new maintenance techniques, such as condition monitoring
- designing equipment with a much greater emphasis on reliability and maintainability
- a major shift in organizational thinking towards participation, team-working and flexibility.

3.3.1. RCM

Reliability Centered Maintenance (RCM) is a maintenance concept which appeared in the late 70's and which provides a framework for complete maintenance management. RCM is rapidly becoming a basic tool of the Third Generation in the evolution of maintenance as discussed above (Moubray, 1997). The formal definition of RCM according to Moubray is: "a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context."

RCM was evolved through research on reliability concerning complex equipment in the 1960s in the aircraft industry. The studies carried out by the American FAA changed the maintenance mentality which prevailed until then, and led to the 3rd generation of maintenance. In particular, two surprising findings were the most important being contrary to the beliefs until then:

- Scheduled repairs had little effect on reliability of complex items, and
- For many items it was found that no effective way of preventive maintenance existed.

The important new concepts that RCM introduced are (Moubray, 1997):

- A failure is an unsatisfactory condition and maintenance attempts to prevent such conditions from arising
- The consequences of failure determine the priority of the maintenance effort
- Equipment redundancy should be eliminated, where appropriate
- Condition-based or predictive maintenance tactics are favored over traditional time-based methods
- Run-to-failure is acceptable, where warranted.

RCM is a more qualitative approach, making it easier to be implemented by the management and to be accepted by the lower employee levels. The two main tools used are the logic diagram and the Failure Mode, Effect and Criticality Analysis (FMECA). A basic logic diagram, which can be enriched depending on the level of detail, is shown in Figure 3.2. The seven basic questions-logical steps in the RCM implementation, part of the FMECA process, are:

- *what are the functions and associated performance standards of the asset in its present operating context?*
- *in what ways does it fail to fulfill its functions?*
- *what causes each functional failure?*
- *what happens when each failure occurs?*
- *in what way does each failure matter?*
- *what can be done to predict or prevent each failure?*
- *what should be done if a suitable preventive task cannot be found?*

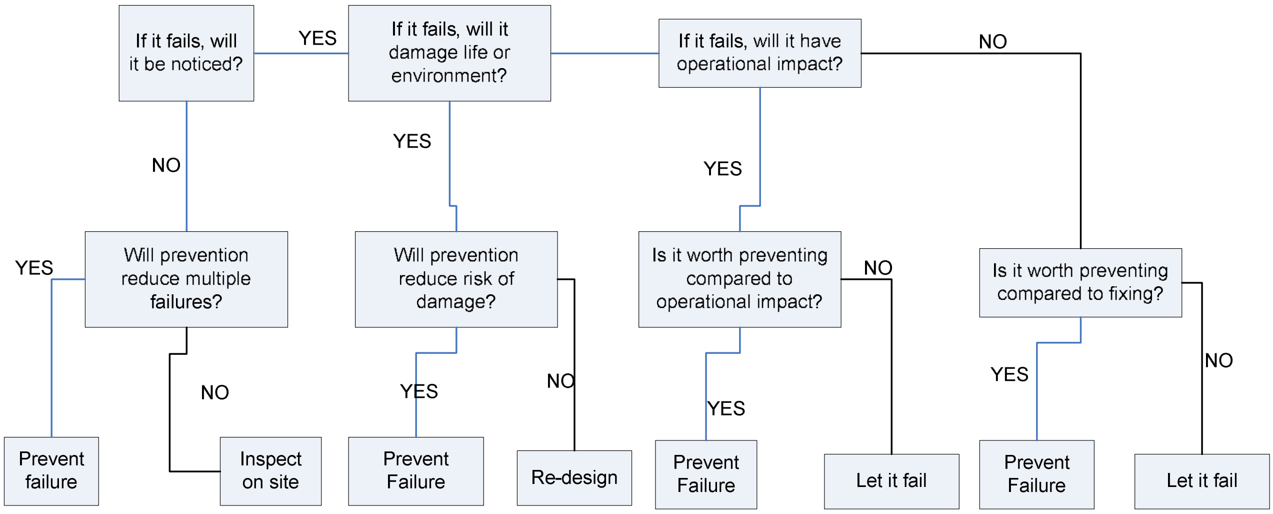


Figure 3.2: RCM logic diagram (source: author)

3.3.2. TPM

Total Productive Maintenance is an innovative Japanese concept, initiated in the mid 50s, when preventive maintenance was first used in Japan. The company which gave birth to TPM was Nippondenso of the Toyota group. Part of the preventive maintenance process in this company was the improvement of reliability of the equipment by the maintenance engineers. The concepts of preventive maintenance, the prevention of maintenance through improvements and the involvement of employees of all levels, created the concept of TPM (Venkatesh, 2007).

In short, the main idea of TPM is the involvement of all employees in the improvement of quality and efficiency of production. The core tools to achieve this are:

1. Improving equipment effectiveness
2. Improving maintenance efficiency and effectiveness
3. Early equipment management and maintenance prevention
4. Training to improve the skills of all people involved
5. Involving operators (occupants) in routine maintenance

TPM has been proven to be a program that works and although it was developed for production plants, it can be implemented easily in the terminal industry. The combination of traditional maintenance ideas with modern management concepts is the key to the success of TPM.

3.4 Proactive task: is it worth?

Traditionally, the maintenance requirements of each asset are assessed in terms of its real or assumed technical characteristics, without considering the consequences of failure. The resulting schedules are used for all similar assets, again without considering that different consequences apply in different operating contexts. This results in large numbers of schedules which are wasted, not because they are wrong in the technical sense, but because they achieve nothing.

However the RCM methodology proposes the following decision making process, in order to avoid wasted money, and to minimize costs. The decision is made mostly based on the cost of a preventive task compared to the cost of failure:

- For failures that are not obvious, a preventive task is worth if it reduces the risk of multiple failures to a reasonably low level. If such a task cannot be found then a scheduled failure-finding task must be performed, if a suitable failure-finding task cannot be found, the secondary default decision is that the item may have to be modified (based on the consequences of the multiple failure).
- For breakdowns with HSE impact, a preventive task is only worth if it minimizes the risk of that failure on its own to a very low level; if it does not stop it altogether. If a preventive task cannot be found which reduces the risk of the failure to a reasonably low level, the item must be modified or the process must be modified.
- If the breakdown has operational impact, a proactive task is only worth if the total cost is less than the cost of the operational consequences and the cost of repair over the same period. If the task is not economically justified, the default decision is no scheduled maintenance. (If this is the case and the operational consequences are still unbearable, then the secondary decision is again modification).
- If a failure has non-operational impact, a preventive task is only worth doing if the cost of the task over a period of time is less than the cost of repair over the same period. If the task is not economically justified, the decision is no scheduled maintenance, and if the repair costs are too high, the secondary decision is again modification.

The costs that every concept for maintenance has to deal with and to minimize are:

- Direct maintenance costs e.g. manual work, spare parts, tools *etc*
- Indirect costs e.g. Downtime costs
- Back-up equipment
- Over-maintenance cost

3.5 Chapter Summary

The perception scientists had about maintenance changed over the years, following the technological evolution. Since the beginning of the 20th century, as mechanization and automation were introduced, engineers realized the importance of careful maintenance and the costs involved in it.

The concepts about maintenance evolved rapidly during the second part of the past century, leading to ideas originating from Japan, regarding the integration of maintenance in management practice and not considering it only as a cost center. The two most modern and acclaimed concepts are RCM and TPM, and the ideas from the first are going to be used in this case study, in order to optimize maintenance in ECT.

4. Preventive Maintenance

Since the earlier days of maintenance research, engineers found out that they could reduce the overall failure rate of equipment sometimes, by replacing a part after certain hours of operation with a new one. It was obvious also, after inspection of mechanical parts, that changes in the behavior, sound and performance of some parts could be noticed just before a failure – in other words deterioration was noticed. Thus, prevention of an unexpected failure just before it happened proved to be an interesting field of research that could reduce the downtime costs.

4.1 Failure rate estimation

In order to have effective spare parts management, good data acquisition and methods of forecasting are required, in order to analyze the demand of the parts and to develop the proper stocking and ordering policies. Data acquisition is the most important and usually difficult part of the process, as usually companies do not have the provision for adequate data input for maintenance and the area is often neglected.

Supposing that adequate and correct data has been collected, a simple forecast using time series analysis or other forecasting techniques will not show the actual situation, as the parts are used intermittently. Consequently, the maintenance departments order more parts than the optimum as they are disconnected from the investment in inventories. In big organizations this results in a huge waste of money as more parts than necessary are ordered.

In order to have the optimum policy, inventory managers and maintenance engineers must work together, using the historical data, conducting failure analysis for the spare parts. The failure rates of the parts to be stocked can be calculated using the historical data using various techniques (Barlow, 1975). A usable estimate of failure rates can be made from even five data points, in the case of Weibull analysis (Huang et al., 1995).Unfortunately, usually the case is that not enough failure data is available, especially in new equipment. In such cases any information can be enforced with failure rate data banks, for some common components in the industry. The reliability information can also be estimated by using the expert judgment, by conducting interviews with the technicians who are responsible for the equipment.

Once obtained, the failure rate in turn will be used to determine the demand rate much more effectively than forecasting techniques. The appropriate inventory and ordering policy can be formed, taking into account the criticality of each part, the acceptable risk of shortage, the lead time and other factors. The ordering policy for the demand forecasted, can be based on Economic Order Quantity (EOQ) calculations with a probabilistic inventory model (Kennedy et al. 2002).

4.1.1 Weibull distribution

The use of the Weibull distribution is dominant in literature and generally in reliability studies, as it is very versatile. The two-parameter Weibull function has the shape parameter β which can represent a constant ($\beta=1$), increasing ($\beta>1$) or decreasing ($\beta<1$) failure rate. The latter is not witnessed in real life often, as it means that the part would have fewer probabilities to fail as time passes (often called "infant mortality"). The case of $\beta=1$ means that components fail randomly and is common for electronic equipment, whereas for $\beta>1$ the component wears out with the passage of time. The scale parameter η of the Weibull distribution represents the characteristic life of the part, measured in time or other units used to measure life (e.g. moves for a quay crane) and it has the property that the reliability at η, R(η) = 36.8%.

4.2 Preventive maintenance

Failures of units can be roughly classified in to two failure modes - catastrophic failure in which a unit fails suddenly and completely, and degraded failure in which a unit fails gradually with time by its performance deterioration. In the former, failures during actual operation might sometimes be costly or dangerous. It is an important problem to determine when to replace or preventively maintain a unit before failure. In the latter, maintenance costs of a unit increase with its age, and inversely, its performance suffers some deterioration. In this case, it is also required to measure some performance parameters and to determine when to replace or preventively maintain a unit before it has been degraded into failure state.

By applying PM the demand for a specific part becomes essentially deterministic. We can use an inventory policy of (s-1,s), practically keeping only one item in stock and ordering the replacement just in time to be used when the PM takes place. This way we can save on top of the minimized downtime, also from the reduced inventory costs. Of course, with PM we minimize unexpected breakdowns, but there is still a probability that a component will fail, based on the Estimated Time to Failure ETBF which is derived as the MTBF after applying PM.

In many cases (Huang, 1995), the MTBF is used to determine a preventive maintenance interval for a component. However, the use of the MTBF metric implies that the data were analyzed with an exponential distribution since the mean will only fully describe the distribution when the exponential distribution is used for analysis. The use of the exponential distribution, in turn, implies that the component has a constant failure rate.

4.3 Age replacement optimization model

We are trying to find the optimal time of preventive replacement, T_p which minimizes the costs of unexpected downtime due to failure. The proposed PM policy is replacement at a certain time T_P after the component's installation, or after failure, whichever occurs first. We call T_P the planned replacement time ranging over (0,∞], When T_P=∞, no replacement takes place and the component runs-to-failure.

Corrective Maintenance costs: C_f = downtime costs + labor costs

Preventive Maintenance costs: C_P = labor costs

Total cost until PM:

$$C(T_P) = C_f[1 - R(T_P)] + C_P R(T_P)$$

where C_f : cost of replacement after fail, C_P : cost of PM replacement

Reliability of equipment:

$$\mathrm{R}(\mathrm{T_P}) = 1 - \int_0^{T_P} f(t)dt$$

where f(t) is the probability density function of the time to failure for the component.

Average life of component:

$$L(T_P) = \int_0^{T_P} tf(t)dt + T_P R(T_P)$$

but f(t) = -dR(T)/dt, so

$$L(T_P) = -\int_0^{T_P} tdR(t) + T_P R(T_P) = -tR(t)|_0^{T_P} + \int_0^{T_P} R(t)dt + T_P R(T_P) = \int_0^{T_P} R(t)dt$$

Average cost per time unit:

$$K(T_P) = \frac{C_f[1 - R(T_P)] + C_P R(T_P)}{\int_0^{T_P} R(t)dt} = \frac{C_f - (C_f - C_P)R(T_P)}{\int_0^{T_P} R(t)dt}$$

In order to find the T_P* which minimizes $K(T_P)$, we differentiate and set equal to zero, which results to the equation:

$$\frac{f(T_P)\int_0^{T_P} R(t)dt + R^2(T_P) - R(T_P)}{f(T_P)\int_0^{T_P} R(t)dt + R^2(T_P)} = \frac{C_P}{C_f}$$

In case of increasing failure rate β>1, Barlow et al. (1960) have proved that the cost function $K(T_P)$ has 'at most' one minimum and it looks like the diagram of Figure 4.1

Assumptions:

1. Each failure is instantly detected
2. We do not take into account the time needed to conduct the repair, which could be different in case of a preventive or a failure task.
3. We assume that the equipment which is repaired or preventively maintained returns to a like-new state – which is not the case usually.

If the failure rate is non-increasing (scale parameter of Weibull, beta<0) it is apparent that the optimal replacement time is T_P*→ ∞ as the used unit tends to have a longer remaining life than its replacement unit.

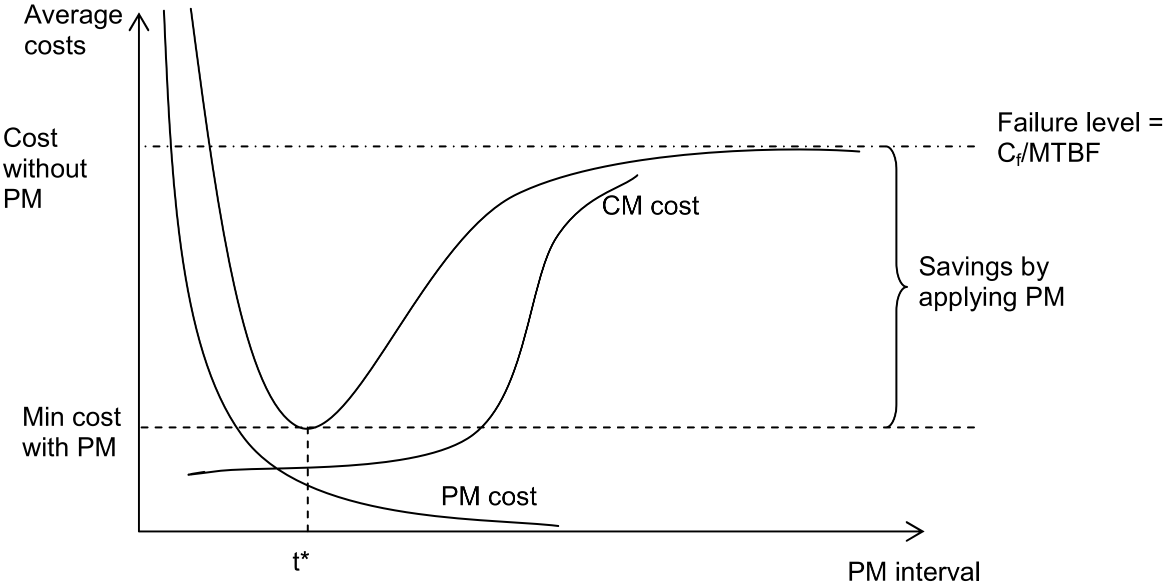


Figure 4.1: Average cost vs. PM interval (source: author)

In case we don't have enough data to estimate the Weibull scale and shape parameters, we can use an approximation for the optimal replacement time T_P*. This approximation is around 40% of the MTBF (Smeitink, Dekker, 1990) of the equipment, which we assume known, in our case from interviews with technicians and maintenance engineers.

4.4 Chapter Summary

One of the oldest but also most commonly used concepts in maintenance is the use of preventive maintenance. The quantitative methods used to optimize the application of preventive maintenance try to minimize the costs of failures and breakdown maintenance, by calculating the optimal preventive replacement time.

In order to calculate this time however, a good estimate of the equipment failure distribution and costs of preventive and failure replacement are needed. The data can be approximated by conducting interviews, if it is not easily available, and the failure distribution can be easily represented by the versatile Weibull distribution.

5. Spare Parts Inventory

5.1 Inventory control importance

In order to schedule maintenance work, it is essential to ensure that the required spare parts and materials are available. It is physically impossible and economically impractical for each spare to arrive exactly when it is needed and where it is needed. For these reasons, we keep spare parts inventories. In order to maintain the optimal level of spare parts which minimizes the total cost of holding the item in cost and the cost of an unavailable item, we use inventory control.

Inventory control is of vital importance, as investment in spares and materials is a critical cost of maintenance. With an excessive investment, we have high capital and thus maintenance costs. On the other hand, if the spare parts needed for repairing and servicing are not available, downtime costs may occur. Generally, spare parts should be stocked only if the risks involved in doing without them are considered to outweigh the total cost of keeping them in stock for a predicted amount of time (Chang et al. 2005).

Spare parts can be divided into the following categories depending on their cost and criticality characteristics (Duffuaa et al., 1998):

- Specialized parts for a limited no. of equipment
- Parts with relatively long lead times
- Parts with slow turnover
- Relatively expensive parts
- Spare parts whose unavailability cause long and expensive downtime or safety risks – also called critical

The costs involved in keeping an inventory of spare parts are, except the obvious item cost, the cost of holding the item in stock. This cost is a percentage of the items value, usually around 10-20% and is calculated taking into account the cost of space per m^2 of storage area, the cost of capital invested considering the bank interest rate and the return of a potential equivalent investment, the cost of deterioration caused by storage and finally, the cost of inflation. ECT calculates its holding cost to be 12%.

5.2 Inventory policies

The requirements for planning the logistics of spare parts differ from those of other materials in several ways: service requirements are higher as the effects of stockouts may be financially remarkable, the demand for parts may be extremely sporadic and difficult to forecast, and the prices of individual parts may be very high (Huiskonen, 2001).

The most basic inventory theory and models (such as EOQ, ABC-analysis, MRP) have been widely applied, in practice, but there is little evidence of the use of more sophisticated applications. In practice, spare part inventories are often managed by applying general inventory management principles, if any, and not enough attention is paid to control characteristics specific to spare parts only. Furthermore, the control is usually focused on local inventories and not so much on the supply chain as a whole (Huiskonen, 2001).

This is the case in ECT, with unorganized warehouse, ordering and inventory policies. The supply chain of spare parts is not optimized, with many different suppliers, scattered warehouses in and out of Delta Terminal and also a ZPMC warehouse in Amsterdam where there is almost no control.

The general approach on spare parts inventory management is based on the following steps (Braglia, 2004):

1. Criticality analysis of the spare parts based on a Failure mode and Effect analysis (FMEA). This first step reduces the problem by focusing on the critical spares only.
2. Classification of the critical parts by ABC analysis. As discussed below, this method, based on Pareto's principle is widely adopted by many firms and is used to focus on the most costly parts of the inventory.
3. The stock levels and policies are defined for the class A parts of the previous step.

It is important to note that although a spare parts inventory may hold thousands of different SKUs, only the most critical ones deserve accurate control and attention, as the study and control of all parts would consume valuable resources without the correspondent savings.

5.2.1 ABC analysis

ABC analysis is based on Pareto's law which states that, for many events, roughly 70-80% of the effects come from 20% of the causes (Chopra, 2008). It is useful to apply this method on the inventory items, in order to obtain a rough idea about the importance of each SKU (stock keeping unit) of spares and to adapt the inventory control respectively.

The analysis is made by constructing the Pareto diagram, after ranking the items in descending order of percentage of cost to the total inventory, starting from the items that contribute the most to the cost. The diagram should look like Figure 5.1 and we see three groups of products emerging. Class A items should be ordered based on Economic Order Quantity (EOQ) calculations. These items have high capital costs and thus a minimum safety stock is kept. Class B parts can be ordered as well with EOQ calculations and the safety stock can be larger. Finally, items belonging to class C are only 10% of the inventory value and thus need minimal control and safety stocks can be kept if there is available space for a large amount of time.

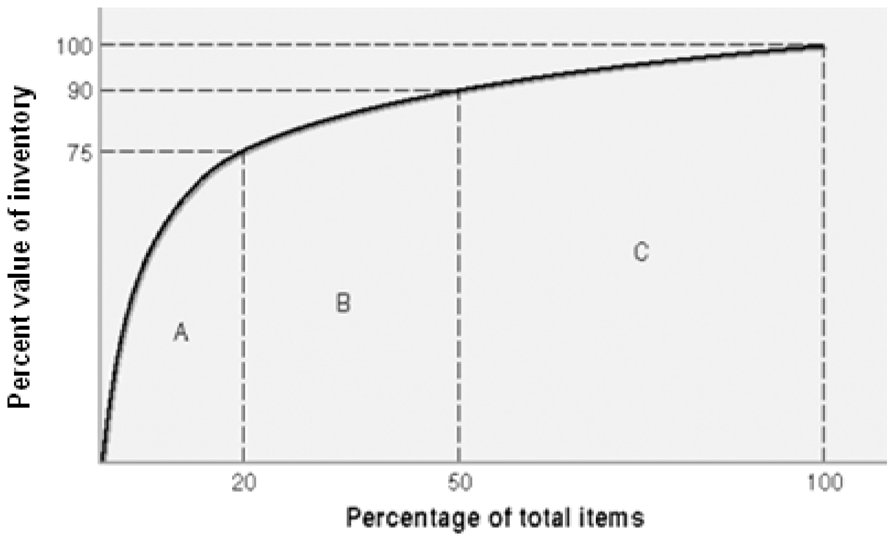


Figure 5.1: ABC analysis (source: author)

5.2.2 Reliability based spare parts policy

Using the ABC analysis, we develop inventory control policies that are based on its cost and we don't take into account the costs incurring from downtime because a part is not readily available. The demand for spare parts is triggered by scheduled maintenance (deterministic) but also by unexpected component failure (stochastic demand). To avoid downtime due to unavailability of spares, the parts needed for smooth operation for a certain length of time must be estimated. We must develop an inventory policy, so that depending on the criticality of each spare part, a different ordering strategy is implemented.

The use of several criteria besides cost is one way to classify spares in order to differentiate more the inventory policies according to each category's needs. Duchessi et al. (1988) propose a two dimensional scheme, based on cost and criticality. The classification on criticality can be made using the following criteria (Duffuaa et al. 1998):

- C_A , high criticality: Parts that are absolutely essential for the operation
- C_B, medium criticality: Parts that have a moderate effect on the operation if they are not readily available
- C_C , low criticality: Parts that are not essential for the operation of the equipment

Besides from the necessity of the spare for the operation, similar classification can be made depending on the MTTR of a potential failure that needs a certain spare, or based on the MMBF of the component.

5.3 Literature review

The literature on general inventory models is vast and cannot be covered with justice in this section. However, in this section the important models dealing with spare parts provisioning for maintenance are reviewed. Then two important models, one dealing with irreparable items and the other with repairable items are briefly stated. The emphasis is on models that link stock levels of spares and material to maintain system effectiveness.

Generally the literature in this area can be divided into two major categories:

1. Irreparable item inventory models
2. Repairable (recoverable) items inventory models

Two reviews have appeared in this area. The first review by Nahmias (1981) covering most of the work that appeared prior to 1981. He organised the review in the following manner:

- The (S-1, s) ordering policies and their importance in managing repairable items.
- The METRIC (Ben-Daya et al., 2000) model and its extensions
- Continuous review models for deterministic and random demand
- Periodic review models under random demand

5.4 Situation in ECT

5.4.1 Warehouse

The warehouse management system is not working perfectly as there are a lot of spare parts with two or more reference codes in Oracle. However, harmonization takes place now and in about a year the system is expected to be working correctly. Also, ECT used SAP before the take-over from HPH, and then had to change to Oracle, a transition which created many problems.

There is also now an ongoing process to use a barcode on all items in the inventory so that the organization can become easier and the checking in & out easier. Plans for the future include the use of RFID tags which would make the allocation of items much more effective and would overcome certain problems such as removing an item by a technician without registering it in the system.

5.4.2 Inventory Policy

Some very expensive and less critical parts are kept in inventory by the supplier (ZMPC) in a warehouse in Amsterdam. This warehouse was created by ZPMC in order to achieve better lead times, as the usual lead time for a spare part coming from China is 4-5 months. The contract states that ECT sets the safety stock for each SKU and in case any spare part is needed from that warehouse, it needs to be delivered within 24 hours. ECT can save on capital costs that way, since it buys the part only when needed and pays only the inventory costs to ZPMC which are set to 10% of the parts value annually. However, this system has shown weaknesses in the past, as the 24 hour limit is rarely satisfied and there have been problems with the stock replenishment. Furthermore, there is no control over the inventory's state by ECT, as some sensitive components (e.g. gearboxes) need to be maintained even out of operation, in the inventory and there is no guarantee that ZPMC does the necessary actions to keep the equipment in perfect shape. Some spare parts have a limited effective period of storage because of lubrication needs or sensitive synthetic parts. These SKUs should be examined regularly and be maintained or thrown away.

The technical specialists are the ones who create the inventory list when a new crane is delivered and they set the safety stock levels. As the crane is working and different failure modes appear, the ss levels are adjusted.

For some expensive equipment that is also repairable (as is the case most of the time), there is a "pool" of spare parts to be shared between cranes of same type. So for example for the three ZP1 cranes, there is one extra spare which is used in case of a breakdown and its place is taken by the overhauled part that broke down.

5.4.3 Repairables

Most of the items in the warehouse are considered repairables, and a few are used only once. Repairables are parts that after a breakdown they are replaced by another one and they are sent to the supplier to be repaired. There are a few cases where the repair is done in-house but only when the technicians have time for a small repair work. There are also cases where some parts are sent to the supplier for preventive maintenance-at time intervals instructed by the technical specialists. The supplier however cannot guarantee a specific time to repair, thus like a lead time, the time to replenish the stock is not certain. One assumption made involuntarily is that the items are "as new" after the repair and there is no deterioration, which maybe the case for electronics but is of course wrong for most mechanical and electrical equipment. Even if deterioration would be considered though, there is no distinction between items of the same pool, making impossible to notice the spare parts that have a problematic reliability. Under the pressure of the maintenance department, an effort is being made to supply each item with a specific code that will allow tracking the history of repairs and probably spotting some reoccurring failures. During the overhaul, all failed parts are removed and sent to a repair shop, from which they eventually return to the maintenance center to be used again as spares. The total number of spares undergoing repair and on hand is a constant.

5.5 Optimal inventory policy

In every warehouse and especially in a spare parts warehouse, optimal inventory policies should be followed, so that costs from unused inventory or costs incurred from lacking a specific part when needed are minimized. Spare parts needed for maintenance have generally a stochastic demand, depending on the failure distribution of the equipment. Thus, determination of the optimal stock level and ordering policy for each part can be made with several methods, such as using the newsboy cost optimization model, with the downtime costs as the respective cost and the same overstocking costs of inventory holding.

In our case though, we can use the preventive maintenance policy to our gain, in order to develop a simple optimal inventory policy. Since the PM age replacement model will provide us with a specific replacement time for each part, we can accept that the demand for spare parts will become deterministic. By having a deterministic demand, we reduce greatly the complexity of the inventory policies and among other benefits, the warehouse will be able to work much more easily on the simple policy together with the maintenance department.

5.5.1 EOQ model

A model we can use in case of deterministic demand is the Economic Order Quantity (EOQ) model, which minimizes the cost of inventory by taking into account, the fixed ordering costs, the holding costs and of course the material costs.

The assumptions of the EOQ model are:

1. The demand is uniform and known.
2. The item cost does not vary with order size (thus, there are no quantity discounts).
3. Complete orders are delivered at the same time
4. Lead time is known, so that inventory can be replenished in time.
5. The cost of ordering is fixed, and not relevant to the order size.
6. The cost of holding inventory is a linear function of the number of items in stock.

The model minimizes the following cost function:

$$TC = CD + \frac{SD}{Q} + \frac{hCQ}{2}$$

where

- TC is total annual cost
- C is material cost

- D is annual demand
- S is fixed ordering cost
- Q is quantity ordered
- h is the capital cost, as percentage of the items value

In order to minimize TC, we take the partial derivatives of TC to Q, we set equal to zero and solve for Q. The result is the optimal quantity to be ordered:

$$EOQ = \sqrt{\frac{2DS}{hC}} \quad (2)$$

5.5.2 MRP

In the case where all the characteristics of demand are known, thus size and specific time, we can use the material requirements model (MRP). The MRP model has a production planning perspective and not so much an optimization target. It is better used for cases of intermittent demand and not for fixed lot size The data needed in order to implement MRP, we need to have available the following data:

- part lead time which is the estimate of time needed to repair the repairable items, or the time needed to receive a new part from the supplier, from the moment of order
- a possible minimum order quantity, set by the supplier
- the current inventory level
- other components needed in order to use a part, often referred to as Bill of materials (BOM)

The decision for ordering is very simple: If a product is needed on $t=T_d$, the order is being made on $t=T_d - L$, where L is the leadtime for this product.

The benefits of MRP are that we have increased inventory visibility, lower stockouts, lower inventory levels and is easy to implement if the data is there. However, it does not address the lot size problem, cannot deal with uncertainty, does not explicitly take costs into account, assumes constant lead times and requires big amounts of data which is difficult to get.

5.5.3 The (S-1, S) model

The (S-1, S) inventory model is a special case of the (s,S) model, where s equals S-1. In the (s,S) model, the policy is to check continuously the inventory level and when it falls to or below s, we order to replenish up to level S. Thus, the (S-1, S) model places one-for-one replenishment orders upon each demand occurence, restoring the initial S inventory level.

This inventory model is especially appropriate when the item has low demand and a relatively high unit cost, compared to the cost of ordering, and the repairable parts that do not apply for PM fit right into this category. However, by using a cost-based approach we can implement this model for other items with higher consumption rates. The optimal model has been studied by many for repairable items (Nahmias, 1981), and the demand distribution usually used is Poisson (see Kang, 1987).

In order to find the optimal S level, we need to determine the demand during the lead time L. The assumptions we make are that:

- The operating time of the equipment has no influence on the number of failures

- The consumed parts before the generated demand time, have no influence on the number of failures in the future.

The decision on the optimal base stock levels is based upon two cost factors; the holding cost and the downtime (or penalty) cost. The holding costs are the costs of keeping the items in inventory until needed. The downtime costs are the costs created by not having available an item because the items needed at a certain point are greater than the items on stock. The chance that such a situation occurs is the possibility of a demand equal or greater than S during the lead time L.

According to Olthof (1994), we can use a simple decision rule according to a part's characteristics in order to determine if it is economical to stock and use (S-1, S) model or not to keep stock at all. The part should be stocked if:

CsI + PrI + PenI + LtI > 0 (3)

In formula (5) each factor CsI, PrI, PenI and LtI is an index for ………,ranging as shown in tables 5.1 -5.4.

Table 5.1: CsI

Consumption Rate (per year)	CsI
6-12 per year	4
3-6 per year	3
1.5-3 per year	2
1 per 8-15 months	1
1 per 15 -30 months	0
1 per 2.5-5 years	-1
1 per 5-10 years	-2
1 per 10-20 years	-3
Less than1 per 20 years	-4

Table 5.2: PrI

Purchase costs (in €)	PrI
250-5000	5
500-1.000	4
1.000-2.000	3
2.000-4.000	2
4.000-8.000	1
8.000-15.000	0
15.000-30.000	-1
30.000-65.000	-2
65.000-125.000	-3
>125.000	-4

Table 5.3: LtI

Leadtime	LtI
No leadtime	-10
0.5-1.5 days	-2
1.5-3 days	-1
3-6 days	0
6-12 days	1
1.5-3 weeks	2
3-6 weeks	3
1.5-3 months	4
3-6 months	5
6-12 months	6

Table 5.4: PenI

Penalty costs (in €/day)	PenI
100-250	-3
250-5000	-2
500-1.000	-1
1.000-2.000	0
2.000-4.000	1
4.000-7.500	2
7.500-15.000	3
15.000-30.000	4
30.000-60.000	5

Olthof (1994) proposes a model which minimizes average yearly costs of holding and downtime (penalty) as described above. The proposed approximation of demand (or ConsumptionRate, CR) distribution is the exponential distribution, which means that we have Poisson created demand. The total cost is calculated as:

$TC = Holding\ costs + Penalty\ costs =$

$$= 0{,}25(PurchaseCosts)\sum_{m=0}^{S}(S-m)p_m + (ConsumptionRate)(PenaltyCosts)(Leadtime)\sum_{m=S}^{\infty}\frac{(m-S+1)}{(m+1)}p_m \quad (4)$$

Where:
S = the stock level
p_m = average time probability

The probability of no consumption during leadtime is:

$$p_0 = e^{-CR\cdot L} \quad (5)$$

If p_0 <1, it means that a stockout will occur and that we might need to have S>0. In order to decide, we must and calculate the TC for various values of S starting from S=0, and choose the S value that minimizes the TC.

5.5.4 Pitfalls of this approach

Of course we should note that the effectiveness of using the PM replacement age to identify demand for spare parts applies only for parts with an increasing failure rate, as discussed in chapter 4 earlier. For parts with constant or for the rarer, decreasing failure rate items, the demand continues to be stochastic, following the exponential distribution for the first case. Also, in effect it is obvious that the method proposed does not eliminate uncertainty, as the failure rate of the equipment is still stochastic. However, we are able to minimize it, depending on how conservative our choice for PM time is.

5.6 Chapter Summary

The inventory in every company should be optimized, in order to keep the holding and backorder costs balanced and low. Even more in a service providing industry like a container terminal, the cost of not have available a spare part when needed can be catastrophic, so the usual practice of the relevant department is to keep in stock more than needed, rising the holding costs.

However, the connection of maintenance scheduling with the spare parts inventory can reduce the total costs, by keeping the correct stock for the different parts, based on criticality.

The various criticality classes of parts can be treated with different inventory models like with MRP, EOQ and (S-1, S) models, yielding the maximum benefit to the company.

6. Data acquisition and analysis and equipment classification

In every research project, the acquisition and analysis of data is one of the most important and time consuming parts. In our case, the data available was complicated to acquire and being in Dutch, was even more difficult for the author to analyze it. Also the lack of a uniform method of input meant that a lot of information was lost in the system. Thus, as described below, in order to get the data for specific equipment, the method of data acquisition through interviews was used.

Furthermore, the enormous number of different spare parts on the ZP1 quay cranes only, meant that a study of all of them is not feasible. A method of criticality classification is proposed, so that attention can be given to the most important parts, according to cost criteria.

6.1 Data collection

The data available in ECT's ERP software system, Oracle, includes information about the breakdown and corrective work orders concerning major systems and not specific components. This means that in order to identify the failure data for specific components, a different approach must be taken, as shown below.

6.2 Connection with RCM

Part of the RCM process is to identify the different components on out equipment and specify their function. In an attempt to get a better understanding and also to help the classification of the different components, a breakdown of the structure of the ZP1 cranes has been made into major systems. The logic of the breakdown was created with the help of the ZPMC manual for the cranes and through interviews with the technical specialists who noted the important systems on the crane. The major systems on the crane and their function are identified in Table 6.1:

Table 6.1: ZP1 Structure Breakdown (source: author)

System	Function
Structure	To act as main support and support all crane systems
Boom hoisting	To lower or raise boom
Main hoisting	To get/put and lower/raise containers
Main trolley traveling	To move main trolley
Catenary trolley revving	To prevent sagging of wire ropes of main hoisting and trolley traveling
Gantry traveling	To move crane on rails
Controlling, Electronics	To control crane
Supplying electrical power	To supply electrical power
Supplying hydraulic power	To supply hydraulic power
Miscellaneous systems	To provide miscellaneous functions

The complete breakdown, in two lower levels and the coding proposed is shown in Appendix 1. The breakdown can be further enhanced by moving to lower levels on the structure of equipment, up to specific components. However that much detail is out of the scope of this thesis. The current breakdown into main systems was used to identify the critical systems and on these get into more into detail, identifying their critical components. Furthermore, the structure breakdown and coding is very helpful if integrated in the ERP of the company (Oracle in the ECT case), as it can minimize the input errors, and make the data retrieval - which is the "Achilles' heel" in most companies - much easier and more reliable.

6.3 Method

The collection of data for ZP1 cranes since the beginning of Oracle implementation, in 2004, gave the results shown in Figure 6.1. The data is censored, with irrelevant information mostly about spreaders missing.

Since each major system consists of almost the same sub-components (see Appendix 1), we choose to study the three systems with the most work orders. For the components of these systems we do a criticality classification which is analyzed below and we choose the two most critical parts to study on their potential for preventive maintenance.

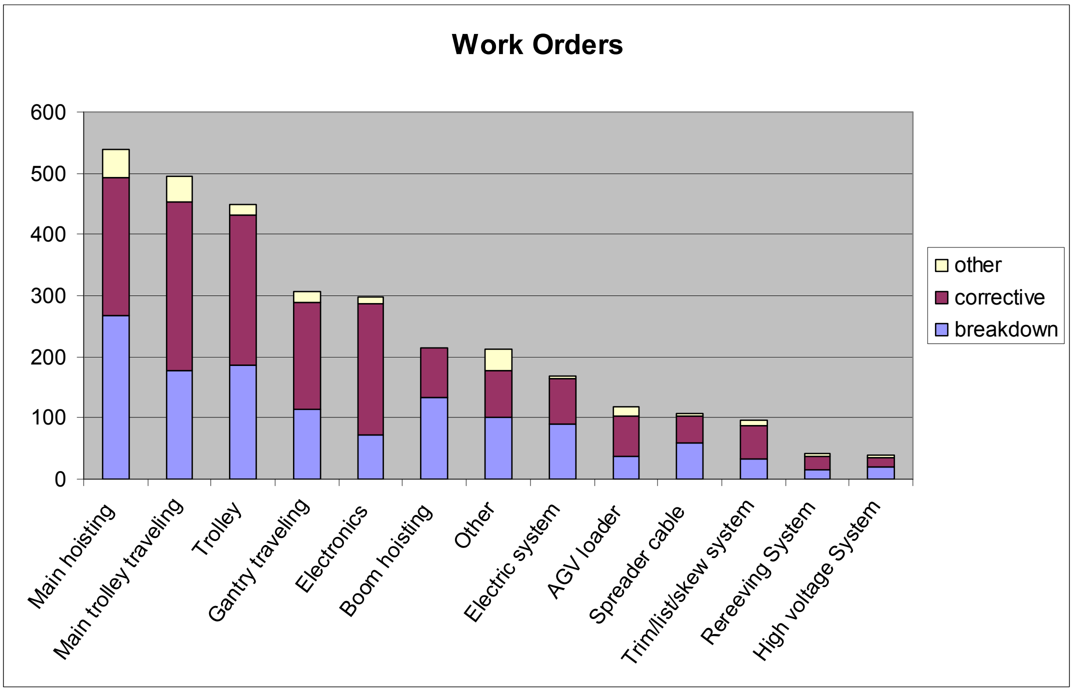


Figure 6.1: Historical data of Work orders per system (source: author)

Corrective work orders are issued after an inspection or a scheduled preventive maintenance work, whereas breakdown orders are issued after an unexpected failure of equipment.

We can clearly see in Figure 6.1 that Main hoisting, Main Trolley traveling and Trolley are the systems with the most failures out of the sixteen registered. Their cumulative percentage as shown in Figure 6.2 below, reach almost 50% of the work orders issued over the last 5 years for the ZP1 cranes. Thus, our study will be focused on these systems and the sub-systems and components that they include.

Also, the reader can notice some systems that are not part of the crane breakdown created by the author. The reason is that Oracle does not have the systems in its database, but the distinction depends on the goodwill of the user that inputs the data. Thus, there are some systems like the AGV loader and the spreader cable that are not considered formally part of the quay crane. Also, some of the systems with fewer work orders are part of other greater systems, like electrical or miscellaneous in our breakdown.

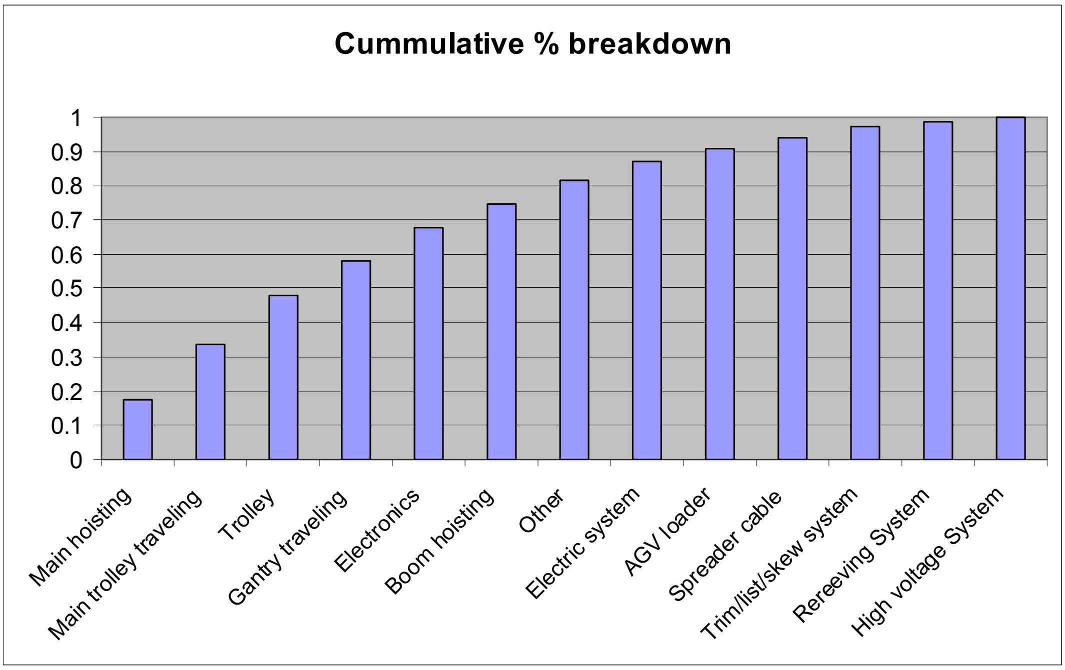


Figure 6.2: Cumulative percentage of work orders (source: author)

6.4 Classification

The classification of spare parts is essential for every company which keeps inventory, as discussed in chapter 5, in order to save time from dealing with unimportant parts. The measure of importance or criticality for each part can be made with many ways, from the simple one or two-dimensional matrices, to multi-attribute weighted calculations. In our case we chose to create a multi-attribute model which quantifies the criticality of each part, by calculating an approximation to the average yearly costs this item would create to the company, based on its reliability.

We assume that the costs incurred by an item are the downtime costs in case of failure and the HSE impact costs. In total we look at 5 attributes (HSE Impact, Operational impact, Occurrence Interval, Repair time, Lead time) of each item, out of which we calculate the average cost through a mathematical formula. The levels for each attributes are chosen to be three, the minimal found in literature (Braglia et al., 2001). This was decided, as a larger number of levels would create a huge number of different outcomes that would be difficult to calculate and handle. Also, the detail in levels would also need to be completed with more final criticality classes, which in our case was not needed as we are trying to spot the most critical parts only as a first step that could be expanded later easily. The resulting total different outcomes for yearly average costs are: $3^5=243$. In order to create an easier way to distinguish between the many different combinations of attributes, we created a decision tree diagram.

The diagram, a sample of which is show in Appendix 2, can calculate the average cost for each spare part, based on a series of steps which depend on plant criticality, time to repair, number of concurrencies and delivery lead time. The classes for each criterion are shown in Tables 6.2-6.6 below. The three possible outcomes for each criterion are High (H), Medium (M) and Low (L).

Table 6.2: HSE Matrix

HSE impact	High	Medium	Low
	100000	10000	1000

Table 6.3: Operational impact

Operational impact	Stoppage	Partial/limited speed	No direct effect
	2474/h	1237/h	0/h

Table 6.4: Occurrence Interval classes

Interval (years)	<2	2-9	>9
	H	M	L
Class multiplier (years)	2	5	10

Table 6.5: Repair time classes

Time to Repair (Hours), with available part	<0.5	0.5-4	>4
	L	M	H
Class multiplier (hours)	0	2	24

Table 6.6: Lead time classes

Part Lead Time (days)	<0.5	0.5-5	>5
	L	M	H
Class multiplier (hours)	1	48	192

As in the RCM approach (Eisinger, Rakowsky, 2001), many different decision diagrams can be potentially proposed for use in spare parts classification. In this paper, a particular decision diagram developed for ECT is presented. The five different attributes considered have been chosen based on interviews with the maintenance engineers and management and based on criteria proposed in academic papers with similar objectives (Braglia et al., 2001). Appendix 2 shows the decision tree developed. The classification of each part is made according to the total average cost incurred through the different nodes, with a method discussed later.

For each criterion the classes, the costs attributed and the reasoning behind them are:

- Health Safety Environment (HSE) impact (Table 6.2): The three classes High, Medium, Low are created based on the severity of a safety or environmental accident. The costs are: H:100000€, M:10000€, L:1000€
- Operational impact (Table 6.3): The three classes are descriptive of the severity of the impact. The costs are for stoppage: 2474€/hour, for limited speed: 1237€/hour and for no direct impact we have no cost/hour.
- Frequency of occurrences (Table 6.4): The three classes were created based on historical data and interviews with technicians, so that they can depict correctly 3 distinct classes of item failures.
- Time to repair (Table 6.5): failures with repair times under 0.5 hour are considered by ECT as not important thus, they constitute the first class.

The second class is up to one shift's time needed and the third over one shift's time.

- Part Lead Time (Table 6.6): the first class of less than a day is intended for items that are available in ZMPC's warehouse in Amsterdam, where ECT has a contract with ZPMC to keep expensive components available within 24 hours. The second is for common lead time of most parts that arrive within 5 working days and the third class is for parts that need longer time to be shipped.

6.4.1 Cost Breakdown and Justification

The costs for operational impact in case of a breakdown - or downtime costs were given by ECT, based on their calculations of the costs arising when a QC is not available. The costs arising are operational costs, estimated at 150€/h, demurrage costs set at 1600€/h and Maintenance and Repair (M&R) costs estimated at 724€/h, which totals to 2474€/h. We can see that the biggest impact on downtime costs is made from the demurrage costs, which is logical since the costs of delaying a container ship that has to follow a strict schedule can be enormous.

In the case of HSE impact, the numbers are chosen arbitrarily, with a very big number (100000€) given to the biggest impact and decreasing 10 times for each lower class of impact. ECT has not calculated approximations of costs for HSE incidents yet, so in case of further study, the numbers can become more precise.

6.4.2 Classification mathematical model

In order to quantify the cost impact of each branch of the decision tree, we use the following formula (6):

$$\textbf{Total average cost} = \frac{\left\{\left[\textbf{Terminal Impact}\left(\frac{\textbf{€}}{\textbf{h}}\right) * \textbf{Time to repair (h)} + \textbf{Terminal Impact}\left(\frac{\textbf{€}}{\textbf{h}}\right) * \textbf{Lead time (h)}\right] + \textbf{HSE Impact (€)}\right\}}{\textbf{Occurrence interval (years)}} \quad \textbf{(6)}$$

For each criterion, the center of its respective class is used, and in case of open classes, a significant small or large number, so that clearer distinction between classes can be made (see "class multiplier" in Tables 6.2-6.6).

The results are sorted in the four following classes from A to D with descending average cost, and thus criticality:

Table 6.7: Criticality classes

Cost Range(€)	>80.000	30.000-80.000	<30.000
Criticality	A	B	C

One example of calculation of a part that belongs to class B would be: a part with low HSE impact of €1000, slowing down of operations, meaning cost of €1237/h, high lead time of over 5 days, high repair time of over 4 hours and an occurrence interval between 2-9 years. Through formula (6) and using the multipliers for each class as shown in Tables 6.2-6.6, we get the average yearly cost of €53.638 which belongs in class B (€30-80.000). The average yearly costs calculated from the model are an indication of the average cost of these items, and not the real average costs, as we use classes to separate the parts into three major categories of importance.

6.4.1 Further detail

Of course this model of decision tree is one of the simplest that could be created with only 5 attributes. Moreover, the final criticality classes could be more than four. However, further detail in criteria would exponentially increase the size of the decision tree and would be outside the scope of this thesis. Potential attributes that could be also considered are:

- Detail in HSE impact – division in internal (human safety) external (environmental) criteria.
- Cannibalism
- Number of potential suppliers
- Possibility of internal repair
- Space required to store
- Deterioration problems
- Redundancy
- ..etc

The consideration of some of the above would greatly increase the value of the decision tree. However the quantification of the cost/gain involved with each one would be very complex and maybe couldn't work with the proposed mathematical model.

6.5 Results of classification

After conducting the above analysis on classification of spare parts and interviews with technical specialists on ECT, the following parts on a crane, from the important system with the most failures were rated as type A (critical):

- Electrical motors
- Gearboxes
- Air condition units of machine housing
- Spreader electric Cables

These parts are similar in each system, so no distinction is needed and they should be treated the same on all three critical systems. Also in most systems of the crane where they appear, they should follow the same proposed PM policy, as their construction and operating characteristics vary only slightly, and thus the failure distributions they follow can be considered the same. Only in the case of gantry traveling system, the motors have a certain degree of overcapacity, so their criticality is not as high. Also we show the results of a spare part that belongs to class B (Plastic drums of boom hoisting), so that we can study its maintenance and inventory policies in the next chapter.

Electric motors

HSE impact	10000€/occurrence
Operational impact	2474€/h
Time to repair	0.5-4 hours
Lead time	0.5-5 days
Occurrence interval	<2 years
Average cost/year	€100.000

A failure in electric motors can be caused by many different factors, but the result would be the halting of their operation. A fault in the stator winding or the bearings are the most frequent causes, which results in other damage in the motor and a time consuming overhaul is needed.

The electric motors have an average HSE impact, as their failure can cause at worst the inability of the boom to lift. Failure during movement is not serious as there are automatic brakes that prevent any unwanted motion. Also their operational impact is very high, as they cause the full stoppage of the crane. Their repair time is also high (1 day) as they are complex equipment and very difficult to move in and out of the crane. The lead time is considered as the average time needed to be overhauled, as the electric motors are repairables and not replaceable. The failed motor is sent to the supplier in Rotterdam and it is returned after repair. The respective lead time is high, as the supplier is located close by, but the transfer is difficult. Finally, the interval of occurrences is estimated through interviews with experts to be medium (every 9 years).

Gearboxes

HSE impact	10000€/occurrence
Operational impact	2474€/h
Time to repair	>4 hours
Lead time	>5 days
Occurrence interval	2-9 years
Average cost/year	€100.000

With gearbox failure we mean the inability of the gearbox to transfer power to the shaft. The cause is in most cases the destruction of gear teeth but also the bearing failure. In the first case, the damage is very big and a complete overhaul is required.

The gearboxes have as the motors an average HSE impact, as the automatic brakes act as a backup in case of emergency, after a gearbox failure. Their operational impact is very high, as they cause the full stoppage of the crane. Their repair time is high because of their complexity and size. Gearboxes are also repairable items, and the lead time – the time needed to send and receive from a Dutch supplier- is high. The interval of occurrences is estimated to be medium (every 8 years).

Air-conditioning units of machinery house

HSE impact	10000€/occurrence
Operational impact	2474€/h
Time to repair	>4 hours
Lead time	>5 days
Occurrence interval	≤2 years
Average cost/year	€240.000

A failure of air-conditioning units we mean the inability of the unit to maintain the low temperature required. The most common cause of failure is the A/C compression damage, which causes leakage and the replacement is often the only solution.

The air conditioning units are of critical operational importance to the crane, as their breakdown stops the crane's electronic systems to protect them from overheating. The HSE impact is medium, as it can cause mild failures to the motors and subsequently to the safety of the operators. Their repair time is about 4 hours, considered medium and the lead time is high, with up to 1 month needed for a replacement to arrive. The estimation of the interval between occurrences is also high, about 2 years.

Spreader Electric Cable

HSE impact	100000€/occurrence
Operational impact	2474€/h
Time to repair	0.5-4 hours
Lead time	0.5-5 days
Occurrence interval	≤2 years
Average cost/year	€120.000

Although the spreader cable has redundant cables, in order to withstand damage, the failure rate is very high in the ZP1 cranes. The cause of failure is the damage to the cable by wear and tear and a replacement is necessary.

The spreader cable is the cable that provides power to the hydraulic systems of the spreader and connects it to the crane. This cable has a high HSE impact as a failure may cause the spreader to release a container it is carrying with catastrophic results. The operational impact is of course high causing the stoppage of the operation. The repair time is medium at almost 4 hours and the lead time is medium with almost a day needed for a replacement to be delivered. Finally, the interval between occurrences is high, estimated at about 2 years.

Plastic drums of boom hoisting

HSE impact	1000€/occurrence
Operational impact	1237€/h
Time to repair	0.5-4 hours
Lead time	0.5-5 days
Occurrence interval	≤2 years
Average cost/year	€30.000 (Class B)

The plastic drums of the boom protect the joints where the wires are in contact with the crane, without a bearing. These parts fail when the friction of the wire causes them to break and let contact between the metal parts of the crane and the metal wires.

Their HSE impact is low, as no important consequence to safety occurs. Their operational impact is medium, as the crane can continue operation, but with limited speed in order to avoid damage because of metal friction. The repair time is medium, with a crane stoppage needed of about 2 hours. Their lead time is medium with almost 3 days needed for a replacement to arrive. Finally, the occurrence interval is high, estimated at about 0.5 years.

The four parts which are classified as critical (class A) are consequently of great importance for the operation of the terminal, and their maintenance and inventory policies should be studied closely by the management. The plastic drums belong to class B, and should be studied with lower priority.

6.6 Chapter summary

Data collection is the most important and sometimes complicated part of a research project. In our case the data on ECT's Oracle software were used in order to identify the systems with the most failures and the information about specific spare parts were acquired through interviews with technical specialists.

In order to avoid the study of unimportant spare parts and to facilitate the managements work, a classification of spare parts is proposed. The classification of equipment into three criticality classes is made through a mathematical model which calculates an estimation of their yearly average cost based on five important attributes. From the results 4 different parts which belong to class A and one belonging to class B are chosen and analyzed.

7. PM and inventory optimization results

7.1 Data collection

In order to decide on whether we will use preventive maintenance or not for a certain part, we need to know several things. We need to know its cost ratio of corrective to preventive maintenance and its type of failure rate, as discussed in chapter 4. The cost of corrective maintenance is the cost of letting the equipment run to failure, thus the occurring downtime cost. This cost can be calculated using a differentiation formula (6) about average cost/year in chapter 6, by multiplying the downtime costs with the repair time needed and adding the labor cost. The cost of preventive maintenance is just the labor cost, since we avoid the downtime and the replacement or overhaul is made in a scheduled downtime of operations. However, for some repairable components, the cost of repairing in case of a breakdown is escalated, as the damage made cannot be restored by a simple overhaul, and the part needs to be replaced. This cost difference makes the use of preventive maintenance even more mandatory, as we will see later on this chapter.

The form of failure rate, whether it is constant, increasing or decreasing can be easily found by analyzing historical data and plotting to find the Weibull scale parameter β. This parameter, as discussed in chapter 4, when being over 1 indicates increasing failure rate, equal to 1 indicates constant and less than 1 means that the component has a decreasing failure rate. The case we are interested in is only for equipment with increasing failure rate, which is sensible to follow an age replacement policy.

However, as in most actual cases, in ECT the historical data was not complete and reliable, so a different method had to be found in order to make at least an estimation of the parameter β. The method followed was the conduction of interviews with the expert personnel of ECT that has knowledge for the crane components. Specifically, technical experts, job engineers and maintenance engineers were interviewed.

Since the concept of failure rate and even more the beta parameter of the Weibull distribution are difficult and the technical personnel could not give information about it, the following questions were made:

- How often is an unexpected breakdown for this type of equipment observed?
- If the component is replaced by a new one, or is overhauled, will the failure be observed at a later time, or the chances remain the same for a breakdown? If the former is true, how much later will it be observed?

The first question is useful in giving us an insight about the MMBF of the component. The second question can determine whether a component has a constant or an increasing failure rate. If the answer is that the chances for a breakdown remain the same, then the failure rate is constant and random and the PM policy is not worth implementing. Otherwise, the rate has an increasing rate and the beta can be approximated by the answer to the second part of the question.

7.2 Decision process

In short, supposing that we have the necessary information about a part, the decision on whether to implement PM or not depends on the cost ratio and the characteristics of the failure rate of the part (β parameter of Weibull distribution). If the part has a cost of corrective to preventive ratio $C_f/C_p \geq 4$ and a $\beta \geq 2$, we can accept that PM will be cost-effective with a reasonable benefit and according to Smeitink and Dekker (1990) the optimal replacement time will be approximately 60% of the MTBF. If we have lower cost ratios, the optimal replacement time will increase towards MTBF and respectively with higher cost ratios the t* would be a lower percentage of MTBF. The basic suggestions for PM decision are shown in Table 7.1 and for further justification of the levels selected the reader can refer to Smeitink and Dekker (1990).

Table 7.1: PM decision process (partial source: Smeitink and Dekker, 1990)

C_f/C_P ratio	β parameter	PM decision (yes/no)	t*/MTBF
-	<2	no	1
≤4	-	no	1
4-5	≥2	yes	0.6
5-10	≥2	yes	0.5
10-20	≥2	yes	0.35
≥20	≥2	yes	0.25

The beneficial effect of PM can be shown mathematically as follows. With the implementation of preventive maintenance, MTBF - or else the failure interval increases. By using (6), we can see immediately that as the larger occurrence interval is dividing the cost, the average yearly cost of a component would be reduced greatly. Since this method does not deal with actual numbers of the failure distributions but approximations, we can say that the PM policies will not be optimal, yielding the minimum cost. They will, however, reduce the down time costs, as it is obvious from Figure 4.1 which shows the average cost plotted against the PM replacement time.

7.3 Preventive Maintenance Results

Since the equipment under review which belong to the A criticality class are mechanical equipment, it was expected that they had an increasing failure rate, and the interviews with the technical experts revealed that. Using the method described above, we managed to collect the necessary data for the four critical components studied in the previous chapter and the results recorded are shown below:

Electric Motors

The electric motors controlling the main systems of the crane are 4 in each crane and cost €40-50.000 each. In the case of motors, the scheduled overhaul cost is the C_P cost, reaches €14.000 and the downtime cost per failure C_f is 2474€/h*24h = €59.376. The cost ratio C_f/C_p is about 4 and the shape parameter β is over 2, which makes it an ideal candidate to apply the age replacement model. The choice of replacement time is chosen as t*=60% of MTBF = 4.5 years.

Gearboxes

The gearboxes are three on each crane, coupled to the main hoist, boom hoist and trolley traveling systems and cost from €100-150.000, being among the most expensive spares in ECT. In the case of gearboxes, the cost ratio C_f/C_p is about 5 and the shape parameter β is over 2, which makes it an ideal candidate to apply the age replacement model. The choice of replacement time is chosen as t*=50% of MTBF = 4 years. This result is consistent with the instructions given by ZPMC in the gearbox manual, which recommends an overhaul every 3-5 years.

Air-conditioning units of machinery house

The air-conditioning units keep the temperature below a certain level in the electronics room of the machine housing. There are two big air-conditioning systems on each crane and they cost about €20.000. For air conditioning units, the preventive cost C_p is around €2500 and the failure cost is 4h*2474€/h = 9896. With a cost ratio of about 5 and a shape parameter *beta* of over 2, the optimal replacement time is calculated as 50% of MTBF ≈ 1 year.

Spreader Electric Cable

The spreader cable is one on each crane and costs €10.000. The preventive cost C_P is €2500 and the breakdown cost is 5h*2474€/h = €12370. With a cost ratio of about 5, and an increasing failure rate distribution with *beta* of over 2, the preventive replacement time is estimated at 50% of MTBF ≈ 1 year.

Plastic drums of boom hoisting

The plastic drums are three on each crane and cost €200 each. These parts, after interviews with the technical experts for cranes, are estimated to have a constant failure rate, meaning that $\beta \approx 1$. So according to our decision model for PM, no matter what the cost C_f/C_p ratio is, it is not economical to use PM for these spare parts, but we should let them run to failure. In practice though, in order to avoid unexpected downtime, the operators and technicians can notice when these plastic drums have deteriorated enough and are close to failure, so they can be replaced during the next scheduled inspection.

7.4 Inventory Management

7.4.1 Parts under PM

For parts that are decided to follow a preventive maintenance policy, the proposed inventory policy is using MRP. This simple inventory model needs as input the demand and lead time for each part and can be implemented easily by ordering the part, specifically to arrive on the time needed for the replacement.

This method results in holding zero inventories, however, it is advised for such critical components to keep at least one of each in inventory. Since there is always a small possibility of a breakdown before the PM time, one part of each can be held in inventory at all times, with the minimal cost, minimizing the possibilities of downtime. As seen below, for repairable items that are common between cranes, we can have only one spare available as a replacement for all the similar parts.

Motors and Gearboxes

The inventory policy for motors and gearboxes can be easily identified now that we have the replacement time. As described in chapter 5 the best model to use is the MRP model, so that we can make sure that there is an available part at the time of each replacement. As the inventory motors and other repairables are pooled and interchanged between cranes that are used (in our case the three ZP1 cranes), the inventory can be holding only one motor at any time, which is the overhauled motor of the last replacement. By spreading out the replacement times on each crane and with the cooperation of the operations department, we can avoid having more than one part in inventory, thus saving huge holding costs, considering the capital cost of these parts.

Air-conditioning units and spreader cables

These parts are replaceable, so a different approach than above is needed. There will not be one part that can be overhauled and interchanged, but rather we have to order a new one for each replacement. Since we still have a fixed demand, we can use an MRP policy, diminishing the inventory holding costs.

An example of implementing the MRP model on the inventory management of one A/C unit is described below. Supposing that the scheduled PM replacement time is set for 2010 june, and consequently as the PM time is 1 year, for every month June thereafter, we will place our order on $t=T_d - L$ = May, as L = 1 month for the case of A/C units. The MRP scheduling is made on a Table 7.2:

Table 7.2: MRP scheduling for A/C unit

ITEM	MONTH	04/2010	05/2010	06/2010	07/2010	…	04/2011	05/2011	06/2011	07/2011
A/C unit	Required	0	0	1	0	0	0	0	1	0
	On-Hand	0	0	1	0	0	0	0	1	0
	Order	0	1	0	0	0	0	1	0	0

7.4.2 Parts under traditional maintenance policies

For spare parts of classes A and B that do not qualify for PM, we can use the (S-1, S) model, which is used very often in spare parts inventory management (Olthof, 1994). For the rest of parts that belong in class C of criticality, we can apply the simple EOQ model using demand forecasted from historical data and/or the instructions of the manufacturer for their maintenance.

Below is an example of an application of the (S-1, S) model on the inventory of the plastic drums which belong to class B of criticality, as shown in the previous chapter, and do not qualify for preventive maintenance. The method used is explained in chapter 5.

Plastic drums of boom hoisting

Consumption rate	2 per year * 2 on each crane * 3 ZP1 cranes = 12 per year
Leadtime	3 days = 0,0082 years
Purchase costs	200€
Penalty costs	1274€/h = 30.000€/day = 11.160.240€/year

Using equation (5) of chapter 5, we calculate:

$$p_0 = e^{-CR \cdot L} = e^{-0{,}0984} = 0{,}906$$

which means that the probability of having appearance of demand during leadtime is very low. However, by using equation (3) and Tables 5.1 – 5.4, we find out that:
CsI + PrI + PenI + LtI = 4 + 5 + 4 – 1 = 12 > 0, so the decision is to stock this item. In order to find out the optimal S level, we calculate the formula (4) for various S levels starting from S=0. As discussed in chapter 5, the total cost (TC) calculated is the average yearly cost of this inventory policy for items with a demand following the exponential distribution.

<u>S=0</u>

$$TC = \text{Holding costs} + \text{Penalty costs} =$$

$$0 + (12/year)(11160240)(0{,}0082)\sum_{m=S}^{\infty}\frac{(m-S+1)}{(m+1)}p_m = 1.098.167€$$

S=1
$TC =$
$0,25(200€)\sum_{m=0}^{S}(S-m)p_m + (12/year)(11160240)(0,0082)\sum_{m=S}^{\infty}\frac{(m-S+1)}{(m+1)}p_m =$
=0,25*200*0,906 + 1.098.167*(0,0445+0,002+…) = 45 + 51064 = 51109€

S=2
TC=0,25*200*2 + 1.098.167*(1/3*0,004+1/2*0,0001+…) = 100 + 2251 = 2351€

S=3
TC=0,25*200*3 + 1.098.167*(1/4*0,0001+…) = 150 + 28 = 178€

S=4
TC=0,25*200*4 + 1.098.167*(1/5*0,000003+…) = 200€

We conclude that for S=3 we have the minimum TC, as for S≥4 the cost is increasing. The policy for this part should be (S-1, S) = (2, 3), so we keep three in stock and when one is consumed, we order a replacement. Besides this policy, other, more complicated group replacement strategies are explained in the next chapter as further research that could be implemented for parts like the plastic drums.

8. Conclusion

As seen in the previous chapters, maintenance can incur great costs in the terminal industry and this is the reason why management treats it as a cost center, trying to minimize the expenses. However, an investment in the modernization of the maintenance concept, the optimization of organization and in a specialized maintenance support software system, may yield benefits for the whole terminal.

We saw that the biggest problem in the case of ECT was the data reliability, which is due partly to the ERP system and partly to the low emphasis on registration from the company. In order to apply any maintenance concept, from the most modern-mostly qualitative, to the older quantitative models, reliable and easily accessible data is needed. The reliability starts from the critical point of data input, which should be easy to handle, with a coding system, so that the people who use the data later can easily find what they are looking for.

8.1 Implementation and recommendations

Even this simple criticality classification model and maintenance and inventory policies proposed, are difficult to be implemented quickly in ECT. The biggest weakness as observed after 3 months of the internship was the data availability which has as a major cause the poor data input. A big leap could be made after the implementation of a universal coding system for work order and spare part data. Although practice has shown that other industry sectors have more advanced maintenance decision management (Dekker, 1996) and the know-how is available, in ECT, maintenance seems to lack the management attention it should have.

Furthermore, the implementation of an integrated management concept like RCM or even better the modern TPM should be considered. The experience from other industries has showed that the benefits overcome the time and costs needed in most cases. However, it is a very lengthy procedure which could need years to be completed and the commitment of the personnel to it should be very high. There has been an effort to start the RCM process in ECT some years ago, but it was so time consuming that it was abandoned. Some small steps that should be considered by the management in order to improve the performance are discussed in sections 8.1.1 and 8.1.2 for the maintenance and inventory departments, respectively.

8.1.1 Maintenance management

- The purchase of the Chinese ZPMC cranes over the European ones may have saved the company a lot in capital investment, however there have been extra maintenance costs and reduced availability. The construction faults of the ZPMC cranes – especially the older generations – should be studied through life cycle cost analysis by the management in order to justify possible buys of Chinese cranes in the future.
- Given the existence of adequate data, a specialized maintenance optimization software package could be used. Since Oracle has maintenance management support, but no analysis capabilities, a program like Imtech's Optimizer Pro package could be integrated into Oracle and give automated results on PM and reliability.
- As discussed in the previous chapter, the PM policies should be integrated with the scheduled inspections, so that efficiency is maximized.

- There should be immediate application of the criticality decision process for each part, even at start with the five-attribute model shown here- so that attention can be given to the most critical ones.
- Historical data should include specific crane number, specific part and not only general system, so that the failure rates could be studied. A coding system could help towards this cause.
- Work orders should be entered with detail and in case of a replacement there should be a connection with the retrieval order in the warehouse, which is not the case in the current situation.
- The ‘silo’ effect in the company’s operation and organization should be avoided. All the departments are working towards the same cause, so the close cooperation of operations, maintenance and warehouse departments should be achieved.
- Even within the maintenance department, the organization should be improved, by making the responsibilities of the relatively young level of maintenance engineers, clearer. Also, the different professions (maintenance engineer, technician, job engineer) of each department should be located in the same building (which is not always the case) as the cooperation could be easier.
- The technicians should be constantly educated about the evolutions in maintenance perception in order to change the prevailing mentality of ‘if it isn’t broken don’t replace it’.
- The operators of equipment can be one of the biggest assets of the maintenance department. They should be educated in order to be willing to help by noting changes in the behavior of the equipment. The TPM concept has this as one of its core pillars, which shows how important the operator contribution can be.
- The construction faults that have been noticed by the technicians and technical experts should be studied, in order to find out if a possible improvement could be economically feasible (Corrective maintenance).
- In connection to the previous point, there should be a group of technical experts at the site of construction to oversee the building of any new ordered cranes and to avoid mistakes of previous models. Especially in the older Chinese cranes, there are a lot of issues that have been noticed for years but not until the 3rd generation of crane, were they addressed during the construction to the supplier.

8.1.2 Warehouse management

- According to the results of this research, the MRP policy, which is very easy to implement, should be used for the parts under PM, with the cooperation of the maintenance department.
- The critical parts which are not under PM should be studied to follow a base stock (S-1, S) inventory policy.
- For the rest of the parts, demand should be forecasted from historical data, and the EOQ model should be used.

- The SKU codes should have a uniform coding system according to system and department, and the double coding should be eliminated from Oracle.
- Each part should at first be equipped with its barcode sticker as a first step in order to facilitate the organization and the access to it. At a later stage, the use of RFID could be used in order to eliminate the phenomenon of 'lost' inventory from technicians who pick up parts and do not register it.

8.2 Further Research

This thesis studied the connection of PM with the optimization of spares inventory, making some assumptions and giving a clear idea for the case of ECT of how to evolve their maintenance concept. However, further research can be made in order to address the problem in more detail. The classification model first of all can be expanded to include more criteria, with a possible change in formula (6).

The increase in number of attributes as well as the number of classes will create a much more complex model, which however can be modeled in a computer program so that results can be given easily. Also, a method with weighted criteria as described by Braglia et al. (2004), using the analytic hierarchy process can be studied.

With regards to maintenance, the acquisition of reliable data can be used as input for the study of failure distributions of the critical spare parts. The Weibull plotting method can give very good estimations of the scale and shape parameter, which in turn can help for the optimization of the PM policy.

For the case of replaceable and cheap spare parts, a policy of group replacement could be studied. For example, regarding the plastic drums, one could calculate the cost/benefit of changing both drums of a crane in case one fails, in order to minimize the required scheduled downtime for repairs. Dekker et al. (1998) have shown several policies of group replacement for light bulbs, incidentally with a case study at ECT.

In the field of spare parts inventory management, a lot of research has been made and the implementation of an integrated policy (e.g. using genetic algorithms by Ilgin, 2007) which jointly optimizes inventory, maintenance frequency and repair capacity can be studied (Smidt et al., 2008). Furthermore, simulation can also be a very good tool for the study of maintenance and spares inventory optimization. It is also suggested for the case of ECT, as the very complex mathematical models can be avoided and with the use of the right software simulation it can be implemented much faster with more accurate results, as Sarker and Haque (2000) show in their research.

This area of research on joint optimization is still not fully developed, although a lot of progress has been made separately on both the maintenance and inventory department.

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APPENDICES

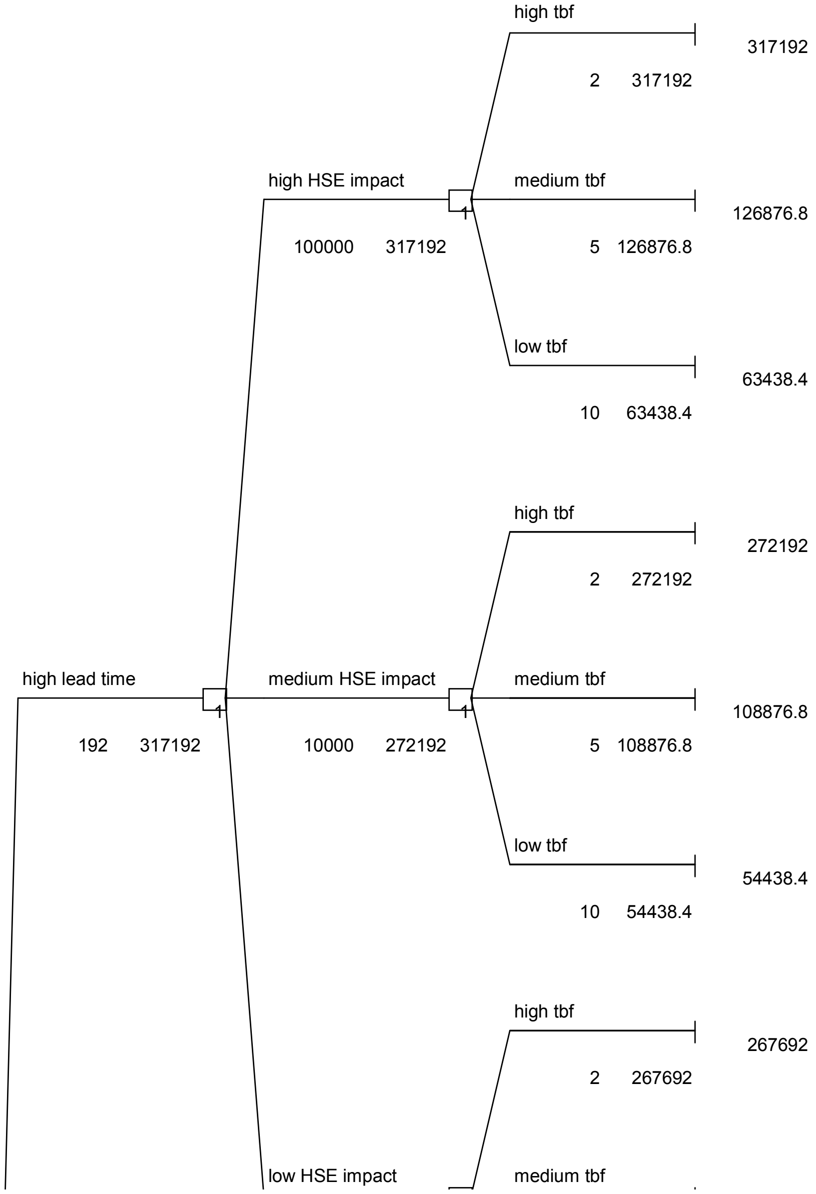
Appendix 1: ZP1 Crane Structure Breakdown

Asset	Description	Parent	Function
XX crane			
QC-XX	Quay Crane Twin Lift		
QC-XX-01	**Structure**	**QC-XX**	**To act as main support and support all crane systems**
QC-XX-01-010	Main Structure	QC-XX-01	To act as main support
QC-XX-01-020	System Supporting Structure	QC-XX-01	To support systems
QC-XX-01-030	Personnel Supporting Structure	QC-XX-01	To support personell
QC-XX-02	**Boom hoisting**	**QC-XX**	**To lower or raise boom**
QC-XX-02-010	BH AC Driving Motor	QC-XX-02	To drive wire rope drum
QC-XX-02-020	BH High Speed Brake	QC-XX-02	To stop drive
QC-XX-02-030	BH Gear Reducer	QC-XX-02	To transmit power to wire rope drum
QC-XX-02-040	BH Wire Rope Drum	QC-XX-02	To (un)wind wire rope
QC-XX-02-050	BH Emergency Drum Brake	QC-XX-02	To stop drum
QC-XX-02-060	BH Wire Ropes	QC-XX-02	To transmit driving power
QC-XX-02-070	BH Sheaves	QC-XX-02	To guide wire rope
QC-XX-02-080	BH Sensors	QC-XX-02	To monitor system positions
QC-XX-03	**Main hoisting**	**QC-XX**	**To get/put and lower/raise containers**
QC-XX-03-010	MH AC Driving Motors L/R	QC-XX-03	To drive wire rope drum
QC-XX-03-020	MH High Speed Brakes L/R	QC-XX-03	To stop drive
QC-XX-03-030	MH Gear Reducer	QC-XX-03	To transmit power to wire rope drum
QC-XX-03-040	MH Wire Rope Drums L/R	QC-XX-03	To (un)wind wire rope
QC-XX-03-050	MH Emergency Drum Brakes L/R	QC-XX-03	To stop drum
QC-XX-03-060	MH Wire Ropes	QC-XX-03	To transmit driving power
QC-XX-03-070	MH Sheaves BG	QC-XX-03	To guide wire rope
QC-XX-03-080	MH Headblock	QC-XX-03	To transfer hoisting inputs to spreader
QC-XX-03-090	MH Anti-Skew Device Boom Head	QC-XX-03	To prevent skewing of spreader
QC-XX-03-100	MH Wire Rope Support Idlers LS/WS	QC-XX-03	To support wire rope
QC-XX-03-110	MH T/L/S & Snag Devices	QC-XX-03	To change spreader position by moving sheave
QC-XX-03-120	MH Spreader Power Cable Reel Driving Unit	QC-XX-03	To (un)reel spreader power cable
QC-XX-03-130	MH Spreader Power Cable	QC-XX-03	To supply electrical power and control signals
QC-XX-03-140	MH Sensors	QC-XX-03	To monitor system positions

QC-XX-04	**Main trolley traveling**	**QC-XX**	**To move main trolley**
QC-XX-04-010	MT AC Driving Motor	QC-XX-04	To drive wire rope drum
QC-XX-04-020	MT High Speed Brake	QC-XX-04	To stop drive
QC-XX-04-030	MT Gear Reducer	QC-XX-04	To transmit power to wire rope drum
QC-XX-04-040	MT Wire Rope Drum	QC-XX-04	To (un)wind wire rope
QC-XX-04-050	MT Wire Ropes	QC-XX-04	To transmit driving power
QC-XX-04-060	MT Sheaves BG/Boom Head	QC-XX-04	To guide wire rope
QC-XX-04-070	MT Main Trolley	QC-XX-04	To support main hoisting operation
QC-XX-04-080	MT Trolley Rail	QC-XX-04	To support main trolley
QC-XX-04-090	MT Towing Rope Tensioners L/R	QC-XX-04	To tension towing ropes
QC-XX-04-100	MT Energy Chain System	QC-XX-04	To guide power cable to main trolley
QC-XX-04-110	MT Sensors	QC-XX-04	To monitor system positions
QC-XX-05	**Catenary trolley reeving**	**QC-XX**	**To prevent sagging of wire ropes of main hoisting and trolley traveling**
QC-XX-05-010	CT Wire Ropes	QC-XX-05	To transmit driving power
QC-XX-05-020	CT Sheaves BG/Boom Head	QC-XX-05	To guide wire rope
QC-XX-05-030	CT Catenary Trolley-s LS/WS	QC-XX-05	To move together with main trolley
QC-XX-05-040	CT Towing Rope Tensioners L/R	QC-XX-05	To tension towing ropes
QC-XX-05-050	CT Sensors	QC-XX-05	To monitor system positions
QC-XX-06	**Gantry traveling**	**QC-XX**	**To move crane on rails**
QC-XX-06-010	GA Driving Units M1-M20	QC-XX-06	To drive gantry wheels
QC-XX-06-020	GA Traveling Wheels	QC-XX-06	To transfer driving power to gantry traveling
QC-XX-06-030	GA Rail Brakes LS/WS L/R	QC-XX-06	To release rail brake
QC-XX-06-040	GA Rail Brake Hydraulic Units LS/WS	QC-XX-06	To supply hydraulic power for rail brake
QC-XX-06-050	GA Sensors	QC-XX-06	To monitor system positions
QC-XX-06-060	GA Miscellaneous	QC-XX-06	To provide auxiliary functions
QC-XX-07	**Controlling, Electronics**	**QC-XX**	**To control crane**
QC-XX-07-010	Cable Reel Data Collector	QC-XX-07	To transfer control data
QC-XX-07-020	Crane Control System	QC-XX-07	To process control signals
QC-XX-07-030	Remote I/O Stations	QC-XX-07	To process control signals
QC-XX-07-040	Automation Sensors	QC-XX-07	To measure container movements
QC-XX-07-050	Glass Fibre Wiring	QC-XX-07	To transmit control signals
QC-XX-08	**Supplying electrical**	**QC-XX**	**To supply electrical**

	power		**power**
QC-XX-08-010	Power Cable Reel Driving Unit	QC-XX-08	To (un)reel power cable
QC-XX-08-020	Power Cable	QC-XX-08	To supply electrical power and control data
QC-XX-08-030	Cable Guider	QC-XX-08	To guide power cable
QC-XX-08-040	Cable Reel Current Collector	QC-XX-08	To transfer electrical power
QC-XX-08-050	Switchgear	QC-XX-08	To secure and distribute incoming medium voltage to transformers
QC-XX-08-060	Transformer House	QC-XX-08	To transform from 22.5 kV to 510 V and 420 V
QC-XX-08-070	Electrical Power Distribution	QC-XX-08	To distribute main power
QC-XX-08-080	Electrical Wiring	QC-XX-08	To distribute electrical power
QC-XX-09	**Supplying hydraulic power**	**QC-XX**	**To supply hydraulic power**
QC-XX-09-010	Hydraulic Power Unit BG L/R	QC-XX-09	To supply hydraulic power to cylinders of main hoisting, trolley and catenary trolling traveling
QC-XX-09-020	Hydraulic Power Unit M-house	QC-XX-09	To supply hydraulic power to 3 drum brake systems
QC-XX-10	**Miscellaneous**	**QC-XX**	**To provide miscellaneous functions**
QC-XX-10-010	Safety Systems	QC-XX-10	To provide safety measures
QC-XX-10-020	Auxiliary Systems	QC-XX-10	To provide auxiliary functions
QC-XX-10-030	Rope Rereeving Device	QC-XX-10	To replace wire ropes
QC-XX-10-040	Elevator	QC-XX-10	To move personnel to several crane levels
QC-XX-10-050	Emergency Drives	QC-XX-10	To act as backup motor
QC-XX-10-060	Maintenance Cranes	QC-XX-10	To lift spare systems or tools
QC-XX-10-070	Air Conditioning System	QC-XX-08	To distribute main power to AC

Appendix 2: Criticality Decision Diagram (sample from excel)



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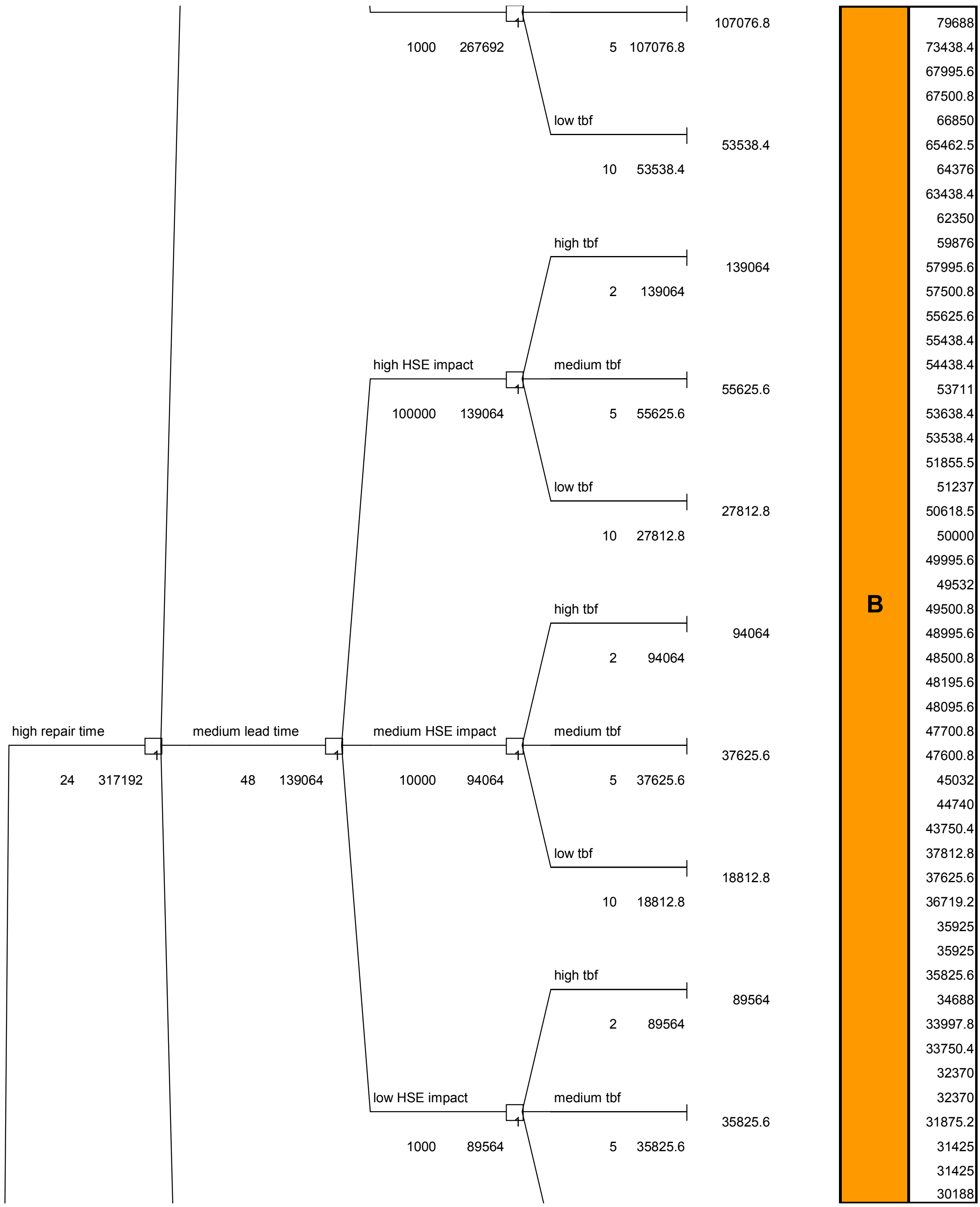
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24 317192
medium lead time
48 139064
medium HSE impact
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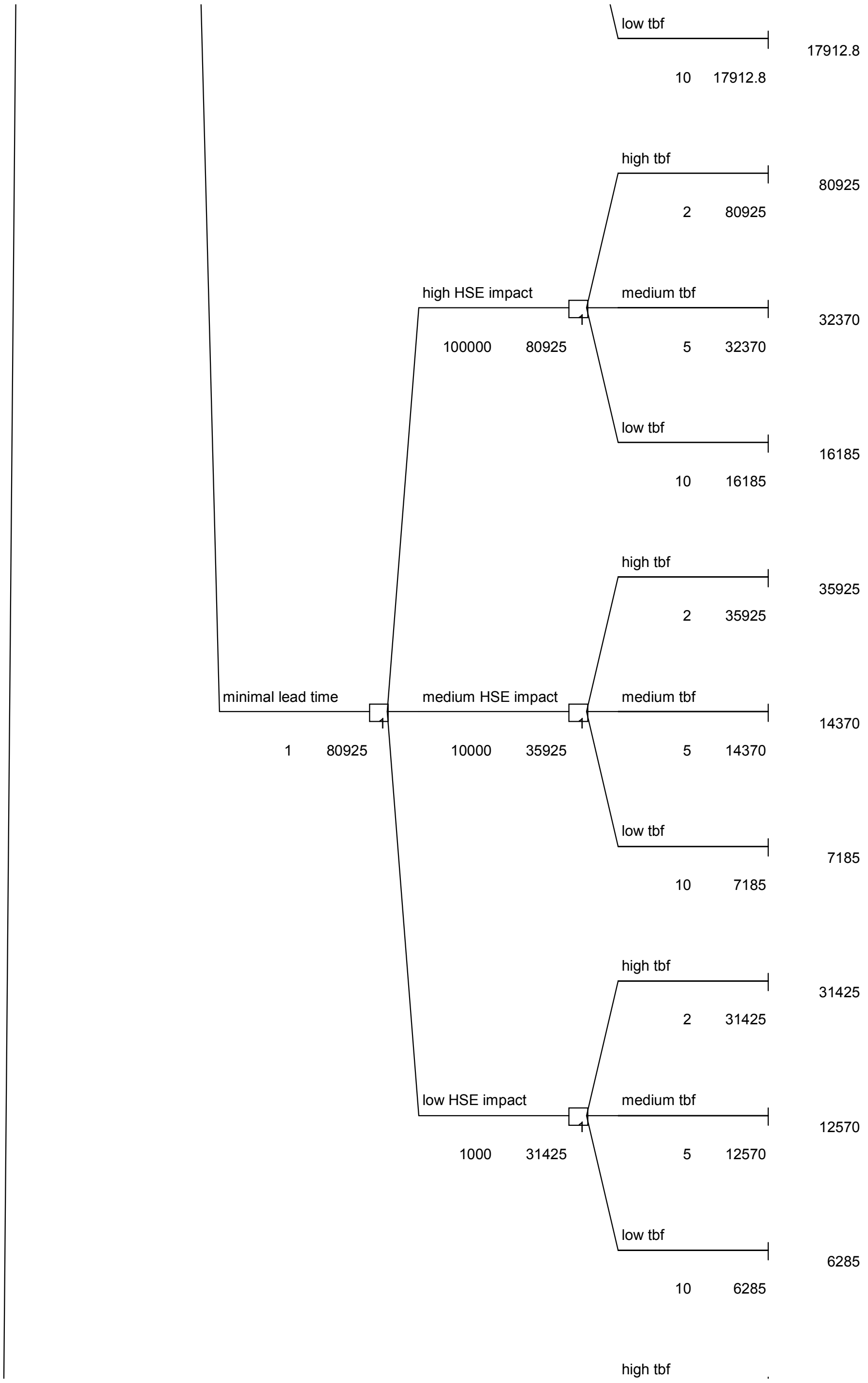

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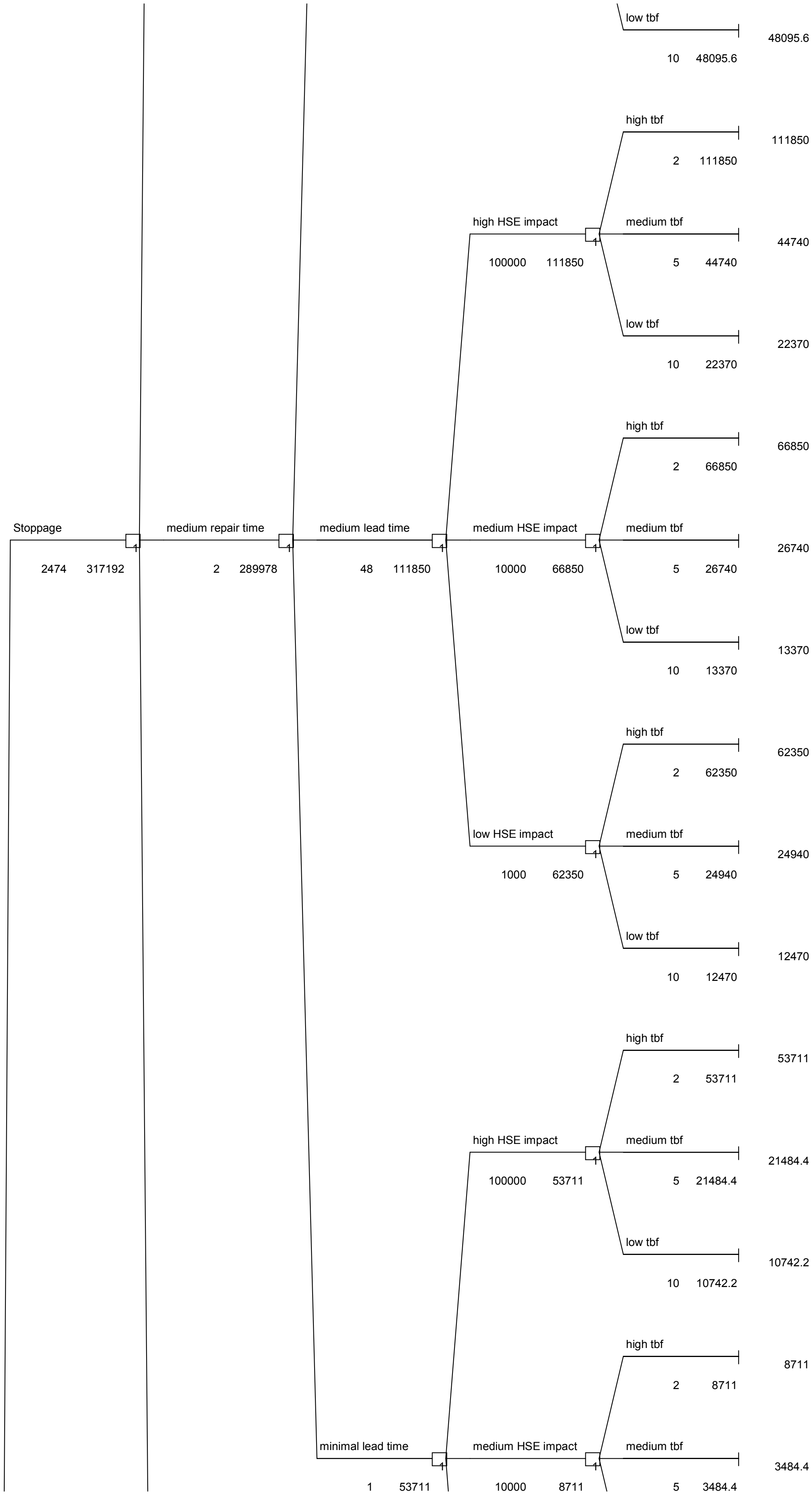
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22370
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2 66850
66850
Stoppage
2474 317192
medium repair time
2 289978
medium lead time
48 111850
medium HSE impact
10000 66850
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low tbf
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high tbf
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