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Increasing spare part availability to achieve maximum system availability at lower cost at SABIC Geleen

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Geleen, August 2013

Increasing Spare Part Availability to Achieve Maximum System Availability at Lower Cost at SABIC Geleen

by

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In partial fulfillment of the requirements for the degree of

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in Operations Management and Logistics

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Abstract

In this master thesis, the spare parts ordering process of SABIC Geleen is reviewed. Firstly, a framework is designed to provide SABIC Geleen with knowledge of the different phases of the spare parts ordering process. Then maintenance data is combined with asset utilization data of 2012 to conclude which phases of the spare parts ordering process were most problematic in terms of lost economic value (i.e. costs of lost production, costs related to safety, health, and environment, and urgent ordering costs). Because most economic value was lost in the spare parts ordering policy and the repair or discard process, for these phases of the spare parts ordering process, redesigns are developed. The redesigns of the spare parts ordering policy particularly consider the sequence of decisions to be taken, the incorporation of the supply lead time in the ordering policy decisions, and the use of different replenishment policies for different types of spare parts. Regarding the repair or discard process, mainly the internal communication (between different departments) is improved regarding defective repairable spare parts, and it is proposed to update the prices and supply lead times of spare parts so that accurate numbers are available to base decisions upon.

The proposed redesigned solutions are applied on practical case studies of SABIC Geleen to explain the methodology of the redesign and to indicate the benefits of using the proposed solution compared with the current situation. The redesigns help to meet the target system availability at lower costs.

Finally, recommendations regarding the use of the redesigned solutions and further improvements of the spare parts ordering process at SABIC Geleen are provided.

PREFACE AND ACKNOWLEDGMENTS

This report is the result of the completion of my master thesis project of the master study Operations Management and Logistics at Eindhoven University of Technology. The project has been carried out at the Site Improvement Polymers department of SABIC located in Geleen, lasted from February 2013 till Augsut 2013. I conducted a challenging project at SABIC Geleen for which I owe thanks to some people.

First of all, I would like to thank dr. S.D.P. Flapper, my first supervisor of the university, for guiding me through the project, the constructive feedback, never-ending critical view on my report, and for his confidence in me. He helped me to stay critical towards my own work to improve the quality of the report and enabled me to excel in my thesis project. I thank him for all the time and effort he put into my research project. Especially I would like to thank him for giving me the opportunity to graduate at his field of research. Furthermore, I would like to thank dr. H. Peng, my second supervisor of the university, for her time and critical questions on my report, which further improved the quality of it.

At SABIC Geleen I would like to thank Walle Hoekstra, my first supervisor at SABIC, who gave me the opportunity to conduct my master thesis project at his department. I thank him for the time and effort spent in my project and I appreciated the critical and practical view on my research. Additionally, I would like to thank ir. J.W. Bisschops, my second supervisor at SABIC Geleen for his advice, information, and comments during my internship. Furthermore, I would like to thank all employees of SABIC Geleen who spent time and effort in my research project and who always made time to answer my questions. Special thanks are in place for my uncle Jan Berix for introducing me at SABIC Geleen and giving me the opportunity to conduct my master thesis project at this chemical multinational.

Furthermore, I would like to thank my family and friends for their support and interest during my entire study and in particular this thesis project, especially my parents, for the support they gave me in my life and providing me with the tools and opportunities to pursue my goals and of course their everlasting and unconditional love. Finally, special thanks are in place for my girlfriend for her never-ending support, confidence and love.

Ralf Berix

Geleen, August 2013

Executive Summary

This report is the result of my master thesis project conducted at the Site Improvement Polymers (SIPol) department of SABIC Geleen.

Introduction

SABIC is a multinational in the chemical process industry and at the site in Geleen Polyolefins are processed continuously (i.e. 24/7). The general feeling of the Site Improvement Polymers department is that spare parts are unavailable when SABIC Geleen wants to do maintenance on the systems. The feeling is supported by the actual utilization rates of 2012, which are for almost all systems (14 of the 16) below the target utilization rate. The Site Improvement Polymers department would like to get more insight in the relevancy of the spare part unavailability and how to solve the problems occurring from unavailable spare parts.

Research questions

The main research question of this master thesis project is formulated as follows:

> ”*Can SABIC Geleen increase the actual utilization rate of its systems, through reduction of the losses related to maintenance, caused by spare part unavailability, by improving the relevant phase(s) of the spare parts ordering process, within the given maintenance budget of SABIC Geleen?”*

The goal of the master thesis was to determine whether spare parts management can be improved, and if so, how it can be improved. In order to determine the relevant phase(s) of the spare parts ordering process and the room for improvement, the following sub questions are formulated to answer the main research question:

1. *Of what phases does the spare parts ordering process exists, based on literature review?*
2. *For each phase in the spare parts ordering process, what are the potential problems that could cause spare part unavailability, based on literature review and practical situations at SABIC Geleen?*
3. *In what phase(s) of the spare parts ordering process is/are the impact of spare parts unavailability the largest for SABIC Geleen?*
4. *How can we improve the problems of spare part unavailability when SABIC Geleen wants to do maintenance at lower costs, based on literature review?*

Analysis on the relevancy of spare parts unavailability

In order to determine the relevancy of the problem that spare parts are unavailable, we determined for all maintenance work orders of 2012 how often a maintenance activity took longer because of unavailability of the needed spare part and determined the economic consequences of the unavailability. The zpm_stat_list transaction of the SAP information system is used to determine how often a maintenance activity was delayed because of spare part unavailability. The dataset is cleaned to obtain the most reliable dataset and filtered because of the vast amount of data ([redacted] maintenance work orders for all plants of SABIC Geleen in 2012). After several cleaning and filtering steps, we retained only maintenance work orders which were delayed because of spare part unavailability. These maintenance work orders were differentiated on the maintenance coding (e.g. corrective or preventive maintenance) to determine what type of maintenance had the highest average impact (determined by multiplying the percentage of work orders belonging to a maintenance coding with the mean delay of the work orders of that maintenance coding). Corrective maintenance work orders on instrumentation or mechanical systems had the highest average impact. These maintenance work orders were combined with asset utilization data from the PROMISE information system to determine the lost costs. Concluding, approximately [redacted] (downtime costs, costs of safety, health, and environment risks, and unnecessary urgency ordering costs) was lost in 2012, which was almost 10% of the total maintenance budget of SABIC Geleen) due to delayed maintenance activities because of spare part unavailability. This is a significant amount of money lost and therefore we concluded that the problem of spare part unavailability is relevant for SABIC Geleen.

DESIGNED SPARE PARTS ORDERING PROCESS FRAMEWORK

In order to be able to solve the problems related to unavailability of spare parts, causing unplanned downtime and decreasing system availability, a decision tree is developed in order to provide SABIC Geleen with knowledge of the spare parts ordering process and what potential problems could be causing spare part unavailability (see Figure 1). The framework is divided in eight phases, which answers the first sub question. For each phase, potential problems are described, which answers the second sub question:

1. The need for a spare part: in this phase it is determined what spare part, in what quantity, with what priority is needed to perform a maintenance activity to remedy the breakdown or malfunction. If this information is not immediately clear, problems related to spare parts unavailability might occur.
2. From need for a spare part to the actual ability to order a spare part: this phase is mainly considered with the administration activities which steps and decisions should be taken to order a new spare part in the most efficient way (i.e. at minimum costs with an as short as possible supply lead time). Problems could be due to assigning a wrong priority to the maintenance work order, or not incorporating the availability of spare parts in the maintenance work planning,
3. Actual ordering of a spare part: this phase is concerned with the need to ensure that the correct spare part is ordered on time in the right quantity. Problems occur if the wrong spare parts is ordered too late and/or in the wrong quantity.
4. Spare parts ordering policy: this phase contains strategic decisions regarding the criticality of the equipment, criticality of the associated components, the decision whether or not a spare part is repairable, the choice for a supplier, the decision on whether or not to stock the spare part, the stocking location decision, the choice on the replenishment policy, and the determination of the parameters of the replenishment policy. The decisions serve as inputs for the associated phases of the spare parts ordering process. Problems occur when spare parts are categorized wrongly. Another problem is that minimum stock levels could be determined at a too low level,
5. Order supply process: this phase exists of the delivery process of a supplier to SABIC Geleen. It is determined whether the correct spare part is delivered on time in the right quantity. If not, problems related to spare parts unavailability occur,
6. Order receipt process: this phase describes the process from the actual receipt of a spare part until it is available for use for the maintenance employees. In SABIC Geleen, delivered spare parts undergo a test to check whether the spare part is according to specification requirements and, when necessary, whether certificates are available. A mismatch between the specification of the delivered part and the reference specification could cause spare part unavailability,
7. Actual use of the spare part: this phase describes the assembly of the spare part in the system. Problems occur if wrong spare parts are assembled or if correct spare parts are assembled wrongly in the systems, and
8. Repair or discard process of a spare part: the disassembled spare part should be either scrapped or repaired, based on the reparability of the spare part. Not properly communicating the decisions to be taken in case of a defective spare part (i.e. the repair or discard process), could lead to spare part unavailability.

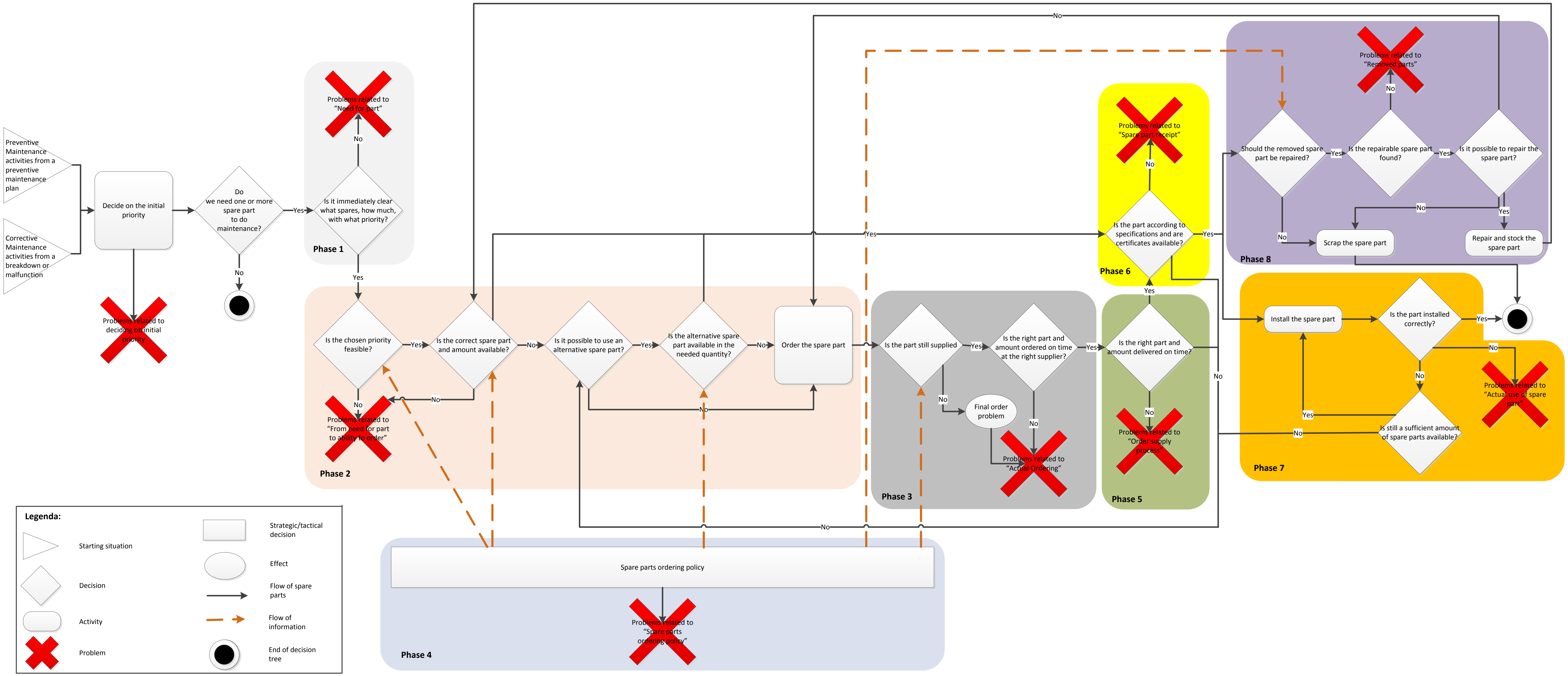

Figure 1: decision tree with steps and decisions to be taken for each phase of the spare parts ordering process

Analysis on what phase of the spare parts ordering process is most problematic

In order to answer the third sub question, it should be determined what phase(s) of the spare parts ordering process caused SABIC Geleen the most negative economic consequences in 2012. The delayed maintenance work orders because of unavailable spare parts, were analyzed using the decision tree indicated in Figure 1. The maintenance work order terminates at one or multiple phases of the spare parts ordering process, and the negative economic consequence per phase of the spare parts ordering process could be determined (see Table 1). Note that for maintenance work orders which were delayed because of more than one phase of the spare parts ordering process, the ratio of the delay caused by the particular phase was multiplied with the asset utilization margin to obtain the lost economic value due to problems related to that phase of the spare parts ordering process.

Table 1: lost economic value (in €) in 2012 for SABIC Geleen per phase of the spare parts ordering process

Phase number	Name of the phase of the spare parts ordering process	Cost lower bound (in €)	Cost higher bound (in €)
1.	Need for a spare part	[redacted]	[redacted]
2.	From need for a spare part to the actual ability to order a spare part	[redacted]	[redacted]
3.	Actual ordering of the spare part	[redacted]	[redacted]
4.	Spare parts ordering policy	[redacted]	[redacted]
5.	Order supply process	[redacted]	[redacted]
6.	Order receipt process	[redacted]	[redacted]
7.	Actual use of the spare part	[redacted]	[redacted]
8.	Repair or discard process of a spare part	[redacted]	[redacted]

Concluding, the spare parts ordering policy and the repair or discard process caused the highest negative economic consequences for SABIC Geleen and therefore the decisions in these phases were redesigned.

Redesigned decisions of the spare parts ordering policy

Finally, in order to answer sub question four, redesigns are provided for the most relevant phases of the spare parts ordering process.

The following decisions should be taken in the spare parts ordering policy of SABIC Geleen:

1. Decide on the decisions and the sequence of them which should be taken in the spare parts ordering policy of SABIC Geleen
2. Decide on the criticality of the equipment
3. Decide on the criticality of the associated spare parts
4. Decide on the reparability of the spare part
5. Decide on how to select a supplier for delivering the spare part
6. Determine whether or not to stock the spare part
7. Decide on the spare parts replenishment policy
8. Decide on the spare parts replenishment policy parameters

Decide on the decisions and the sequence of them which should be taken in the spare parts ordering policy of SABIC Geleen

The current decisions and sequence of the decisions taken in the spare parts ordering policy of SABIC Geleen are compared with literature. Several shortcomings of the currently used framework of SABIC Geleen were discovered. Based on literature, knowledge and experience at SABIC Geleen, the framework has been redesigned (see Figure 2).

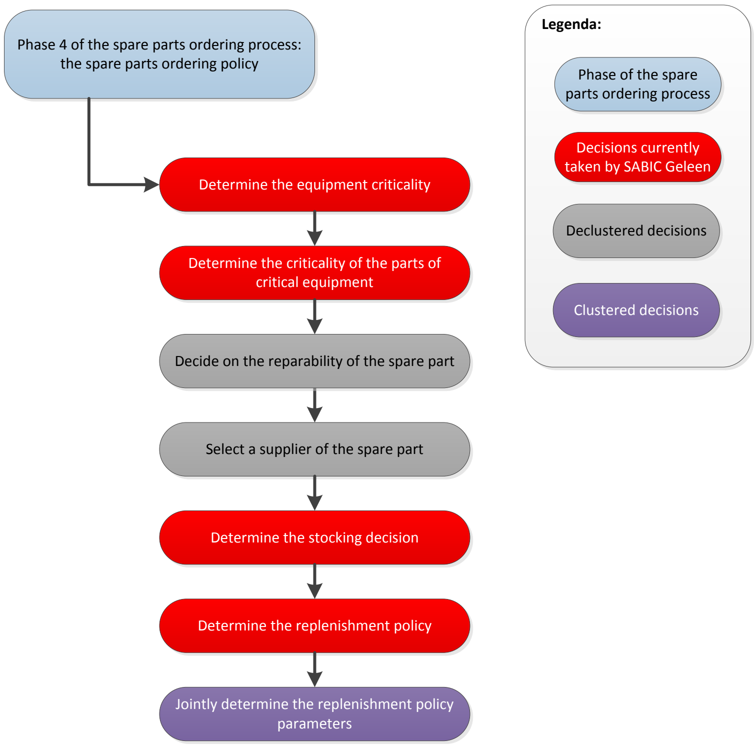

Figure 2: adjustments of the decisions and sequence of the spare parts ordering policy

DECIDE ON THE CRITICALITY OF THE EQUIPMENT

Based on the comparison of literature with the current criticality determination tool of SABIC Geleen, we determined that the current tool meets all criteria as specified by literature. Furthermore, because the determination of the boundary values and the risk acceptance level is company-specific and currently based on industry benchmarking data, no redesign is made for this decision of the spare parts ordering policy and it is proposed to use the risk matrix that SABIC Geleen is going to use from January 2014 to determine the criticality of the equipment.

DECIDE ON THE CRITICALITY OF THE ASSOCIATED SPARE PARTS

Currently SABIC Geleen uses the FMEA methodology, which is according to literature the appropriate tool to determine what components are critical for the functionality of the equipment. For each component a Risk Priority Number is determined, based on the severity, probability of occurrence, and detectability of the failure, where a higher number depicts a higher criticality. Severity and occurrence are measured on a five-point scale, which is coupled to the criticality matrix, whereas detectability is measured on a ten-point scale to determine the height of the Risk Priority Number. It is proposed to use the same dimensions for each ranking scale in order to prevent the Risk Priority Number to be skewed. Therefore, we developed a five-point ranking for the detectability scale.

DECIDE ON THE REPARABILITY OF THE SPARE PART

Currently, SABIC Geleen decides on the reparability of the spare part based on two decisions; a non-economic decision where it is decided whether it is technically feasible to repair the component and an analysis based on cost models (i.e. economic criteria). The economic decision is currently purely based on the costs of repair versus the purchasing costs at SABIC Geleen. Currently, the Maintenance Engineers decide, based on their experience, whether a damaged spare part is repaired or not and what repair costs are acceptable. Literature proposes to also incorporate supply lead times of the component to determine whether it is more cost efficient to repair or discard the component after failure. The Level Of Repair Analysis model is used and solved using the greedy algorithm. An Excel tool is designed to aid the employees of SABIC Geleen with making the reparability decision of a spare part

DECIDE ON HOW TO SELECT A SUPPLIER FOR DELIVERING THE SPARE PART

SABIC Geleen needs to explicitly determine whether a supplier is able to guarantee the demanded quality of the spare part, while this is assumed by models in literature. SABIC Geleen does classify vendors on twelve criteria to determine whether a supplier is qualified to supply components to SABIC Geleen. We used these variables, but also included supply lead time, as it is an important factor to base the supplier selection decision on. An Analytical Hierarchy Process is used to calculate the weights of each variable and determine whether a supplier is qualified for delivery. An Excel tool is developed to help the employees of SABIC Geleen with calculating the weights of the criteria.

Once a demand for a spare part occurs, SABIC Geleen demands tenders from the qualified vendors and the supplier which offers the component at the lowest price is allowed to deliver the part. We again incorporate the supply lead time in this decision. An Analytical Hierarchy Process is used to calculate a benefit-cost ratio. The supplier with the highest benefit-cost ratio, i.e. the shortest lead time at the lowest costs, is then chosen to deliver the demanded component to SABIC Geleen. For helping the employees of SABIC Geleen when selecting a supplier of a spare part, we designed an Excel tool.

DETERMINE WHETHER OR NOT TO STOCK THE SPARE PART

Literature proposes to include spare part criticality, price, demand value, and spare part specificity as variables to determine the decision on whether to stock a spare part or not. However price, demand value, and specificity have an effect on stock levels, but not on the decision whether or not to stock a spare part. Therefore, the stocking decision is based on criticality and the expected supply lead time, exactly as SABIC Geleen currently determines the stocking decision. However, because SABIC Geleen is going to use a newly developed risk matrix, a new matrix is developed to base the stocking decision on (see Table 2: matrix used to make a decision which spare parts to stock).

Table 2: matrix used to make a decision which spare parts to stock

		Equipment criticality			
		1	2	3	4
Spare parts expected supply lead time	> 5 days				
	3 < days ≤ 5				
	1 < days ≤ 3				
	8 ≤ hours ≤ 24				
	< 8 hours				

DECIDE ON THE SPARE PARTS REPLENISHMENT POLICY

Currently, SABIC Geleen uses the (R,s,S)-replenishment policy for all components which are stocked on site in Geleen. Because the review period for all but floor stock components is small compared to the delivery lead time, (s,S)-replenishment policies may be assumed. The use of a continuous base-stock replenishment policy is optimal for components with a high price and low demand volumes, e.g. spare parts. The continuous base-stock replenishment policy assumes stationary demand during the component’s lifetime. If this is not the case for a spare part of SABIC Geleen, another replenishment policy should be chosen which is able to incorporate seasonal effects of the demand of spare parts. More research is needed for this topic.

Decide on the spare parts replenishment policy parameters

Currently, SABIC Geleen calculates the order-up-to level of a component using the Economic Order Quantity model. The Economic Order Quantity model only incorporates costs in the decision how many spare parts to reorder, and does not include the supply lead time. This could lead to stock levels which are not sufficient for meeting the target fill rate. In order to include the supply lead time of a component in the determination of the order-up-to level, the item approach could be used. For each component it is determined how many should be stocked to achieve the target fill rate and the investment costs can be calculated.

Designing the system approach for determining the spare parts replenishment policy parameters

Using the ordinary item approach to calculate the maximum stock level is non-optimal; it does not incorporate the effect on the availability of the system and the needed investment. Therefore, a system approach is proposed to calculate the maximum stock levels. The Multi-Echelon Technique for Recoverable Items Control (METRIC) technique is proposed. Using the METRIC technique instead of the item approach achieves the target system availability at lower costs. An Excel tool is developed for aiding the employees of SABIC Geleen in the calculation of the order-up-to levels of the components using the system approach. Using the system approach compared with the item approach for the case study of SABIC Geleen, achieved the target system availability at almost 40% lower investment costs.

Redesigned decisions of the repair or discard process

The main problem areas in the repair or discard process of SABIC Geleen are:

1. The defective repairable spare part is not directly sent to the repair shop
2. The repairable spare parts are not tracked and traced
3. The Maintenance Field Planners do not differentiate components on the different spare parts categories
4. The discard procedure is not followed or even forgotten by the Maintenance Engineers
5. The increase of stock levels when a new spare part is already ordered before the repaired spare part will return to stock after a successful repair
6. The supply lead times and prices are not updated in the SAP information system

The defective repairable spare part is not directly sent to the repair shop

Currently, a repairable spare part is not always directly sent to the repair shop because of the following causes:

1. The Maintenance Field Planners do not always contact the Maintenance Engineers when technical support is necessary which causes the component to be unnecessary delayed,
2. It is not clear what actions should be taken regarding the defective repairable spare part, and
3. The Maintenance Field Planner has forgotten to send the spare part to the repair shop.

The following redesigns are developed for the above mentioned problems:

1. The Maintenance Engineers of the Site Improvement department should filter the notifications on the status Technical Support Necessary and contact the Maintenance Field Planner in case previously unknown notifications are discovered.
2. The Maintenance Engineers should describe in the Technical Mission Statement the exact actions which need to be taken regarding the defective repairable spare part.
3. The replenishment proposals of repairable spare parts should be used as a reminder for the Maintenance Engineer to check with the Maintenance Field Planner whether the components are delivered to the repair shop for revision. The proposals should be sent to the Maintenance Engineer of the Running Business department.

THE REPAIRABLE SPARE PARTS ARE NOT TRACKED AND TRACED

Currently, SABIC Geleen hired a dedicated job leader to track and trace all maintenance orders to external parties. We propose to also use a track and trace system on the repairable spare parts so that the Maintenance Engineers of the Site Improvement department are able to track the status of the component

THE MAINTENANCE FIELD PLANNERS DO NOT CHECK THE AVAILABILITY OF THE SPARE PARTS AND DO NOT DIFFERENTIATE COMPONENTS ON THE DIFFERENT SPARE PARTS CATEGORIES

Before the Maintenance Field Planners make the planning of the maintenance activities they should check with the Purchase Schedulers whether the needed spare parts are immediately available or that they should be ordered. Furthermore, they should differentiate the spare parts into different categories (i.e. strategic, CMI, non-stock, and floor stock) because each category has different supply lead times. Incorporating the availability of the spare part and the expected supply lead time leads to a more realistic maintenance planning.

THE DISCARD PROCEDURE IS NOT FOLLOWED OR EVEN FORGOTTEN BY THE MAINTENANCE ENGINEERS

In order to solve this problem, it is proposed to make it impossible for the Maintenance Engineers to issue a replenishment order for a repairable spare part before they issued the dispose command. It is proposed to keep using the replenishment proposal as a reminder for the Maintenance Engineer to issue the dispose command if necessary.

THE INCREASE IN STOCK LEVELS WHEN A NEW SPARE PART IS ALREADY ORDERED BEFORE THE REPAIRABLE SPARE PART WILL RETURN TO STOCK AFTER A SUCCESSFUL REPAIR

The same solution is proposed as the solution to solve the problem that the discard procedure is not followed or even forgotten.

THE SUPPLY LEAD TIMES AND PRICES ARE NOT UPDATED IN THE SAP INFORMATION SYSTEM

Supplier information should be updated periodically using a feedback loop. Ideally, the suppliers should inform SABIC Geleen when the supply lead time or price of the component changes. This is however not always the case, and therefore resources are needed to determine for which spare parts with what frequency the supplier information should be updated to achieve at a cost efficient solution. Additional research is needed to determine for which spare parts and with what frequency the supply information should be updated.

CONCLUSIONS AND RECOMMENDATIONS

The goal of this master thesis was to improve spare parts availability, in order to increase the performance of the chemical plants (measured in actual utilization rate compared to the target utilization rate), through a reduction in the losses due to maintenance of the systems at lower costs. Although system availability is influenced by more factors than spare part unavailability, an increase in system availability at lower costs is used as objective.

Using the provided redesigns could achieve the target system availability at lower costs. Determining the Risk Priority Number, based on equally dimensioned scales, and the redesigned tool to determine which spare parts to keep on stock improves the focus on critical spare parts of critical equipment and decreases the possibility of spare part unavailability and thus downtime costs (i.e. between [redacted] and [redacted]). Furthermore, including the supply lead time when determining the reparability of a spare part and the choice of a supplier decreases spare part unavailability and thus downtime costs. Using the continuous base-stock replenishment policy for spare parts is optimal when demand is stationary during the lifetime of the component. For components with non-stationary demand, another replenishment policy has to be selected. More research is needed on this topic. Finally, determining the base-stock level for components with stationary demand during the lifetime using a system approach is optimal, i.e. the target system availability is met at lower costs than using an item approach. For a simplified case study (i.e. a compressor consisting of three components) the gain when using the system approach was approximately 40% of the investment costs. For complex equipment (consisting of multiple components) it is likely that the gain is even larger. SABIC Geleen owns approximately [redacted] pieces of equipment which indicates the room for money to be saved using the system approach.

Several recommendations are proposed to SABIC Geleen to improve the spare parts ordering process:

- Implement and apply the redesigned number and sequence of decisions of the spare parts ordering policy (e.g. stocking decision, replenishment policy determination, parameter decision) to achieve the target system availability (target utilization rate) at lower costs.
- Implement and apply the redesigned decisions of the repair or discard process to achieve the target system availability at lower costs.
- Develop redesigns for the time between the discovery that a spare part is needed and the actual ability to order the component, and the actual ordering of the spare part of the spare parts ordering process because SABIC Geleen lost a significant amount of money in 2012 in these phases.
- Record maintenance and asset utilization data in one information system (e.g. SAP) to be able to more easily compare maintenance data from the SAP system and asset utilization data from the PROMISE system. Furthermore, improve both maintenance data and asset utilization data registration to be able to make more reliable estimations regarding e.g. failure distributions of components and the production loss because of unavailability of a spare part. More research is needed on this topic.
- Investigate what replenishment policy should be used for components with non-stationary demand during the lifetime of the component.
- Investigate the problem of black stock to be able to discover the relevancy of the problem for SABIC Geleen and develop redesigned solutions if the problem is relevant.

TABLE OF CONTENTS

1. INTRODUCTION

This chapter provides an introduction of the problem researched in this thesis. First, the research area, SABIC Geleen (section 1.1), and especially the Site Improvement Polymers department (section 1.2) is introduced. Section 1.3 presents the problem introduction as revealed by SABIC Geleen. Finally, an outline of this master thesis report will be given (section 1.4).

1.1. COMPANY DESCRIPTION OF SABIC GELEEN

This research project is conducted at SABIC Geleen, one of the three production locations for SABIC in Europe (the other two are in Teesside, United Kingdom, and in Gelsenkirchen, Germany). SABIC was founded in 1976 with the aim to convert oil by-products into useful chemicals, plastics, fertilizers and metals. It grew fast since its foundation; the total yearly worldwide production in 1985 was 6.5 million tons, whereas production was increased to 69 million metric tons in the year 2011, where chemicals contribute with the largest production of more than 44 million metric tons, which is more than 60% of the total production value (see Figure 3).

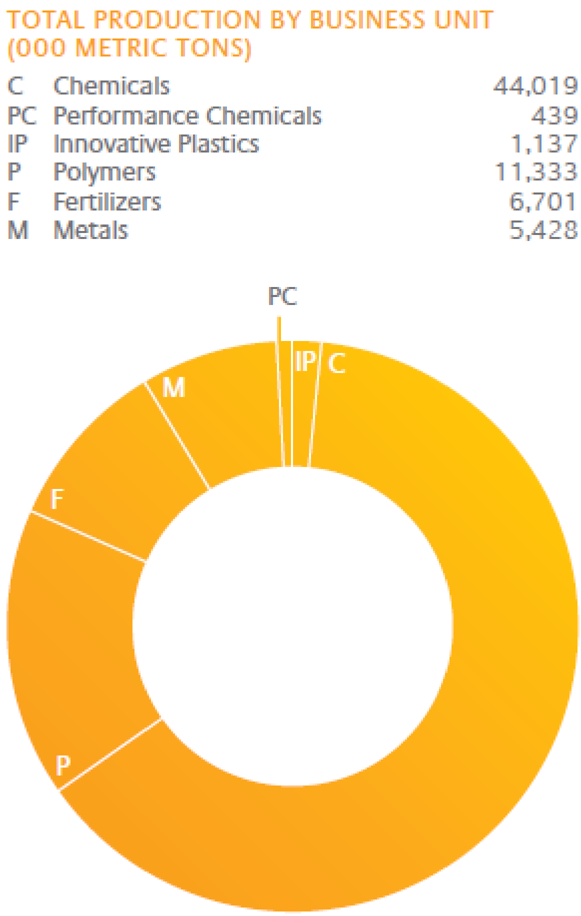

Figure 3: total worldwide production per business unit in 2011

On the site in Geleen approximately 1,250 employees are working to keep the ten chemical plants for processing plastics, gasolines and other chemical products operating. See Table 3 for the plants owned by SABIC Geleen and the products that each plant processes. Note that Logistics concerns the transportation of the gasses and liquids produced by the naphtha crackers over the complete site in Geleen. In 2007, the amount of products which were produced on site Geleen and sold in Europe could be seen in Table 4. Note that ethylene and propylene is used as raw materials for the production of polyethylenes and polypropylenes and is therefore not sold to external parties. It happens occasionally that one or more of the polyethylene or polypropylene plants could not perform with the full capacity (e.g. because of a small stop or turnaround). The amount of ethylene and propylene exceeding the internal demand is then transported in the pipes, which are connected to the Ruhr area (Germany) and the harbor in Antwerp (Belgium). If another party uses ethylene or propylene, SABIC receives a refund for this, but the frequency, amount and revenues from this refund is unknown.

Table 3: plants owned by SABIC Geleen and the products they produce

Plant Type	Name of the plant	Production
FP01	High Density Poly Ethylene 3 (LD3) High Density Poly Ethylene 4 (LD4)	High Density Poly Ethylenes
FP03	Low Density Poly Ethylene 15 (S15) Low Density Poly Ethylene 16 (S16) Low Density Poly Ethylene 17 (S17	Low Density Poly Ethylenes
FP05	Poly Propylene factory 3 (PPF3) Poly Propylene factory 6 (PPF6)	Poly Propylenes
FP06	Naphtha cracker 3 (NAK3)	Ethylene, Propylene, Benzene, Butadiene, Methyl-tert-butyl-ether and Liquid Hydrocarbons
FP07	Naphtha cracker 4 (NAK4)	Ethylene and Propylene
FP08	Logistics (LOG)	-

Table 4: amount of products (in kton/year) produced in 2007 by SABIC Geleen and sold in Europe (Source: sabic-limburg.nl, 2008)

Product	Amount produced in 2007 in Geleen (in kton/year)	Amount sold in 2007 in Europe (including 2.2 million ton from Saudi Arabia) (in kton/year)
Ethylene	1,265	n/a
Propylene	745	n/a
Polyethylene	940	2,400
Polypropylene	620	1,200
Chemicals and aromatics	1,180	7,200

The mission of SABIC is “to responsibly provide quality products and services through innovation, learning and operational excellence while sustaining maximum value for our stakeholders”. The incorporating vision is “to be the preferred world leader in chemicals” (SABIC Vision + Performance Report & Accounts, 2011).

1.2. Site Geleen Organization structure

The site in Geleen is divided into four different departments (see Figure 4 for the organization structure of SABIC Geleen).

- Site Services,
- Manufacturing Polymers,
- Manufacturing Chemicals and Intermediates, and
- Site Improvement

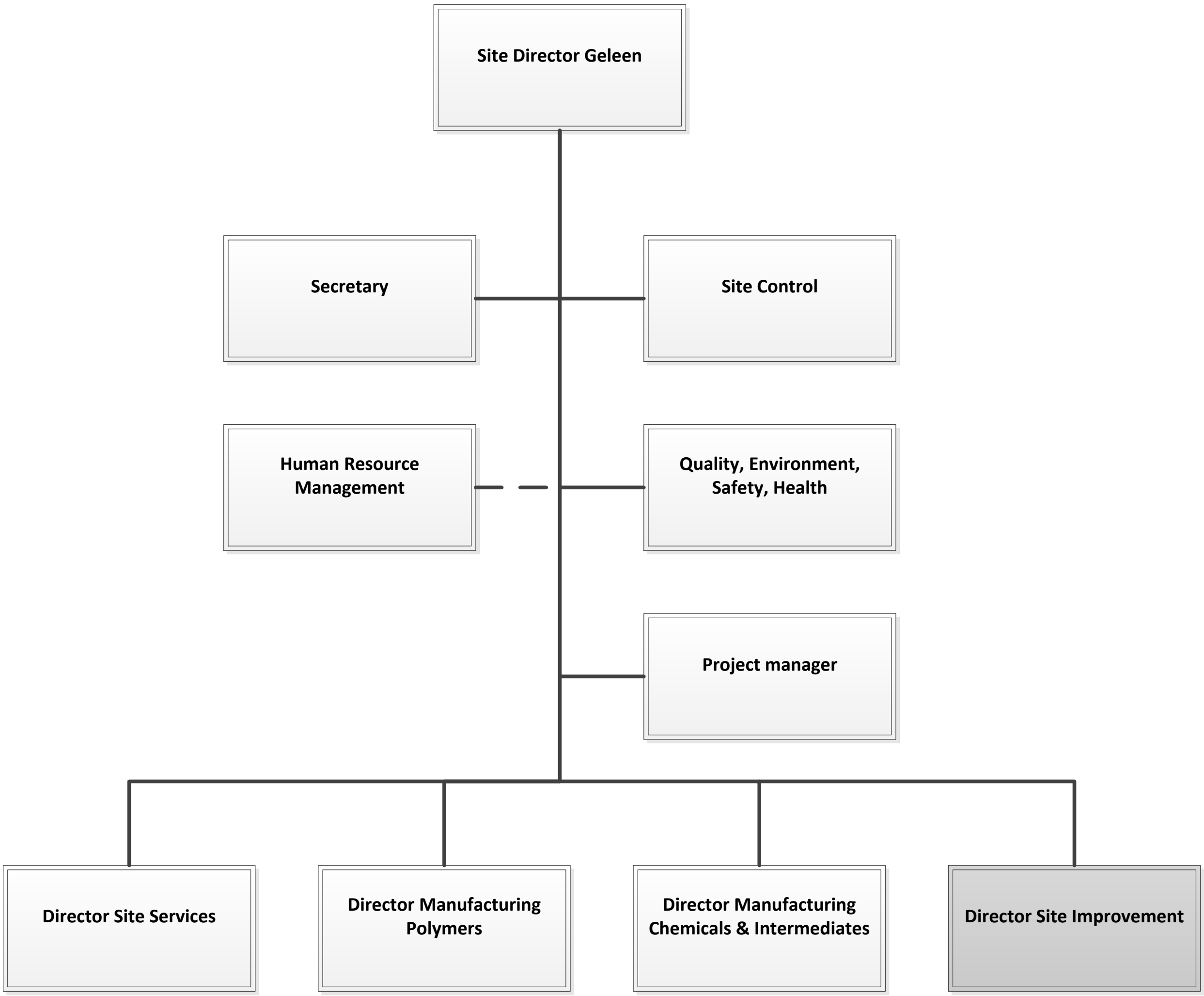

Figure 4: SABIC Geleen site organization structure
(source: Intranet SABIC Europe organization structure manuals, 2012)

The Site Services department strives towards a maximum synergy for executing maintenance and inspections together with Manufacturing Automation systems. It considers performing long-term planned or highly complex maintenance activities.

The manufacturing polymers department and the manufacturing chemicals and intermediates department, also called the Running Business department, are operating the chemical systems within determined frameworks or operating windows as safe and cheap as possible. These departments also determine what amount of what product within what time limit needs to be produced. Running Business performs short-term commonplace maintenance activities in order to keep the process up.

SABIC Geleen finds it important that the “systems are being used safely, cost efficiently and with integrity” (Manufacturing Excellence Work Processes, Meeting and Organization Structure; the coherency, 2012)). SABIC Geleen demands attention to short-term as well as long-term safety, efficiency and integrity of the systems, which seems difficult to combine in organizations. That is because long-term attention receives a lower priority than the day-to-day short-term issues when operating the systems. SABIC Europe recognizes this difficulty in combining short-term and long-term focus and, in order to increase the priority of the long-term agenda, they founded the Site Improvement department. The department focuses on (Manufacturing Excellence Work Processes, Meeting and Organization Structure; the coherency, 2012):

- Laying a foundation for the operation of the chemical systems so that they can be operated with integrity (the system is able to operate its intended function without being degraded or impaired by changes or disruptions in its internal or external environments), safety and at minimum costs (i.e. maximum cost efficiency),
- Initiating and working out projects to improve safety,
- Initiating and working out projects to improve cost position, and
- Laying a foundation for the maintenance of the systems so that they can be operated with integrity, safety and at optimum cost.

The department determines the boundaries of the maintenance process parameters, the time intervals of when the maintenance activities are performed and the content of the maintenance tasks to be performed within the time windows. Site Improvement works together with the Running Business (RB) and Site Services (SS) department to be able to combine short-term and long-term focus on improving the operation of the chemical plants.

1.3. Problem Introduction

In multiple interviews with the manager Reliability & Integrity of the Site Improvement Polymers department, multiple problem or improvement areas were mentioned. The difference between a potential problem and an improvement is that for an improvement, it is striven to achieve a condition superior to the one before the implementation of the improvement, whereas for a problem, there is a gap between the actual and the desired state. From the above definitions, solving a potential problem has priority over improving a condition because the need to close the gap between the actual and desired state is mostly larger than the need to decrease the space for improvement. The manager mentioned six potential problems that he would like to have solved and three improvement areas:

- Low experience of the maintenance employees,
- Unavailability of spare parts when wanting to do maintenance,
- Obsolete stock of spare parts,
- Data management in general,
- Procedures and work processes,
- Too high requirements on maintaining the chemical systems by the Dutch Government, suppliers of (parts of) chemical systems, and other external parties like those who perform oil inspections or repair the repairable spare parts,
- Improvement through better or other collaboration between the maintenance department and the production department,
- Improvement through better or other collaboration between different maintenance sub departments (e.g. electrical and mechanical), and
- Improvement through better or other collaboration with external maintenance and repair parties.

The above-mentioned problem and improvement areas are evaluated upon the following criteria:

- Relevance for SABIC Geleen: are there topics which should be taken care of immediately, or can the topic wait for solving the problem or improvement. The trivial question for this criterion is: "How much can we gain by solving (part of) the problem or improving the situation?",
- The time needed for analyzing and redesigning the selected problem or improvement area,
- Available time of the master student: the master thesis project should be finished within five months,
- Chance of success: the possibility that the problem or improvement is (partially) solved within the given time limit,

- Knowledge and experience of the master student with the topic, i.e. what is the real value of the master student for the company, and
- Requirements of the university.

Ideally a decision matrix including weight factors for each criterion should be given, so that the potential problem with the highest overall score should be selected. However, quantitative data to determine the scores on each selection criterion were not present. Therefore, it was chosen to hold multiple open interviews between the company supervisor, the first supervisor of the university and me. These interviews served as the basis to determine the topic on which the master thesis will focus on. We could have determined a decision matrix with qualitative scores on the selection criteria but we chose not to because it became apparent from the interviews what the main problems of SABIC Geleen were and where I could contribute most because of my expertise and interests.

The topic chosen for this master thesis is:

"spare parts are not (timely) available when SABIC Geleen wants to do maintenance on the systems"

The manager Reliability & Integrity of the Site Improvement Polymers department mentioned this topic and his feelings of negative consequences multiple times in the open interviews. However, he also mentioned the topic of obsolete stock of spare parts. This topic is however subsidiary to the unavailability of spare parts, because the unavailability of spare parts increases the probability of downtime. The effects of having unavailable stock are more severe (e.g. downtime effects), and therefore need more attention, than having too much of spare parts in stock (e.g. tie on working capital). The reason that some topics of obsolescence are however incorporated in the master thesis is that the reasons for having too many spare parts are mostly also the reasons for having too little spare parts. Both the company and university supervisors agreed with the chosen subject. Other employees (e.g. Maintenance Engineers, Reliability Engineers, SAP Key Instructors, Maintenance Field Planners) of SABIC Geleen underpinned the feeling that this subject causes problems for their company.

The potential problem that spare parts are not timely available when needed can result in downtime which could result in major negative economic effects like decreasing operating profits (Espíndola, Frazzon, Hellingrath, Pereira, 2012). The potential problem of spare part unavailability could have different causes. It could be that the wrong spare parts have been ordered by the person which makes a work order, based on a notification. A malfunction could be ascertained by either a process operator or by maintenance employees when they periodically inspect the system and its parts. This malfunction is then registered in a so-called notification which is the basis for a work order to solve the malfunction. If the part is not available, a purchase order is made, either automatically by the SAP system or by the purchasing department (if the spare part is not in the assortment or when they priority of the notification is urgent (i.e. priority 0 or 1)) and the spare part is ordered at the supplier. Another possible cause for the spare parts to be not timely available when needed could be that the spare parts ordering policy is not correct. It could be that the correct spare parts have been ordered, but they are ordered in the wrong quantity or too late in time for example.

In order to give a first indication on whether the problem is relevant, we checked the actual performance of 2012 in comparison to the targeted performance. The performance of the chemical systems is measured using key performance indicators (KPIs) based on (Monthly Report Plant, 2012):

- uninterrupted supply of processed product (total production, technical on-stream factor, utilization rate),
- quality of processed product (on spec production, first class products, efficiency, Good Manufacturing Practice),
- safety, health and environment (complaints, Occupational Safety and Health Administration recordables, environmental reports, emission/pollution reports),

- people (illness rate, overwork rate and number of violations of the working hours act), and
- finance (fixed cost)

For determining the urgency of spare parts unavailability, we check the utilization rate of the different plants of SABIC Geleen. The utilization rate is defined as the ratio between the actual amount of products produced versus the maximum theoretical amount of production and is calculated with the following formula:

$$Utilization\ Rate = \frac{(CTP - LE - LB - LM - LP)}{CTP} * 100\% \qquad (1.1)$$

where the CTP is defined as the capacity to produce, i.e. the theoretical maximum produced amount of product with the best possible quality and on time with respect to batching times and variable costs. The realized produced amount of product is calculated by subtracting lost production related to external losses (LE), business losses (LB), losses related to maintenance (LM), or losses related to production (LP). The utilization rate indicates the amount of realized production compared to the target. When the actual utilization rate is below target, it shows that the losses are higher than budgeted, which might indicate problems with spare part unavailability. See Table 5 for the actual and target utilization rates of 2012.

Table 5: actual and target utilization rates for 2012 per product per plant

Plant Type	Name of the plant	Actual Utilization Rate in 2012 (in %)	Target Utilization Rate in 2012 (in %)	Products produced
FP01	High Density Poly Ethylene 3 (LD3)	[redacted]	[redacted]	High Density Poly Ethylenes
	High Density Poly Ethylene 4 (LD4)	[redacted]	[redacted]	
FP03	Low Density Poly Ethylene 15 (S15)	[redacted]	[redacted]	Low Density Poly Ethylenes
	Low Density Poly Ethylene 16 (S16)	[redacted]	[redacted]	
	Low Density Poly Ethylene 17 (S17)	[redacted]	[redacted]	
FP05	Poly Propylene factory 3 (PPF3)	[redacted]	[redacted]	Poly Propylenes
	Poly Propylene factory 6 (PPF6)	[redacted]	[redacted]	
FP06	Naphtha cracker 3 (NAK3)	[redacted]	[redacted]	Ethylene
		[redacted]	[redacted]	Propylene
		[redacted]	[redacted]	Benzene
		[redacted]	[redacted]	Butadiene
		[redacted]	[redacted]	Methyl-tert-butyl-ether
FP07	Naphtha cracker 4 (NAK4)	[redacted]	[redacted]	Ethylene
		[redacted]	[redacted]	Propylene
FP08	Logistics (LOG)	[redacted]	[redacted]	Ethylene
		[redacted]	[redacted]	Propylene

From Table 5 one concludes that only two (Low Density Poly Ethylenes from system 17 and Propylene transportation from Logistics) product plants from sixteen met the target utilization rate in 2012. The fourteen product plants failed to meet their target with on average [redacted]

From this analysis it is clear that the utilization targets are not met by almost all plants, which means that the losses are too large for these plants. See Table 6 for the percentage of the actual utilization rate in 2012 lost because of losses related to maintenance. The average losses related to maintenance in 2012 depict the percentage at which the utilization rate could have been maximally higher, were there no losses related to problems with maintenance. Therefore, the average losses as depicted in Table 6 indicate the upper bound of the room of improvement if we could solve all problems related to maintenance.

Table 6: average losses (in % of the capacity to produce) related to maintenance in 2012 per plant

Plant Type	Name of the plant	Average losses related to maintenance in 2012 (in % of the capacity to produce)
FP01	High Density Poly Ethylene 3 (LD3)	[redacted]
	High Density Poly Ethylene 4 (LD4)	[redacted]
FP03	Low Density Poly Ethylene 15 (S15)	[redacted]
	Low Density Poly Ethylene 16 (S16)	[redacted]
	Low Density Poly Ethylene 17 (S17)	[redacted]
FP05	Poly Propylene factory 3 (PPF3)	[redacted]
	Poly Propylene factory 6 (PPF6)	[redacted]
FP06	Naphtha cracker 3 (NAK3)	[redacted]
FP07	Naphtha cracker 4 (NAK4)	[redacted]
FP08	Logistics (LOG)	[redacted]

A possible explanation for part of the losses in maintenance could be because spare parts are not available which unnecessarily delays the maintenance activities. This in turn increases the losses related to maintenance and this could be part of the explanation that for almost all plants the actual utilization rate of 2012 did not meet the target. The conclusion based on this first analysis is that there is room for improvement regarding the losses of maintenance. The improvement might be partially done by guaranteeing better spare part availability.

1.4. Chapter summary

The first chapter introduced the situation and the problem statement of SABIC Geleen: almost all plant types did not meet their target utilization rate in 2012. A large portion (on average [redacted] of the total capacity to produce) is due to losses in maintenance. This percentage also includes losses because of unavailable spare parts, which delay the maintenance activities. This master thesis project will focus on spare part unavailability.

2. ANALYSIS OF THE PROBLEM STATEMENT

Chapter 1 provided an introduction of the research area and the problem statement of SABIC Geleen. The problem which is selected will be analyzed in more detail in this chapter to conclude whether the feeling of the manager Reliability & Integrity is correct and that spare parts are unavailable when needed to do maintenance. In section 2.1 we will discuss the data we need to make the analysis. Because of large amounts of maintenance data, the dataset should be filtered to obtain only relevant data from the dataset. Because the data are not very reliable the dataset should also be cleaned as well. The filtering and cleaning of the dataset is described in Appendix E – Cleaning and filtering the zpm_stat_list. In section 2.2 the analysis is performed and it is concluded in section 2.3 whether the chosen problem area is indeed relevant for SABIC Geleen.

2.1. DATA REQUIREMENTS AND SOURCES OF INFORMATION

To determine the relevance of the problem of the unavailability of spare parts, it should be checked using data. We would like to extract the following information from maintenance and asset utilization data:

1. How often took maintenance activities longer for **system**, Y, because **spare part** X was not available?
2. What were the **economic consequences** of this unavailability of a spare part?

The economic consequences of unavailability should be determined using the criterion percentage of the time per year (in this case 2012) that a spare part is unavailable multiplied by the costs of unavailability, i.e.

$$economic\ consequences\ (in\ €/year) = unavailability\ (in\ \%/year) * cost\ of\ unavailibility\ (in\ €) \quad (2.1)$$

This multiplication is needed because both terms are important for determining the seriousness of unavailability of spare parts. Percentage alone does not say a lot about the seriousness of the consequences of unavailability because a spare part can be unavailable a lot of times, but if the monetary value of this unavailability is close to zero, the total costs will also be low. The same reasoning can be given for the measurement of monetary value. This makes clear that we need to use both measurements to select the spare parts for which we can gain most.

The data we need to have in order to answer the first question, i.e. how often it was that maintenance employees had to wait with the maintenance activity because of spare part unavailability is found in the SAP R/3 Plant Maintenance information system. SABIC Geleen uses the SAP R/3 Plant Maintenance information system to store and analyze data of orders and parts which are important to guarantee maximum customer satisfaction because of high quality goods which are delivered on time with the least amount of costs possible. According to SAP, “efficient plant maintenance is vital to a company’s ability to optimize and harmonize its production processes which is able to lead to a strategy with considerable operational benefits” (Stengl, Ematinger, 2001), which is in the interest of SABIC Geleen. The data is retrieved using the zpm_stat_list transaction for the year 2012 (see Appendix C – Subset of zpm_stat_list data including a definition list and a timeline for a subset of the zpm_stat_list data, a definition of each column and a corresponding timeline). Note that for the timeline, the date at which the order is ready for budgeting (Date PLND) could be after the actual finish date (Date ABPR) when one deals with a work order with high (i.e. 0 or 1) priority. Furthermore, the start and finish date for the Technical Mission Statement (Date TOS and TOS Del) are only applicable if the order demanded such a statement. The same holds for the demand and delivery of material (Date WFMA and WFMA Del). Finally, it could be that the actual start date (Date Start) and the actual finish date (Date ABPR) could be earlier or on exactly the same date as the desired start date (Req. Start) or desired finish date (Basic fin.) respectively.

The data of 2012 is retrieved because all of the following maintenance activities were performed in 2012:

- Maintenance activities in small stops: the malfunction is inspected and the risk is taken to not immediately repair the system but to do the activities in the near future because it might be economically more efficient (e.g. the production run could be finished before the maintenance is done) or because of clustering efficiency (e.g. more maintenance activities on the same system could be done at the same time during a small stop). The maintenance activity is stop-related,
- Maintenance activities in turnarounds: the activities in the turnarounds are not within the scope of the master thesis because another department is responsible for these activities but it also has implications for the Site Improvement department. This is because maintenance activities might go wrong in the turnaround (e.g. because of limited knowledge or experience of the maintenance employees. See section 5.7 for a detailed explanation of this topic), and therefore another maintenance activity should be undertaken after the turnaround, which is the responsibility of the Site Improvement department,
- Maintenance activities because of a breakdown or malfunction. These activities could be performed when the system is operating, and
- Maintenance activities because of a preventive maintenance plan or inspection. The activities could be performed when the system is operating.

It was mentioned by several employees of different departments of SABIC Geleen that 2012 was a bad year in terms of the availability of the systems because of more breakdowns with a bigger negative economical, safety or health impact than preceding years (e.g. there were some problems with gearboxes in the high density plants and some problems with electric motors in the low density plants). Although the negative effects might be larger for 2012 than it was for the previous years, still the conclusions and implications for 2012 regarding the most problematic phase(s) of the spare parts ordering process or the category of spare parts which appears to be most unavailable might give insights for the previous years as well. Because 2012 was not a good year we should keep in mind that the gain of improving the situation for 2012 is an upper bound (i.e. because in 2012 the negative economic effects were larger than the previous years, also more gains could be made). Furthermore, the conclusions and implications are based upon the newest information available. One should finally note that we do not need to compare data from several years as the goal of this master this is to discover and redesign issues of spare part unavailability, so therefore the retrieval of data of one year is enough to make the analysis.

The notifications and work orders of 2012 retrieved from the SAP system are useful data for answering the first research question because one can see for which orders the actual finishing date was later than the desired end date. If these orders also had a WFMA status during the ordering process and exceeded the desired end date, this could be an indication that the order was too late because of lack in material. However, the problem could be that the pre-maintenance activities (e.g. opening the work order or authorizing it) have had such a long lead time that the desired end date is almost passed and certainly not achievable anymore (see Figure 5: example of a work order with a long lead time in the scheduling process of the work order Figure 5 for a graphical indication).

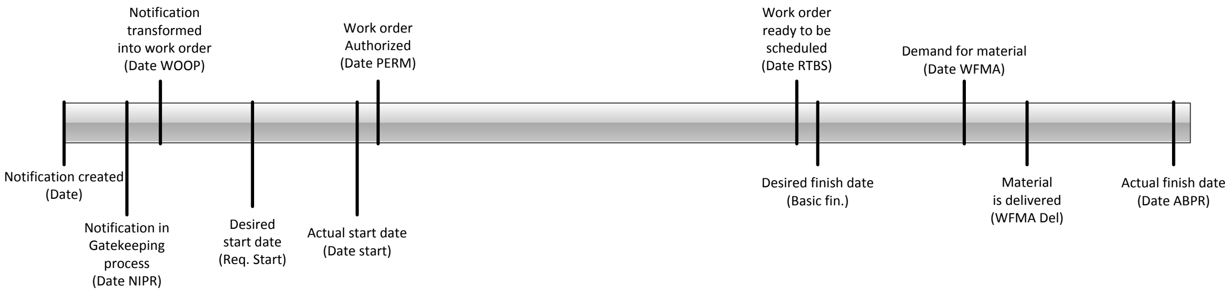

Figure 5: example of a work order with a long lead time in the scheduling process of the work order

In this example, the lead time of the scheduling of the work order was too long (a long period between the authorization of the work order and the moment that the work order is ready to be scheduled) and we would have wrongly concluded that the delay of the work order was due to spare part unavailability (because the moment between demanding and delivery of the material is relatively short), whereas we should have concluded that the pre-maintenance activities have had a relatively long lead time which caused the work order to be too late.

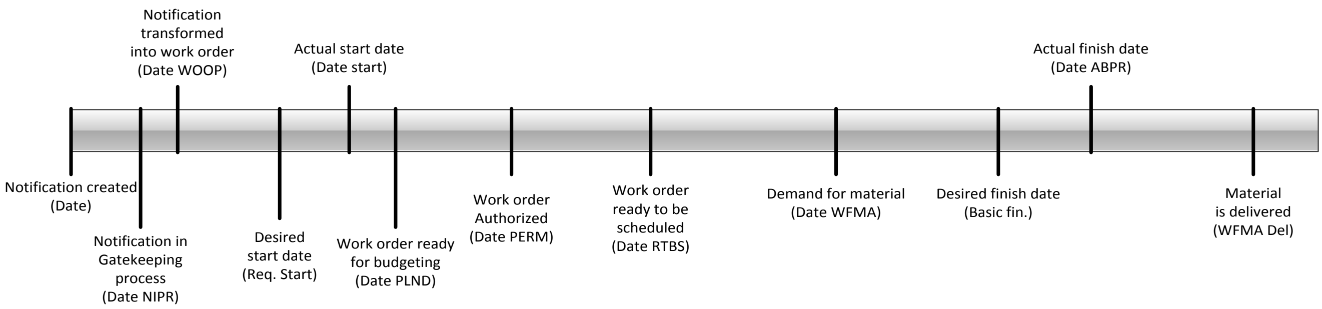

Figure 6: example of a work order with a delivery date of the ordered material after the approval date

We need to make a distinction between a WFMA status which is still open after the date of approval (i.e. WFMA Del is after the date ABPR), i.e. the date on which production approves the plant ready for processing again (see Figure 6 for an example), and the WFMA status deletion date before the date of approval is reached (see Figure 7 for an example).

When the WFMA status is still open after the date of approval, it looks like employees are stocking spare parts because the spare part is not needed anymore for the maintenance activities while production already approved it. This possibly could point at low confidence of the Maintenance Field Planner and maintenance employees in the ordering process. They will order an additional amount and stock the parts locally so that they have some parts in stock in case the order process is not fast or reliable enough. It could be possible that the maintenance men are judged on their ability to keep the systems up running. In order to ensure themselves that aspects outside their own control, e.g. the not timely delivery of spare parts, will not hinder their performance, they will buffer against these aspects, e.g. by ordering more than necessary and stock it locally. Because this ordering could be locally initiated, the warehouse has no knowledge of these parts in stock, and it is therefore also not recorded in the SAP system, and therefore inefficiencies occur (e.g. spare parts are ordered because the inventory level according to SAP is too low, but the spares are available in the local warehouses). This locally initiated stock is the so-called black stock. Several employees of SABIC Geleen (i.e. Maintenance and Reliability Engineers, and Purchase Schedulers) mentioned that SABIC Geleen has problems with black stock.

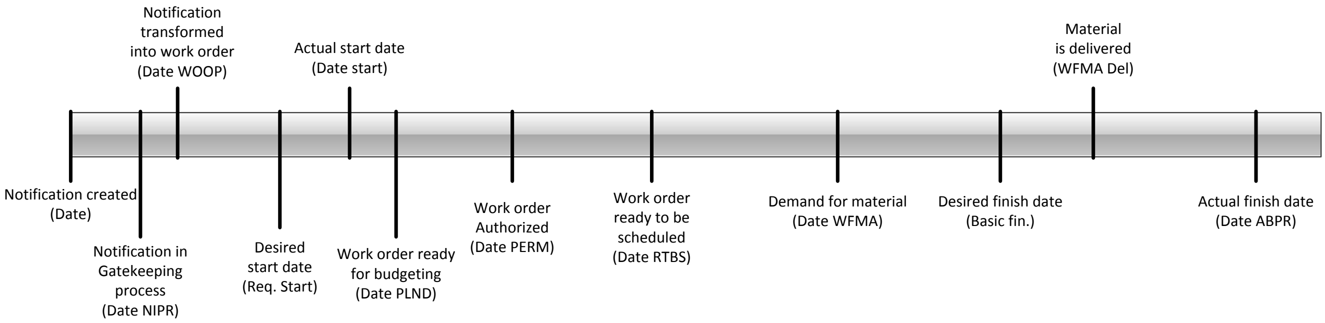

Figure 7: example of a work order which was approved too late because of a too long delivery time of material

When the WFMA status is closed before the maintenance work order is approved by production but after the desired finish date (Basic fin.), indicated in Figure 7, it is possible that the maintenance activities were delayed because of lack in spare parts. When the material is received, the activities can proceed, but this delay in material availability is likely to have caused the delay in the maintenance activities.

For the orders which were too late because of material unavailability we need to check whether the work order had a long time before it was processed, whether the lead time of the authorization and budgeting took a long time, or that the delay in the work order was caused by long delivery lead times. Furthermore, it could be investigated for the delayed work orders whether this delay was because of problems with the order policy (e.g. demanded material was not in stock while it actually should have been or that it was a decision of SABIC Geleen to not keep the part on stock).

For answering the second research question, i.e. what the economic consequences of the unavailability of a spare part were, the following costs are taken into account:

- Downtime cost (measured by the amount of tons of production lost multiplied by the asset utilization margin of SABIC Geleen). We assume that all tons of produced product by SABIC Geleen could always be sold to the customers,
- Cost related to solving safety, health or environmental issues (e.g. because of a leaking pipe, the underlying ground is polluted and needs to be remediated), and
- Cost of urgency ordering the spare parts when it was not really necessary (e.g. if more than one spare part was demanded and only one (say X) of the two was urgency ordered and had to wait for the other part, it was perhaps unnecessary to order part X with urgency).

The economic consequences could be found in the PROMISE asset utilization database (see Appendix D – Subset of asset utilization data including a definition list for a subset of the PROMISE asset utilization data and a definition of each column). Because no order numbers are depicted in the asset utilization database, the date and description of the notification should be searched for in the asset utilization data. If there is no match, we have to conclude that there was no production loss caused by spare part unavailability. If we found a similar description in the asset utilization data as was indicated in the zpm_stat_list at the same date, the production loss in tons could be read from the asset utilization data and multiplied by the long-term (ten to fifteen years) average asset utilization margin, dependent for the plant at which the production loss appeared,

$$\begin{aligned} &Economic\ value\ of\ lost\ production\ (in\ €) \\ &\qquad = amount\ of\ lost\ production\ (in\ tons) * asset\ utilization\ margin\ (in\ €/ton) \end{aligned} \tag{2.2}$$

One should note that if the maintenance activity is stop related, it is assumed by SABIC Geleen that the plant otherwise would be processing with maximum capacity, whereas for non-stop related maintenance activities, the actual capacity utilization degree just before failure is used to calculate the production loss. This implicates that the potential gain to be found by a (re)design to overcome the negative economic consequences is an upper bound.

We should note that the value of the long-term average asset utilization margin may not be valid because of the following reasons:

- The management of SABIC Geleen is mostly interested in the amount of production loss in tons and to a lesser extent in money lost because of production loss. Therefore, the asset utilization margin is based on a long-term yearly average. However, because of the economic crisis, current margins are significantly below the average utilization margin.
- It is complex to let the PROMISE system keep track of the actual asset utilization margin because of potential quality issues (e.g. when starting a new production run) and different margins per product

type. This means that, in order to have a valid asset utilization margin, the PROMISE system should keep track of the type of product produced and the quality of the produced product (as lesser quality means a lower asset utilization margin and higher quality means a higher margin). This would make the PROMISE system a lot more complex which is unnecessary given the fact that the management of SABIC Geleen is only to a less extent interested in the monetary value of the lost production.

Despite the potentially invalid long-term asset utilization margins, we still use the data for estimating the economic consequences of spare part unavailability. We do not need an exact monetary value of the lost production while the economic consequences are used for determining how much could be gained approximately by solving (part of) the problem of spare part unavailability. We should note now that the value to be found is an upper bound (i.e. it is an absolute maximum value) of how much could be gained. A lower bound could be found when using the actual average asset utilization margins of 2012 for the plants (because the margins are now significantly below average because of the credit crunch), not incorporating the average margins of the past years. See Table 7 for the plants actual production margins of 2012 and the long-term average utilization margins for all types of factories. Note that because FP02 is owned by DSM, the actual production margin is unknown for SABIC Geleen. Furthermore, FP04 and FP08 do not have asset utilization margins as these plants do not produce products but take care of the transportation process (FP04 is the expedition of the plastic pallets in big bags, FP08 is concerned with the transportation of liquids and gasses from, to, and between the naphtha crackers). For these plants, money is lost because a tank or silo has to be emptied to create enough buffer capacity. FP05 produces products for two different markets with different margins, i.e. the molding and extrusion market (see the first indicated asset utilization margin in Table 7 for FP05), and the automotive market (see the second utilization margin in Table 7 for FP05). FP06 and FP07 (both naphtha crackers) produce ethylene and propylene (see the first asset utilization margin in Table 7 for FP06 and FP07). FP06 is also concerned with the production of benzene (see the third asset utilization margin in Table 7), butadiene (the fourth asset utilization margin), and methyl tert-butyl ether (the fifth asset utilization margin in Table 7).

Table 7: actual asset utilization margin of 2012 and long-term average asset utilization margin per plant type (in €/ton)

Plant Type	Asset utilization margin of 2012 (in €/ton)	Long-term average asset utilization margin (in €/ton)
FP01	[redacted]	[redacted]
FP02	[redacted]	[redacted]
FP03	[redacted]	[redacted]
FP05	[redacted]	[redacted]
	[redacted]	[redacted]
FP06	[redacted]	[redacted]
		[redacted]
		[redacted]
		[redacted]
		[redacted]
FP07	[redacted]	[redacted]
		[redacted]

The employees of the Asset Utilization department (Process Technologists) mentioned that it is not always properly written down when a production loss was caused by an unavailable spare part. Therefore we should keep in mind that the conclusions based on the used data might not be totally valid but they should give an impression on how much to gain by solving (part of) the problem and where to focus on when (re)designing.

2.2. Data analysis of the work orders

Since the amount of work orders for the year 2012 is very large (more than [redacted] work orders), time resources are insufficient to analyze all work orders, which demands for a selection of work orders (also see (De Groof, 2010). Time and effort is spent on work orders with the highest impact on the analysis because the potential gains by solving (part of) the problem are also the highest. Ideally we would have determined the impact of a delay because of spare part unavailability in economic terms (i.e. how much money is lost because of the unavailable spare part). This information is not available in the SAP system, but it is depicted in the PROMISE asset utilization database (see Appendix D – Subset of asset utilization data including a definition list for a subset of the data). Unfortunately, there is no direct link between a work order and the economic consequences. In order to link the information, one should check whether the cause of breakdown or malfunction indicated in the notification/work order matches with the cause indicated in the PROMISE asset utilization database. However, because time resources are not sufficient to do this, we first estimate the coding with the highest impact. Impact is estimated on the criterion percentage multiplied by mean delay (see formula E.1). We focus on the mean delay because it is a robust statistic, i.e. it is the least sensitive to outlier values. We did not check for univariate outliers because an extreme delay value compared to the mean delay does not necessarily mean that it is an invalid value.

2.2.1. Determination average impact of different maintenance codes

The work orders which were indicated as too late and also did not meet the schedule finish date are the input of our analysis. We first determined the amount of orders belonging to each code (see Table 8) to give an idea for which code the impact of a delay may be most problematic. For these codes, the mean delay is calculated (see Table 9) and the impact is calculated, using formula E.1, based upon this information (see Table 10). From there on, the codes with the highest impact are selected and analyzed in more detail (see Table 12).

Table 8: number and percentage (number of orders with a code divided by the number of orders which did not meet the schedule finish date) of work orders of 2012 belonging to a maintenance coding

Plant	# of work orders remaining (they had a demand for material and did not meet the scheduled finish date)	# of orders with a 21 code	% of orders with a 21 code	# of orders with a 22 code	% of orders with a 22 code	# of orders with a 23 code	% of orders with a 23 code	# of orders with a 24 code	% of orders with a 24 code	# of orders with a 30 code	% of orders with a 30 code	# of orders with a 40 code	% of orders with a 40 code	# of orders with a 60 code	% of orders with a 60 code	# of orders with a 67 code	% of orders with a 67 code
FP01	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP02	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP03	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP04	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP05	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP06	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP07	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP08	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Sum	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

From Table 8 our hypothesis is that orders with a 60 code (i.e. corrective maintenance activities) are most problematic because most orders belong to this category. Note that the percentages in the sum row of the table are calculated by the following formula:

$$(sum\ \#\ of\ orders\ with\ a\ code / sum\ \#\ of\ orders\ which\ did\ not\ meet\ schedule\ finish\ date) * 100\% \qquad (2.3)$$

As is mentioned in Appendix E – Cleaning and filtering the zpm_stat_list, we need to multiply the percentage of orders which are too late with the mean delay in order to have a more valid conclusion on which maintenance coding could be most problematic. See Table 9 for the mean delays (in days).

Table 9: mean delay of work orders of 2012 for each maintenance coding (in days)

Plant	Mean delay of work orders with a 21 code	Mean delay of work orders with a 22 code	Mean delay of work orders with a 23 code	Mean delay of work orders with a 24 code	Mean delay of work orders with a 30 code	Mean delay of work orders with a 40 code	Mean delay of work orders with a 60 code	Mean delay of work orders with a 67 code
FP01	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP02	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP03	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP04	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP05	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP06	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP07	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP08	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Avg.	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Also from Table 9, the first impression is that the average delay is highest (i.e. [redacted]) for work orders with a 60 code. In order to make a more valid conclusion, we multiply the percentages of Table 8 with the mean delays indicated in Table 9 to come up with the average impact for each code (see Table 10). For example, the first cell of Table 10 (the average impact of code 21 for plant FP01) is calculated as:

$$(\text{[redacted]}\ (\%\ of\ orders\ with\ a\ 21\ code\ for\ FP01)/100) * \text{[redacted]}\ (mean\ delay\ of\ orders\ with\ a\ 21\ code\ for\ FP01) \approx \text{[redacted]}$$

Table 10: average impact of a delay for work orders of 2012 per maintenance code (in days)

Plant	Average impact of a work order with code 21	Average impact of a work order with code 22	Average impact of a work order with code 23	Average impact of a work order with code 24	Average impact of a work order with code 30	Average impact of a work order with code 40	Average impact of a work order with code 60	Average impact of a work order with code 67
FP01	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP02	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP03	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP04	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP05	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

FP06	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP07	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP08	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Sum	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

From the summed row of Table 10, one sees that the summated average impact for work orders with a 60 code is very large (i.e. [redacted] days) compared to other codes (the second largest average impact for a code is [redacted] days for code 67, which is more than twelve times less than the average impact for a work order with code 60).

For determining the impact of a delayed work order, we need to combine the frequency with the average delay. An important assumption that we make to be able to estimate the impact of a delay of a maintenance work order is that the effect of delay is equal for each code, e.g. the effect of a delay for a preventive work order is equal to a delay of a corrective work order. This manager Reliability & Integrity of the Site Improvement Polymers department mentioned that:

> "**regardless the code, a delay in the maintenance activities would cost about the same"**

Therefore it is justified to use the same weight factors for comparing the average impact for each code. Our initial hypothesis is therefore confirmed and we conclude that corrective maintenance orders have the highest impact of a delay. A logical explanation for the higher impact of the delay for corrective maintenance activities is that the failure appeared unpredicted. If at that moment no or not enough stock of the needed part is available to solve the problem or the delivery lead time of the spare part is long and unreliable, the maintenance activity could not be finished on time. Because of the highest average impact we focus on the work orders with a 60 code for our further analysis and (re)design in the master thesis.

2.2.2. Calculating the economic effects of corrective maintenance work orders

In paragraph 2.2.1 we focused on the impact of a delay of a maintenance work order, but did not relate the impact to economic effects which is needed to obtain a reliable conclusion which type of maintenance work order should be topic for further research.

The economic consequences are used to estimate how much we could gain by solving (part of) the spare part unavailability problem and how much we should maximally invest in (re)designing the issue to solve the problem in a cost efficient way.

The selected work orders, i.e. the corrective maintenance activities which had a delay need to be further analyzed to determine whether money was lost because of the delay in the work order. As discussed in section Data requirements and sources of information2.1, the following costs are taken into account:

- Downtime cost (measured by the amount of tons of production lost multiplied by the asset utilization margin of SABIC Geleen). We assume that all tons of produced product by SABIC Geleen could always be sold to the customers (see Table 7 for the asset utilization margins),
- Cost related to solving safety, health or environmental issues (e.g. because of a leaking pipe, the underlying ground is polluted and needs to be remediated), and
- Cost of urgency ordering the spare parts when it was not really necessary (e.g. if more than one spare part was demanded and only one (say X) of the two was urgently ordered and had to wait for the other part, it was perhaps unnecessary to order part X with urgency).

The downtime costs could be determined by combining asset utilization data from the PROMISE system with the selected work orders from the SAP system (as explained in section 2.1). The downtime costs could then be calculated using formula 2.2. A problem with the data from the asset utilization database is that it is not recorded how much production quantity is lost because of spare part unavailability. The cause text of the problem in the PROMISE system is consulted in order to determine whether the complete production loss is caused by part unavailability. When this was not the case (i.e. only a fraction of the production loss is caused by spare part unavailability), it is estimated (based on input of the Manager Reliability & Integrity of the Site Improvement Polymers department) that 10% of this production loss is attributable to the lack of material.

For the remaining work orders which did not have a production loss, it was determined whether there was an increased risk of safety, health or environmental issues which could have appeared because the maintenance activity could not be performed within the scheduled time because of spare part unavailability. This information is retrieved from the long text of the notification (iw23: display notification). Together with the responsible Maintenance Engineer for the plant, the risk was validated (i.e. was the risk (partly) contributable to the unavailable spare part) and estimated in economic terms.

Finally, it was checked whether it was necessary to order the spare part with urgency, which costs additional money. If for example the order was delayed 2 weeks because it did not receive budget authorization and therefore, the part needed to be urgently ordered in order to minimize the delay, this could have been prevented by permitting authorization earlier. In Table 11 the urgently ordering costs are indicated for the suppliers of the spare parts of the selected work orders. Note that the local and central warehouses of SABIC Geleen are also assumed to be suppliers of spare parts (strategic and floor stock spare parts are per definition stocked locally, whereas centrally managed inventory is stocked centrally). For suppliers which are not defined as key supplier by SABIC Geleen, transportation of the goods is the responsibility of SABIC Geleen. Ideally, the transportation is done by the central warehouse, with costs of [redacted] per loaded kilometer. If that is not possible, a cab needs to be hired (with approximately [redacted] per loaded kilometer).

Despite the relatively low costs of urgently ordering and additional transport costs compared to costs of lost production, we analyze the work orders on these costs because it is not known for how many maintenance work orders materials are urgently ordered. If it would be the case for a great amount of maintenance work orders, the total impact of urgently ordering costs and additional transport costs would be high.

Table 11: urgently ordering costs and additional transport costs (in €) for the suppliers of spare parts of the selected work orders in 2012

Supplier	Lower bound urgently ordering costs (in €)	Upper bound urgently ordering costs (in €)	Additional transport costs (in €)
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

Applying all the above mentioned costs to the selected corrective maintenance work orders of 2012 determines how much money we have lost in 2012 and what SABIC Geleen could have (partially) saved if they solved the spare parts unavailability problem. From the analysis, about [redacted] could be saved, which is about 9.7% of the total maintenance budget of SABIC Geleen in 2012, which was [redacted] (Site Geleen: fixed costs 2012 December, 2012). We should note however, that one failure caused about 76% (about [redacted]) of the total costs. If this outlier is removed, still approximately [redacted] could be saved by solving (part of) the problem of spare part unavailability.

2.2.3. Analysis of the corrective maintenance work orders on breakdown category

Because we concluded that the corrective maintenance work orders had the highest impact, we focus further on these maintenance activities in our analysis. Corrective maintenance activities could be distinguished between activities related to automation, electrics, instrumentation and mechanical failures. We analyze which of these failure categories have the highest average impact of a delay and therefore is chosen as the topic of (re)design in the master thesis. See Table 12 for the average impact of a delay for work orders of 2012 per category of the 60 code (in days). The failures related to instrumentation and mechanics have the highest average impact (i.e. [redacted] and [redacted] days respectively) and therefore these work orders are selected for further analysis and (re)design.

An important assumption that we make to investigate what breakdown category causes the largest effects is that regardless of the category of the breakdown, **the probability of a complete production stop, production loss or no production loss is distributed evenly among the categories and different plants**, e.g. the chance that an automation failure causes a complete production stop, a certain amount of production loss during operation, or no production loss at all is the same as the chance for a same kind of failure in the electrical, instrumentation, or mechanical category and is approximately equally for all plants.

Table 12: average impact of a delay for work orders of 2012 per category of the 60 code (in days)

Plant	Automation	Electrical	Instrumentation	Mechanical
FP01	[redacted]	[redacted]	[redacted]	[redacted]
FP02	[redacted]	[redacted]	[redacted]	[redacted]
FP03	[redacted]	[redacted]	[redacted]	[redacted]
FP04	[redacted]	[redacted]	[redacted]	[redacted]
FP05	[redacted]	[redacted]	[redacted]	[redacted]
FP06	[redacted]	[redacted]	[redacted]	[redacted]
FP07	[redacted]	[redacted]	[redacted]	[redacted]
FP08	[redacted]	[redacted]	[redacted]	[redacted]
Sum	[redacted]	[redacted]	[redacted]	[redacted]

2.3. Analysis of the underlying components for the selected work orders

For the remaining work orders the underlying components, the date at which the component is ordered and delivered and information on the urgency of ordering (i.e. with urgency or ordinal ordering) were revealed (iw33: display order, components tab, purchasing data, purchase requisition, purchase document, goods receipt). SABIC Geleen makes a distinction in the spare parts they use based on the criticality of the part in the system. The categorization of SABIC Geleen on criticality for spare parts is followed in the master thesis. It is outside the scope of the project to discuss the validity of the grouping of spare parts in a certain criticality category. SABIC Geleen has Material Master Data Managers which are responsible for keeping up to date the material specification, the class of products in which they belong, the article numbers and the creation or changing of an article number. SABIC Geleen came up with the following five categories:

- Strategic spare parts: critical spare parts which should be delivered within two hours to the maintenance employee and are stored locally at the plant warehouses because the defective component could be immediately replaced by a new part (e.g. manometers). The maintenance employee does not have to wait two hours for the spare part to arrive, but is able to take it from the local stock and replace the defective spare part immediately.
- Centrally managed inventory (CMI): critical spare parts which should be delivered within two to twenty-four hours to the maintenance employee are stored in the central warehouse. Because the defective component could not be immediately removed from the equipment (e.g. a compressor needs to be stopped), it is not necessary to stock the spare part locally because other maintenance activities, which take more than two hours, are needed (e.g. opening the compressor) before the defective component could be replaced.
- Non-stock spare parts: parts which are not critical for the performance of the system and have relative short and reliable lead times (three to ten days delivery time when the material is ordered at a key supplier and on average nine days when the material needs post-processing).
- Floor stock spare parts: consist of consumable materials like work wear and disposable cloths which are obtained contractually from suppliers with a usual lead time of one to two days. Because of the non-criticality of these items, planning and control of these items are the responsibility of the warehouse administrator (and not of the Maintenance Engineers of the Site Improvement department) and are not recorded within the SAP system because of their non-criticality. Floor stock spare parts are not within the scope of the master thesis because the Site Improvement Polymers department is not responsible for this type of spare parts and because no information is recorded in the SAP system which makes it difficult to gather data on this category.
- Free format text spare parts: do not have an article number because they are not in the assortment of SABIC Geleen.

In order to reveal for the spare parts with an article number to which category they belong (i.e. strategic, CMI, non-stock or floor stock), the article number could be filled in into the display material transaction of the SAP system (mm03: display material, basic data 2). For the strategic and centrally managed spare parts, we know that, because a Material Resources Planning (MRP) is made, these parts should be on stock, either locally (for the strategic spare parts) or centrally (for the CMI). Furthermore, the minimum and maximum stock amount is determined by the Maintenance Engineer or the Purchase Scheduler respectively. It is checked whether the part was on stock at the moment it was demanded in the SAP system (mb51: Material Document List). For all spare parts which should have been on stock (i.e. which belonged to the strategic or centrally managed inventory category), they actually were on stock at the moment they were demanded.

2.4. Chapter summary

We conclude that the corrective maintenance activities have the highest impact of a delay (calculated based on frequency multiplied with average delay of a maintenance code), i.e. for all plant types in the year 2012, unavailability in spare parts for a corrective maintenance activity caused an average delay of [redacted] days (see Table 10). We also made a distinction between the automated, electric, instrumentation and mechanical related maintenance activities. From Table 12 it became apparent that the average impact for instrumentation and mechanical related breakdowns are largest (i.e. [redacted] and [redacted] days respectively). Therefore, we further focus on instrumentation and mechanical related corrective maintenance activities.

For the corrective maintenance activities related to instrumentation and mechanical issues which were delayed because of spare part unavailability, we decided for the demanded whether they were urgently ordered or not.

Furthermore, it was determined for the demanded material to which category of spare parts it belongs (i.e. strategic, centrally managed inventory, non-stock, floor stock, or free-text-format spare parts). Spare parts which belong to the strategic and centrally managed inventory spare parts categories should be on stock in the local and central warehouse respectively. It appeared that all spare parts which were determined to be on stock actually were at the moment SABIC Geleen demanded them.

For the corrective maintenance work orders which were delayed because of spare part unavailability, it was researched whether they actually caused negative financial consequences, either by a lost amount of production, costs related to safety, health and environment issues (e.g. costs of remediating polluted ground), or costs of unnecessary urgently ordering the spare parts (e.g. of three demanded components are two components ordered with urgency, while the other component is not urgently ordered and therefore delivered too late). About [redacted], which is nearly 10% of the maintenance budget of SABIC Geleen in 2012, could have been maximally saved if we solved all the problems related to spare part unavailability. A note we should make is that one malfunction contributed to more than 75% of the total costs. After deleting this work order, still 2.3% (about [redacted]) of the maintenance budget of 2012 could have been maximally saved. Based on the information of this chapter and chapter 1, the research design for this master thesis project will be given in the next chapter

3. RESEARCH DESIGN

This chapter provides the research design of the master thesis project, based on the information given in the first two chapters. Firstly, the research goal (section 3.1) and questions (section 3.2) are formulated. In section 3.3 the research area restrictions are presented. Then, the research deliverables are presented and lastly, the outline of this report is indicated.

3.1. RESEARCH GOAL

The goal of this master thesis project is to increase the utilization rate of the plants as much as possible up to the target utilization rates, by decreasing the losses of maintenance caused by spare part unavailability at the lowest possible costs within the maintenance budget of SABIC Geleen. In order to achieve the goal, we developed the spare parts ordering process at SABIC Geleen, based on scientific literature. Based on the spare parts ordering process, a decision tree is developed in order to determine which phase(s) of the spare parts ordering process is/are the most problematic for SABIC Geleen. Based on this information, a (re)design for the problematic phase(s) will be provided.

3.2. RESEARCH QUESTIONS

With this research goal, the main research question is formulated:

> ***"Can SABIC Geleen increase the actual utilization rate of its plants, through reduction of the losses related to maintenance, caused by spare part unavailability, by improving the relevant phase(s) of the spare parts ordering process, within the given maintenance budget of SABIC Geleen?"***

In order to be able to develop a (re)design of the relevant phase(s) of the spare parts ordering process that will fulfill the objective of decreasing the losses of maintenance related to spare part unavailability and therewith improving the actual utilization rates of the plants, first we need to discover what phases are distinguished in the spare parts ordering process. For all phases, it will be investigated what potential problems for SABIC Geleen are and how these could be solved. With this information, the following questions will be answered:

1. *Of what phases does the spare parts ordering process exists, based on the literature review?*
2. *For each phase in the spare parts ordering process, what are the potential problems that could cause spare part unavailability, based on the literature review and practical situation at SABIC Geleen?*

Then, based on the data (as described in chapter 2), it is researched what the actual problems are for SABIC Geleen in the spare parts ordering process. This information is needed to answer the following question:

3. *In what phase(s) of the spare parts ordering process is/are the impact of spare parts unavailability the largest for SABIC Geleen?*

When it is clear what the problems are in the spare parts ordering process for SABIC Geleen, we determine how we could solve this problem. The question below will be answered:

4. *How can we improve the problems of spare part unavailability when SABIC Geleen wants to do maintenance at minimum costs, based on the literature review?*

3.3. RESEARCH DELIVERABLES

Based on the research goal and the main research question, the following deliverables of the master thesis project are determined:

- A design of the spare parts ordering process of SABIC Geleen to be able to identify potential problem areas, based on a literature review
- A design of a decision making tool, a decision tree, which aids employees of SABIC Geleen to systematically arrive, for any work order with a delay because of spare part unavailability, at relevant problem causes and areas
- A (re)design or solution approach of the most relevant problem causes and areas of the spare parts ordering process of SABIC Geleen
- Excel tools for aiding the employees of SABIC Geleen with the determination of selecting a supplier, whether to repair the defective spare part, and the calculation of the replenishment policy parameters

3.4. REPORT OUTLINE

The outline of this master thesis report is shown in Figure 8. The first chapter provided the problem statement of SABIC Geleen, which was analyzed based on relevancy in chapter 2. With that information, a research design is developed in this chapter. Then, firstly the theoretical aspects of this research are discussed in chapter 4 until chapter 17. From chapter 8 until chapter 17, the theoretical frameworks are compared with the current methodology of SABIC Geleen. In the final paragraph of each chapter, the redesigned solution is applied to practical examples of SABIC Geleen.

Chapter 4 will answer the first research question. In chapter 5, potential issues for each phase of the spare parts ordering process will be discussed, based on issues found in scientific literature, as well as practical issues experienced by SABIC Geleen. The second research question is answered in chapter 5.

In chapter 6, a decision tree is developed as input to be able to answer the third research question. In chapter 7 the selected work orders function as input in the decision tree. From there on, one systematically arrives at the phase(s) of the spare parts ordering process which caused the highest negative effects, in order to answer the third research question.

In chapter 8 until chapter 16, decisions regarding the spare parts ordering policy are redesigned. In the first paragraph of these chapters, literature is reviewed on the decisions. In the second section, the current situation of SABIC Geleen is described, which is compared with literature in the third section. Based on the differences between the current situation and literature, redesigns are developed in the fourth section. Finally, the current decision and the redesigned decision are applied on a practical example of SABIC Geleen to determine the benefits of using the redesigned solution.

Chapter 17 describes the main problem areas of SABIC Geleen in the repair or discard process of spare parts. In each paragraph, a problem area is extensively described and a solution is proposed in order to reduce the effects of the problem.

Finally, chapter 18 will provide the conclusion of this research and recommendations regarding this research project for SABIC Geleen.

3.5. CHAPTER SUMMARY

Chapter 3 described the research design to investigate the problem statement of SABIC Geleen. This master thesis project will develop (re)designs or solution approaches to the phases of the spare parts ordering process which have the largest negative consequences. We develop the (re)designs and solution approaches in order to improve the actual utilization rate by having less losses related to maintenance, caused by spare part unavailability. The (re)design should be cost efficient, i.e. the cost of the (re)design should be lower than the amount of money to be gained when the problem is solved. Before developing a (re)design for one or more phases of the spare parts ordering process, we first have to design the spare parts ordering process.

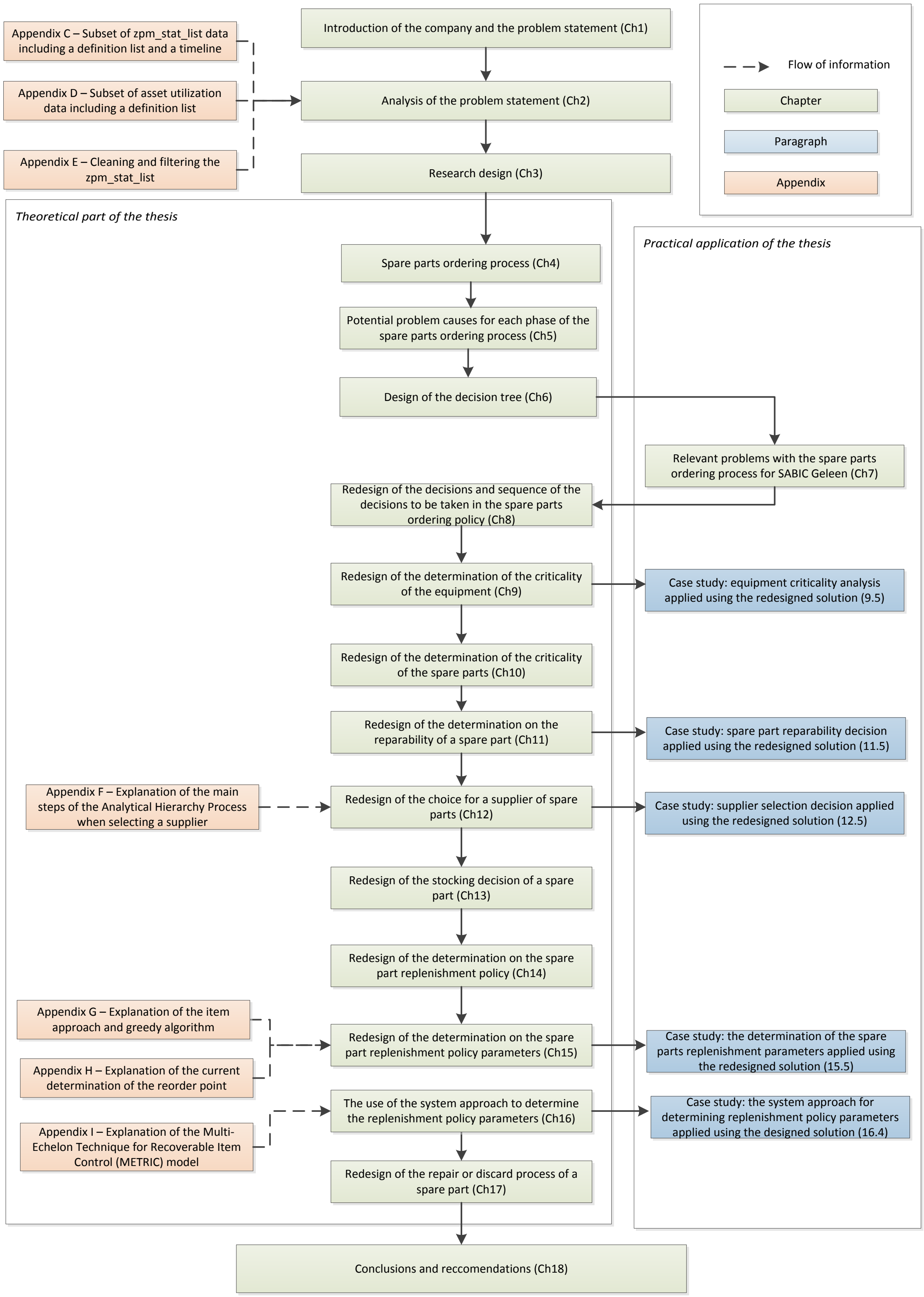

Figure 8: outline of the master thesis report

4. THE SPARE PARTS ORDERING PROCESS

Chapter 1 introduced the topic of this research; the utilization rate of the plants should be improved by decreasing the losses related to maintenance caused by spare part unavailability. From the moment that one realizes that a spare part is needed to do the maintenance until the final assembly of the new part and the removal of the old part, there are eight phases which belong to the so-called spare parts ordering process. The spare parts ordering process is defined as:

> **"the process of knowing that one needs a spare part to perform the maintenance activity to the actual assembly of the new part and the removal of the old part and all steps and decisions in between"**

From the master thesis of Van Lith (2004), the paper of Fortuin and Martin (1999) and internal discussions with the first supervisor of the university, the problem of not having spare parts available when wanting to do maintenance can be divided in the following eight phases (see also Figure 9):

- Need for a spare part,
- From need for a spare part to actual ability to order the spare part,
- Actual ordering of the spare part,
- The spare parts ordering policy,
- Order supply process,
- Order receipt process,
- Actual use of the spare part, and
- Repair or discard process of a spare part.

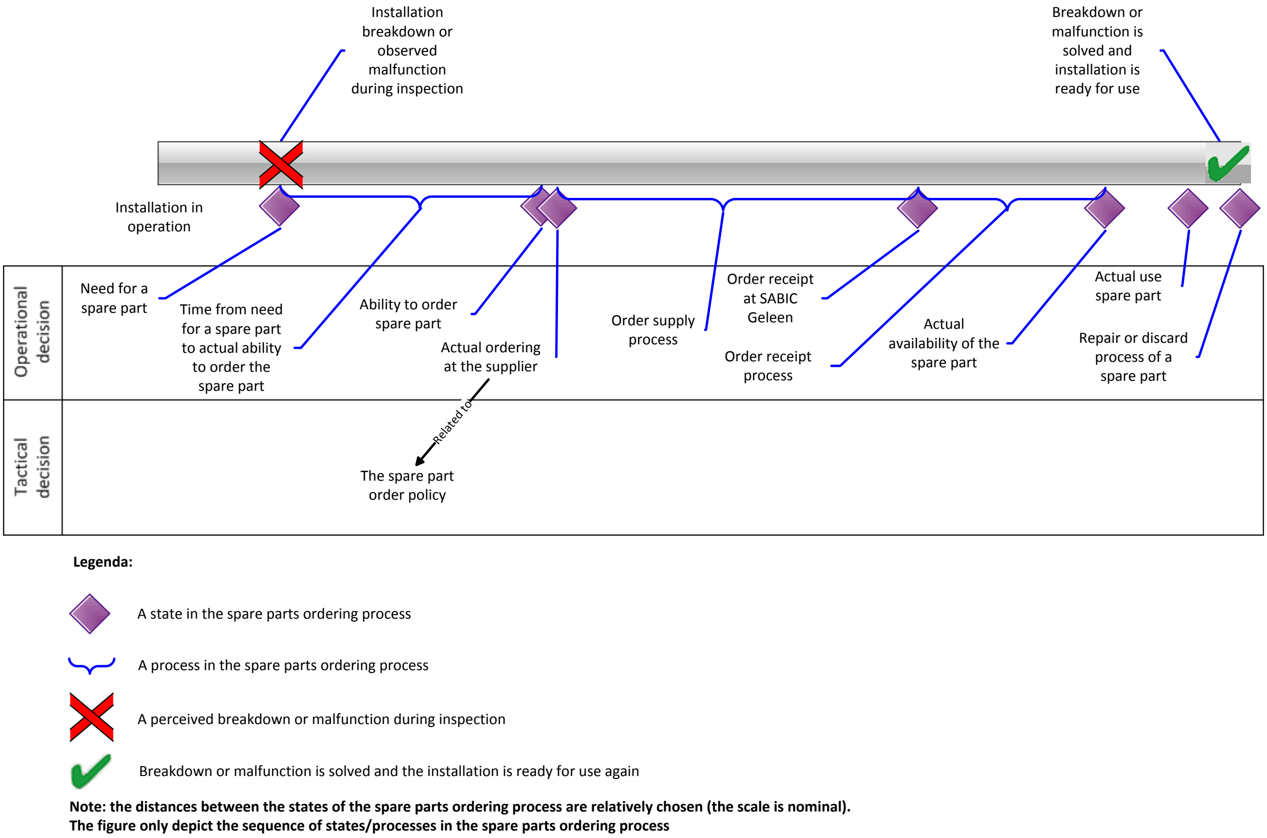

Figure 9: graphical depiction of the spare parts ordering process

Driessen et al. (2010) also developed eight phases in their framework which is comparable with the above mentioned phases. Using a model or framework for indicating the spare parts ordering process increases "the efficiency, consistency and sustainability of decisions on how to plan and control the spare parts supply chain" (Driessen et al., 2010, pp. 2).

The phases are described further in detail in section 4.1 until section 4.8. Note that all but the spare parts ordering policy regards operation decisions, whereas the order policy includes decision on a tactical decision level.

Fortuin and Martin (1999) distinguish three phases, the initial phase, which is not covered in their paper, the normal phase, which covers aspects of section 4.2 (the use of alternative spare parts), section 4.3 (the final order problem), section 4.4 (the stock levels and decision which part to stock) and section 4.5 (the delivery lead time and the reliability of it). Van Lith (2004) discusses four phases, the initial purchase phase, the normal phase for stock parts, the normal phase for repair parts, and the scrap phase. The initial purchase phase considers the lead time from knowing that a spare part is needed (section 4.1) until the part is received (section 4.5). Also parts of section 4.4 (the decision to stock certain spare parts) is covered in the initial purchase phase by Van Lith (2004). The normal phase for stock parts considers parts of section 4.4 (the determination of the height of the reorder point). The normal phase for repair parts considers section 4.8 (the lead time for collecting disassembled parts, refurbishment, and receipt in stock). Finally, the scrap phase also partially considers section 4.8 (the scrapping of spare parts). Driessen et al. (2010) discuss the following eight phases:

- Assortment management (is partially concerned with section 4.2 (information on substitution spare parts) and section 4.4 (the decision to stock the parts locally, centrally or not),
- Demand forecasting (covers aspects of section 4.1 (what spare part is needed in what quantity with what priority), but also aspects of section 4.4 (the number of parts to stock)),
- Parts return forecasting (is concerned with section 4.1 (what spare part is needed)),
- Supply management (is concerned with section 4.2(determining the supply lead time), section 4.3 (the final order problem) and section 4.4 (the choice on the supplier)),
- Repair shop control (takes into account parts of section 4.8 (the lead times for the repair of the spare part)),
- Inventory control (concerns section 4.4 (which spare parts to stock, at which stocking location, and in what quantities, the replenishment policy and its parameters)),
- Spare parts order handling (concerns section 4.2 (accepting, adjusting or rejecting the order for spare parts, and prioritizing amongst spare parts orders)), and
- Deployment (is concerned with section 4.4 (when to replenish spare parts inventories and what quantities to repair or procure, but also aspects of section 4.6 (check the quality, quantity and the lead time of the received spare parts)).

4.1. Phase 1: Need for a spare part

The first phase of the spare parts ordering process is concerned with determining whether a spare part is needed to do a planned or unplanned maintenance activity. When it is clear that one needs at least one spare part, ideally it should be immediately clear what spare part(s) in what amount and with what priority the part(s) is/are needed. If it is not directly clear what spare part in what quantity with what priority is needed, this could lead to possible delays in the maintenance activity, with the possibility of unnecessary downtime and costs.

From scientific literature, another cause of possible unnecessary delaying the maintenance activity is that it is unclear for the maintenance employees at which supplier the new spare part should be ordered. The potential suppliers to order a spare part are:

- The local warehouse (in case of a strategic spare part)
- The central warehouse (in case of centrally managed inventory)
- The key-supplier (in case it was decided that the spare part is not stocked at the site of SABIC Geleen and a preferred supplier is determined for the spare part)
- The non-key supplier (in case it was decided that a spare part is not stocked at the site of SABIC Geleen and no preferred supplier is determined for the spare part)

The decision at which supplier to order the spare parts are clear for more than 99% of the spare parts for SABIC Geleen. Therefore, this decision is not relevant for SABIC Geleen, and this step is not considered in the first phase of the spare parts ordering process.

4.2. PHASE 2: FROM NEED FOR A SPARE PART TO ACTUAL ABILITY TO ORDER THE SPARE PART

The second phase of the spare parts ordering process is predominantly concerned with administration activities. It is about which steps and decisions SABIC Geleen needs to take to order a new spare part in the most efficient manner (i.e. at minimum cost and with an as short delivery lead time as possible). It is therefore crucial to transfer the information from the first phase of the spare parts ordering process (i.e. what spare part in what quantity with what priority) as quickly as possible to the responsible persons or information systems so that the new spare parts can be ordered in the right quantity with the right priority in order to reduce the possibility of unnecessary economic, safety, health and/or environmental consequences.

4.3. PHASE 3: ACTUAL ORDERING OF THE SPARE PART

This phase of the spare parts ordering process is concerned with the actual ordering of the spare part(s) at the supplier. When an employee of SABIC Geleen orders a spare part at a supplier, this person needs to make sure that the correct spare part is ordered on time with the needed quantity. If one of the formerly mentioned aspects is incorrect, this could lead to possible delays in the maintenance activity as a new procurement order for the correct spare part in the right amount has to be made. In the meantime, the maintenance activity has to be delayed because of spare part unavailability, which could lead to an increased possibility of unnecessary downtime and costs.

This phase also takes into account the final order decision when the prescribed supplier of the spare part decides to take the part out of production, or when it would be more efficient for SABIC Geleen to switch suppliers (e.g. because of lower ordering costs or shorter, more reliable delivery lead times).

4.4. PHASE 4: THE SPARE PARTS ORDERING POLICY

Phase four of the spare parts ordering process is a tactical (medium-term, i.e. monthly or quarterly) or strategic (long-term, i.e. yearly or longer) decision making phase and is related to the actual ordering (see section 4.3). Decisions to be taken in this phase of the spare parts ordering process are:

- The criticality of (part of) the system where the spare part is located and a following Failure Mode and Effect Analysis or Reliability Centered Maintenance study for highly critical (parts of) systems in order to decide what spare parts to stock on what location,
- The reorder point,
- The order-up-to-level or order quantity,
- The stock review period,
- The categorization of the spare part as a consumable or a repairable spare part, and
- The choice of the supplier.

4.5. Phase 5: Order supply process

This phase of the spare parts ordering process is concerned with the delivery process of the spare part from the supplier to SABIC Geleen. The activities in the order supply process phase are to rudely check whether the correct part in the right quantity is delivered on time according to an agreed delivery lead time (e.g. we demanded three bearings to be delivered in five days). If one of the former mentioned aspects is incorrectly (e.g. a seal is delivered instead of a demanded bearing), one could choose to contact the supplier that the wrong spare part is delivered and wait for the correct part to arrive, or one could use an available alternative spare part.

4.6. Phase 6: Order receipt process

This phase of the spare parts ordering process is about how long it takes for a spare part to travel from the actual receipt by the warehouse of SABIC Geleen (either local or central warehouse) and the actual availability of the spare part for the maintenance employees. When the correct spare part is delivered on time in the right quantity, a more detailed test is needed on whether the part matches the specifications or drawings (e.g. is the bearing of the correct model and size). Also, required certificates (e.g. safety certificates) because of governmental legislation need to be available to guarantee that the part could be installed and used safely for its intended use for a prescribe time period (e.g. the bearing is safe to assemble under high pressure for maximally 5 years).

4.7. Phase 7: Actual use of the spare part

When it is clear that the spare part is rightly specified and has the required certificates available, the spare part could be assembled in the system to perform the maintenance activity. It could be that the part is assembled incorrectly, which might cause additional system downtime and costs.

4.8. Phase 8: Repair or discard process of a spare part

When the maintenance activity is finished, several parts may have been removed from the system, either to repair them (if the spare part is a repairable part) or to dispose them (if the spare part is a consumable part), which is of concern in phase eight of the spare parts ordering process, based on the tactical or strategic decision of the spare parts ordering policy (see section 4.4). When a spare part is unnecessarily scrapped, an available alternative spare part needs to be searched, or a new spare part needs to be ordered, which increases the possibility of unnecessary downtime and cost.

4.9. Chapter summary

In chapter 4, the first research question, i.e. of what phases the spare parts ordering process exists, is answered. The following phases are part of the spare parts ordering policy:

- Need for a spare part,
- From need for a spare part to the actual ability to order the spare part,
- Actual ordering the spare part,
- The spare parts ordering policy,
- The order supply process,
- The order receipt process,
- The actual use of the spare part, and
- The repair or discard process of a spare part.

For all the above mentioned phases, it is discussed what tasks or decisions are concerned with each phase. In the next chapter, based on the practical situation at SABIC Geleen and information from scientific literature, potential problems for each phase are discovered.

5. Potential problems in the spare parts ordering process based on scientific literature and practical issues of SABIC Geleen

In this chapter, potential issues for each phase of the spare parts ordering process will be discussed, based on issues found in scientific literature, as well as practical issues experienced by SABIC Geleen.

5.1. Phase 1: Need for a spare part

The process of doing the maintenance activity is started when either a process operator or a maintenance employee discovers a problem or malfunction (i.e. corrective maintenance), or when the maintenance employee performs a maintenance activity according to the maintenance plan (i.e. preventive maintenance). For corrective maintenance activities, it is first determined whether the problem could be solved immediately (e.g. a bolt is loose and needs to be tightened) or that additional steps are needed to solve the problem. If it could be solved immediately, the maintenance activity is executed and documented. If not, a notification is

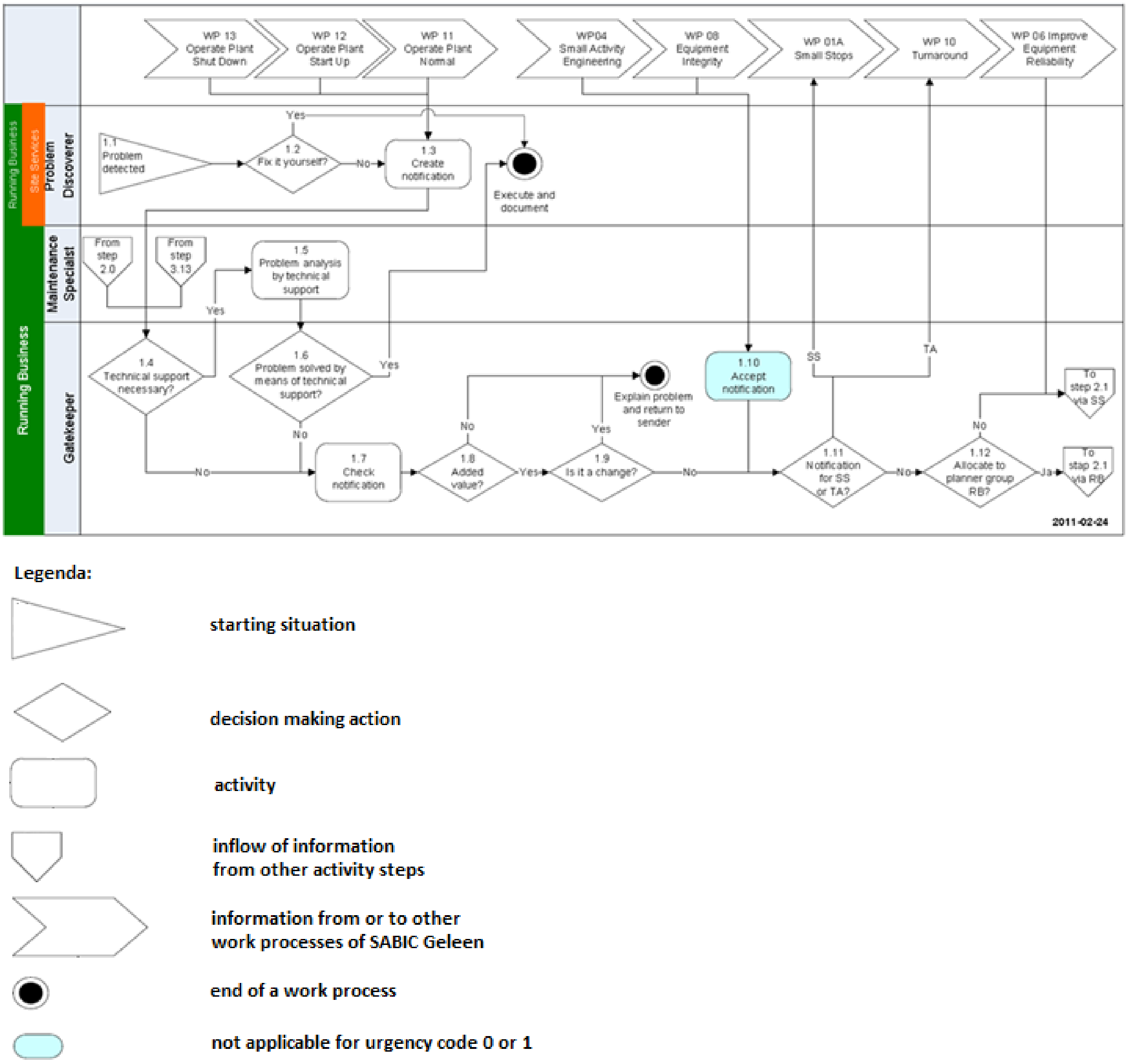

Figure 10: detailed flowchart of work process 01 (do maintenance) of the notification creation activities (Source: Intranet SABIC Europe Work Processes)

created by the problem discoverer and a spare part is needed to solve the breakdown or malfunction so that the system is able to perform with the intended functionality (i.e. produce the demanded quantity with the prescribed quality at minimum costs in the least amount of time) (see Figure 10 for the flowchart of a part of the work process of SABIC Geleen for creating a notification).

If it is clear that the maintenance activity could not be performed immediately because a spare part is needed to execute the maintenance activity, ideally it should be immediately clear which part we need (Van Lith, 2004) in what quantity with what priority from which supplier (Driessen et al., 2010). If it is clear which part is needed in which quantity at what priority, the spare part could be ordered immediately and possible downtime effects because of delay in the first phase of the spare parts ordering process are minimized. If it is not clear, additional time is spent to reveal which spare part is concerned with the maintenance activity and in what quantity it is needed with what priority. In the most unfavorable situation, the additional time to identify the needed spare part leads to additional downtime and costs.

Another potential problem, related to the problems mentioned above, is the determination of the urgency of the needed spare part. When the problem discoverer has limited knowledge and experience about possible consequences of a malfunction or breakdown, it is possible that the problem discoverer has difficulties in determining the priority of the needed spare part. SABIC Geleen has partially solved this problem by holding notification meetings. Persons with extended knowledge about consequences of failure check the given priority of the notification, and if correct approve the notification before the notification could be transferred into a maintenance work order. The notification meeting takes time which in the most unfavorable situation leads to additional downtime and costs.

5.2. PHASE 2: FROM NEED FOR A SPARE PART TO ACTUAL ABILITY TO ORDER THE SPARE PART

As mentioned earlier in section 4.2, it is crucial that the information of the first phase of the spare parts ordering process (i.e. what spare part is needed in what quantity at what priority) is transferred as quickly as possible to the responsible persons or information systems to be able to order the correct spare part in the right quantity with the correct priority as fast as possible in a cost efficient way. The priority determined by the problem discoverer in phase one of the spare parts ordering process, is checked by the superordinate of the problem discoverer, together with the supervisor plant maintenance, the day shift supervisor and the assistant of the operations manager (see the gatekeeper swimming lane of Figure 10). If the priority is validated, or adjusted before validation in case of a wrongly specified priority by the problem discoverer, the notification could be transferred into a maintenance work order (Driessen et al., 2010).

A potential problem in this phase of the spare parts ordering process is mentioned by the manager Reliability & Integrity of the Site Improvement Polymers department in open interviews. He stated that: “a lot of maintenance activities receive an unnecessary high priority, despite the checking of the priority in the notification meeting”. The undesired effects of setting unnecessary high priorities to maintenance activities is that relatively small defects receive an equal priority than more severe defects. This causes the planning of maintenance activities to be less effective (Velagić, 2012). Velagić discussed in her master thesis that not all assigned priorities are of the needed priority level because sometimes maintenance employees assign higher priorities to the maintenance activities to speed up the work (2012). Another possible reason for assigning priorities higher than actually needed is the limited knowledge and experience of the problem discoverer on the consequences (economic, safety, health and environment) of a malfunction or breakdown.

This problem was recognized by the manager Reliability & Integrity of the Site Improvement Polymers department. In order to (partially) overcome this problem, SABIC Geleen introduced an additional checking step, the gatekeeping meeting.

Another possible issue in this phase of the spare parts ordering process is mentioned by the Purchase Schedulers of the Purchasing Department. They stated that “the gatekeeper (i.e. the responsible person in the notification meeting) does not discriminate between the four different spare parts categories (i.e. strategic parts, CMI, non-stock parts and floor stock parts). Furthermore, they do not significantly address whether the demanded spare parts are actually available”. The danger of not taking into account the distinction between the four different spare parts categories when ordering a spare part is that each category has other mean delivery lead times, and the reliability of the lead time may be different as well (Driessen et al, 2010). The gatekeeper should, when assigning or validating a priority of a maintenance activity, take into account that components with a longer or less reliable lead time should be ordered earlier in time so that all components are available when the maintenance activities are planned to start. Note that the delivery date for a spare part does not necessarily need to be equal to the start date of the maintenance activity as not all maintenance tasks and the corresponding spare parts “commence simultaneously” with the start of the work order (Driessen et al., 2010, pp. 6).

Potential problems also arise when the needed spare part is not available while it should have been (e.g. a strategic spare part or CMI should be stocked either locally or centrally at the Geleen site). In order to reduce the negative economic, safety, health or environmental effects of spare part unavailability, SABIC Geleen could search for an alternative spare part to (temporarily) solve the problem (Fortuin & Martin, 1999 and Driessen et al., 2010).

Finally, the Purchase Schedulers have the feeling that “when the gatekeeper more actively expedites the ordered spare parts, i.e. follows the ordered part and determines whether the promised lead time by the supplier will be achieved, timely adjustments in the maintenance planning could be made when necessary (if the delivery lead time of the spare part is longer than expected). In that way, a better maintenance planning could be made where less maintenance activities need to wait for the material before they can be executed.

5.3. Phase 3: Actual ordering at the supplier

The Maintenance Field Planners of SABIC Geleen determine whether materials and services are necessary in order to perform the maintenance activity. If so, the materials and services have to be prepared, i.e. the Purchase Department generates a material list and uses the available information systems to acquire the necessary materials or services (see Figure 11 for the flowchart of the decisions to make to be able to order materials or services). From there on the material, repair, and overhaul is documented in work process 19.

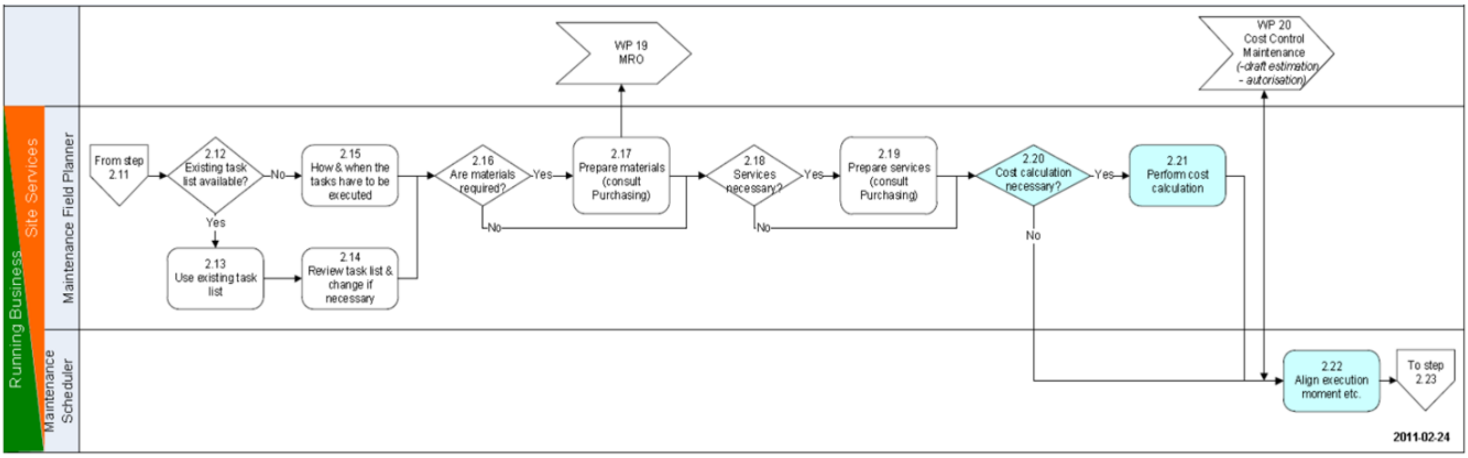

Figure 11: detailed flowchart of work process 01 (do maintenance) of the decision to order materials and/or services (Source: Intranet SABIC Europe Work Processes)

Spare part unavailability could be caused in this phase of the spare parts ordering process by ordering the wrong spare part, or by ordering the correct spare part in the wrong quantity. Another possible reason for spare part unavailability could be that the corrects parts are ordered in the right quantity but too late in time, so that because of the delivery lead time the parts are not available when the maintenance activities are planned to be started. The former mentioned problems could be caused by human mistakes by ordering the wrong spare part, the wrong quantity, or by ordering the part too late. Another possible reason could be that wrong or lacking information in the ordering procedure caused the ordering of wrong materials.

Finally, another potential problem related to this phase of the spare parts ordering process is the final order decision when a supplier of a spare part decides to stop the production of the spare part (Fortuin & Martin, 1999 and Driessen et al., 2010), or when it is more cost efficient for SABIC Geleen to switch suppliers. The Maintenance Engineer of SABIC Geleen is responsible for finding a comparable alternative spare part and for adjusting the specification of the part in the SAP system and on the technical drawings, before the spare part is approved for ordering. This procedure takes time while demand for the spare part already occurred. The final order problem for consumable spare parts is extensively discussed by Bakx (2010) and Beekhuizen (2011).

5.4. Phase 4: The spare parts ordering policy

Phase four of the spare parts ordering process is a tactical (medium-term, i.e. monthly or quarterly) or strategic (long-term, i.e. yearly or longer) decision making phase and is related to the actual ordering (see section 4.3). Decisions to be taken in this phase of the spare parts ordering process are:

- The criticality of (part of) the system where the spare part is located and a following Failure Mode and Effect Analysis or Reliability Centered Maintenance study for highly critical (parts of) systems in order to decide what spare parts to stock on what location,
- The reorder point,
- The order-up-to-level or order quantity,
- The stock review period,
- The categorization of the spare part as a consumable or a repairable spare part, and
- The choice of the supplier.

SABIC Geleen uses the equipment criticality for determining the criticality of (parts of) the systems. For determining the equipment criticality it is investigated what the economic, safety or environmental effects are, assuming that the system just failed and by distinguishing between the costs of lost production. The Reliability Engineers of the Site Improvement Polymers department determine focus on highly critical (parts of) systems by means of an RCM or FMEA study. In the FMEA study, among others, it is determined what spare parts are needed to decrease the effect of failure to the desired level.

For SABIC Geleen, the decision of where to keep the spare part on stock is related to the criticality. The strategic spare parts are stocked in the local warehouses near the plants because these parts should be available within two hours after a demand occurs. These components are stocked locally because a defective component can be replaced immediately, whereas spare parts are stocked in the central warehouse on site in Geleen when other maintenance activities are needed (e.g. the gearbox should be stopped and opened) before the defective component (e.g. a gear) could be replaced which take more than at least two hours of time. For (parts of) systems which are less critical (i.e. non-stock spare parts), it is decided to be stocked at the key supplier because unavailability of these spare parts does not directly affect the functionality of the system (and therefore are not able to decrease the effect of a failure).

A possible problem with the categorization of spare parts according to criticality categories is that the danger exists that spare parts are classified in the wrong category. Parts that should be available within a specific time period (e.g. 2 hours for a strategic part) might not be available if they were wrongly categorized (e.g. as a non-critical spare part with a delivery lead time of on average between three and ten days) because the desired lead time is not met.

If it is determined that the spare part belongs to a (highly) critical (part of an) system and that the spare part should be stocked locally (strategic spare parts) or centrally, it also should be determined what the minimum (reorder point) and maximum (order-up-to-level or order quantity) stock levels should be (Fortuin & Martin, 1999; Van Lith, 2004; Driessen et al., 2010). Deciding on the minimum stock level also determines how much of safety stock is kept to buffer against variability in demand or supply lead times. At SABIC Geleen, the Purchase Scheduler develops and keeps up-to-date the inventory parameters (i.e. the reorder point and the order-up-to-level or order quantity) with the purpose of optimizing the general stock level of SABIC Geleen (see Figure 12 for the flowchart of the inventory management activities). The required minimum stock for an article number, based on the guidelines and the FMEA study or Bill Of Material (BOM) is determined by the Maintenance Engineer of the Site Improvement department. The choice on the values of the minimum stock is financially approved by the Manager Operations, because he is responsible for the plant on which costs are accounted if a spare part is needed. Therefore he decides whether the proposed minimum stock level, and the corresponding costs, is agreed upon. The maximum stock level is determined by the Purchase Scheduler. The Site Improvement Maintenance Engineers do not determine the maximum stock level because they only have knowledge of the stock levels of the spare parts needed for the plant they are responsible for. The Purchase Scheduler receives all minimum stock levels from the Site Improvement Maintenance Engineers and he determines, together with them, based on the failure rate, potential consequences of failure of the spare part, and ordering costs of the spare part, the maximum stock level for each article number.

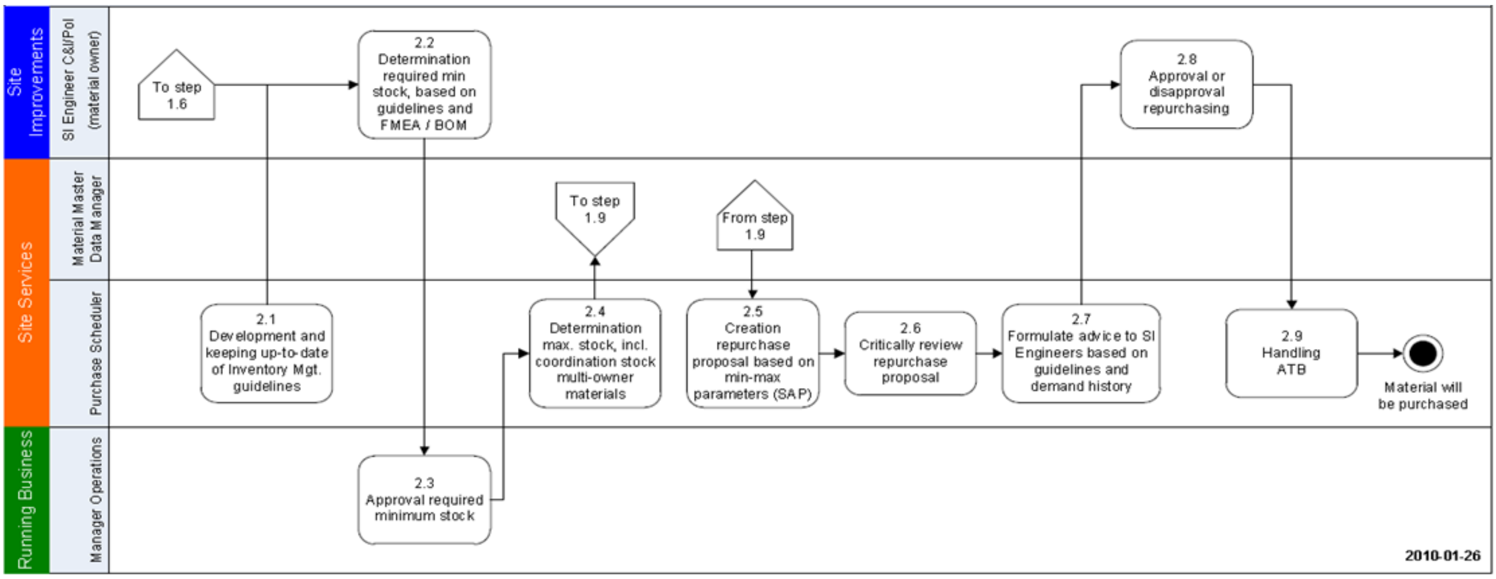

Figure 12: detailed flowchart of work process 19 (MRO) of the inventory management activities (Source: Intranet SABIC Europe Work Processes)

Potential problems regarding the minimum stock levels are stated by the Purchase Schedulers. It is the responsibility of the Maintenance Engineer to determine the minimum stock level for each part. The feeling of the Purchase Schedulers is that “the minimum stock levels are mostly chosen at a low level”. This decision seems to be a logical one if one regards that a company strives to as little inventory of spare parts as possible, because it ties up working capital. However, if stock levels are chosen at a too low level, the fill rate (the percentage of demand for spare parts which is directly delivered from stock) will go down which could possibly increase downtime of the systems. Another potential problem with the stock levels is that the wear of the components in the system is dependent on the product configuration which is being processed. Because the demand in products change, also the wear of the component changes and it would be better to coordinate the wear rates of the production with the stock levels of the spare parts. In that way, higher wear rates correspond with higher minimum stock levels, and lower wear rates correspond with lower minimum stock levels.

Furthermore, a decision which should be taken into account in this phase of the spare parts ordering process is with what frequency the inventory position is checked (i.e. continuously or periodically), which directly indicates the possible moments at which orders are placed at the supplier (Driessen et al., 2010). Each spare parts category has a different frequency of inspecting the inventory levels. The centrally managed inventory spare parts are reviewed periodically, based on an Material Resources Planning (MRP), on a weekly basis (every Monday morning, the MRP checks automatically the current inventory levels with the determined minimum and maximum inventory levels). When the current inventory level for an item is below the minimum level, a new part is directly ordered. For strategic spare parts, the periodic review is each half hour, because these parts are more critical for the functionality of the system than the CMI spare parts. A possible issue with the different stock review periods is that wrongly classified spare parts are reviewed too often (which increases operational costs) or reviewed too little (which increases the possibility on system downtime and costs).

The categorization of the spare part into a consumable or a repairable spare part has implications for phase 8 of the spare parts ordering process (see section 4.8). If the spare part is indicated as a repairable, it should be sent to an internal or external repair shop after disassembly in order to bring it preferably into an as good as new state, whereas consumable spare parts should be scrapped after disassembly because it is technically impossible or economically inefficient (it is cheaper to order a new spare part then to repair it) to repair them.

Finally, in this phase one should decide on the supplier of the spare part, because it has implications on the agreed delivery lead time length and reliability of the lead time (see section 4.2) and it also could have implications on the final order problem (see section 4.3).

When one or more of these decisions are chosen wrongly, the needed spare part may be unavailable, with potential negative economic, safety, health, or environment effects.

5.5. Phase 5: Order supply process

The order supply process of spare parts is concerned with the delivery of the spare parts from the supplier to SABIC Geleen. Causes of spare part unavailability for this phase of the spare parts ordering process could be due to badly specified ordering procedures, not following correctly specified ordering procedures, or because of missing values in the data. The former mentioned causes could lead to ordering the correct spare parts at the supplier in the correct quantity and believed correct lead time. However, it could be that the supplier changed the article number or the minimum order quantity of the spare part. Results are that the incorrect spare part is delivered or that the correct spare part is delivered, but in the wrong quantity. Furthermore, it could be possible that the lead time of delivering the spare part is changed, either in time or in reliability, but it is not communicated to SABIC Geleen or this change is not administered in the SAP information system. The ordering party expects the spare parts to be delivered within a certain time window but actually it takes longer because the lead time is now longer (because of an increased worldwide demand of technical systems) and more unreliable (e.g. unreliable shipping times) which possibly could harm the performance of SABIC Geleen (Fortuin & Martin, 1999). The relevancy of this issue is mentioned by a Reliability Engineer of the Site Improvement Polymers department.

5.6. Phase 6: Order receipt process

This phase of the spare parts ordering process is about how long it takes for a spare part to travel from the actual receipt by the central warehouse of SABIC Geleen and the actual availability of the spare part for the maintenance employees. Before the spare part is handed over to the maintenance employees for use, the part is tested based on the specification and drawings of the spare part at the central warehouse of SABIC Geleen.

Delays in this phase of the ordering process could be due to a mismatch in the specification of the delivered part and the reference specification or drawing, used by the central warehouse, which causes the spare part to be disapproved (Driessen et al, 2010). If the disapproved spare part regards a strategic spare part, it is sent back to the plant which demanded the part so that the Gatekeeper can take necessary actions to determine whether the part is correct and the reference specification or drawings should be adjusted, or whether a new spare part should be ordered. Finally, the required certificates for installing spare parts (e.g. for parts which are assembled in a high steam pressure environment) might be missing which unnecessarily delays the order receipt process and therewith might lengthen the system downtime.

5.7. PHASE 7: ACTUAL USE OF THE SPARE PART

If all required spare parts are available to perform the maintenance activity, the equipment should be made ready (e.g. removing the insulation) so that the maintenance activities could be performed on the system (see Figure 13 for the work process of the execution activities). The Execution Responsible is responsible for a timely execution of the maintenance activity, according to schedule and he is responsible for following the progress of the maintenance activity in a daily progress meeting. In case of insufficient progress by complications of any nature, some sub maintenance tasks should be rescheduled. In case the maintenance activities were outsourced to an external service supplier or contractor, this party needs to transfer the job back to the maintenance employees of SABIC Geleen when the work is performed and finished (i.e. technical complete). The Shift Supervisor finally checks if the system is transferred back to the satisfaction of all parties. It might be possible that remaining work is performed after transferring the maintenance activity (e.g. scaffolding or assembling the insulation).

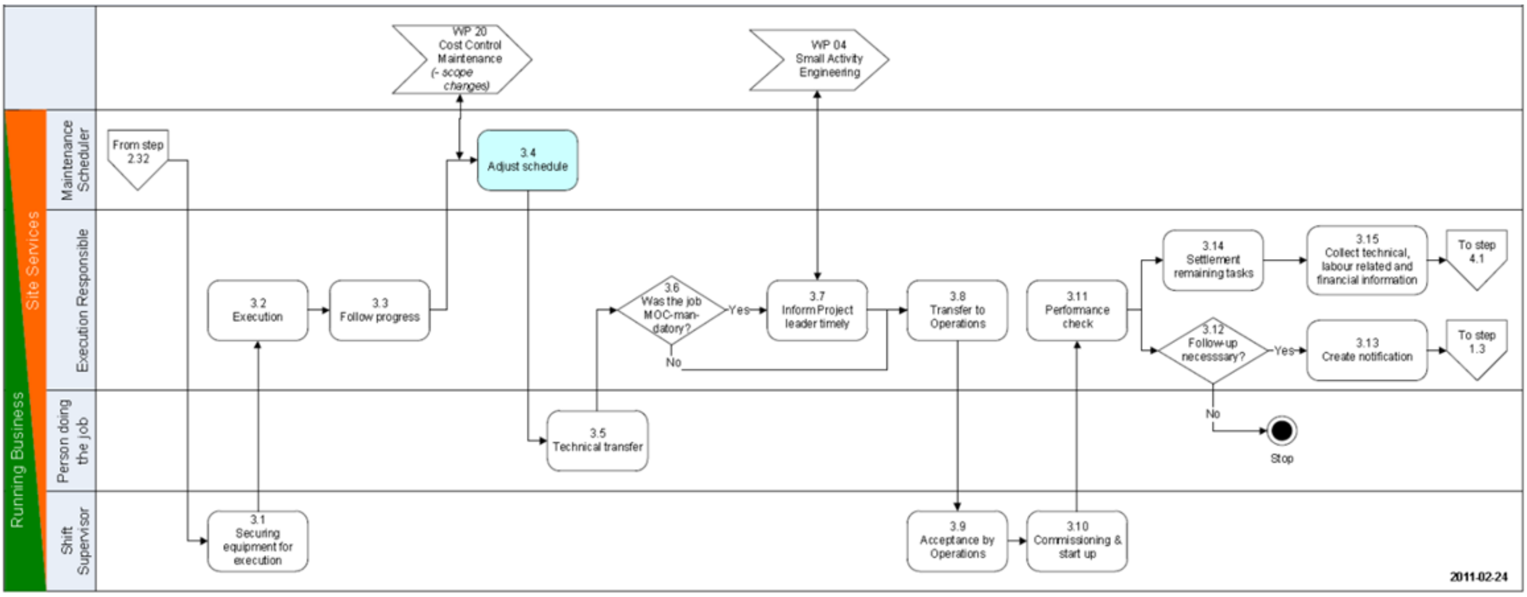

Figure 13: detailed flowchart work process 01 (do maintenance) of the execution activities (Source: Intranet SABIC Europe Work Processes)

Different maintenance parties (internal maintenance employees or external maintenance parties) could have different levels of skills, experience, and expertise. The manager Reliability & Integrity of the Site Improvement Polymers department mentioned that the feeling within the Site Improvement Polymers department is that in the past years, the skills and expertise of its own maintenance personnel decreased. A possible reason for the decrease in skills and expertise is that SABIC Geleen tries to postpone maintenance activities as much as possible within planned small stops or bigger turnarounds of the plant to achieve cluster efficiencies. Because there is desirably an as long as possible time between these moments, it is likely that maintenance employees easier forget how to solve a malfunction or breakdown. Other potential causes of less skills and expertise could be that the knowledge or experience is lower for hiring new maintenance employees in the last years because of worse educational requirements, because of turnover or retirement of the current experienced maintenance employees. Less skills and experience may cause more mistakes, either by installing the wrong spare part or by installing the right spare part incorrectly in the system, which causes the system to malfunction or break down shortly after overhaul.

5.8. PHASE 8: REPAIR OR DISCARD PROCESS OF SPARE PARTS

When the maintenance activity is finished, several parts may have been removed from the system, either to repair them (if the spare part is a repairable part) or to dispose them (if the spare part is a consumable part), which is of concern in phase eight of the spare parts ordering process, based on the tactical or strategic decision of the spare parts ordering policy (see section 4.4). A potential issue in this phase of the spare parts ordering process is that the removed repairable spare parts are stored temporarily somewhere in the plant before they need to be sent to the repair shop (internally when the spare part is repaired by own maintenance personnel or externally when it is repaired by employees of an external maintenance party) for repair activities. It is the responsibility of the Maintenance Engineer to check whether the part could be repaired or should be disposed when it is irreparably damaged. Because it might not be clear where the spare part is temporarily stored after disassembly from the system, the Maintenance Engineer needs to search the location of the part somewhere in the plant, before he could determine whether it is possible to repair the part or not. This takes additional unnecessary time while the repair should already be started (Van Lith, 2004). In the most unfavorable situation, this additional searching time leads to downtime and costs.

Other potential issues could be that maintenance employees might have limited knowledge on what spare parts are categorized as repairable spare parts. It might be that the maintenance employees remove the malfunctioning part from the system and disposes it, because the employees do not know that the part was actually a repairable spare part. As soon as a repairable spare part is sent to the repair shop (either internally or externally), the value of the spare part is temporarily booked on a suspense account, the technical service repairable account (TDRP) until the spare part is repaired and delivered to the central warehouse. Because the part might be disposed by the maintenance employee, the part could never return in stock and therefore the value of the part remains at the TDRP suspense account. The same problem arises when the repairable part is sent for repair and the maintenance employees conclude that it is technically impossible or economically undesirable (i.e. it costs more to repair the part in an as-good-as-new state than to order a new spare part) to repair the spare part. In that case, the part is disposed and a scrapping procedure has to be followed. This may be forgotten which causes the value of the repairable spare part to remain on the suspense account, while the value of the spare part should actually have been reversed from the account. Periodically, the suspense account is checked when the value on the account is too high (i.e. more than [redacted]).

Another possible issue for SABIC Geleen might be the change in the reference specification of the spare part (e.g. the spare part is no longer categorized as a repairable spare part but as a consumable spare part). When this is not (properly) communicated towards the Maintenance Engineer and the maintenance employees, unnecessary time and costs are lost.

Finally, long and unreliable repair lead times could cause system downtime if the repairable spare part is still at the repair shop when a new demand for the repairable spare part arises (see for example Van Lith, 2004 and Driessen et al., 2010).

5.9. CHAPTER SUMMARY

Chapter 5 answered the second research question: what are potential problems that could cause spare part unavailability for each phase in the spare parts ordering process.

Potential issues regarding the first phase of the spare parts ordering process are related whether it is immediately clear what spare part in what quantity with what urgency from which supplier is needed to perform the maintenance activity, in order to minimize the probability and effects of downtime.

A potential problem regarding the second phase of the spare parts ordering process is the determination and validation of the priority of ordering the spare parts. Furthermore, the feeling is that there is not, or not enough, discrimination among the four different spare parts categories and their different delivery lead times. Also the feeling is that spare parts are not, or not enough, expedited (i.e. checked whether the promised delivery date will be met). Finally, in order to minimize the effects of spare part unavailability, in this phase it is also checked whether SABIC Geleen could use alternative spare parts to (temporarily) perform the maintenance activity.

Problems which might cause spare part unavailability regarding the third phase of the spare parts ordering process are related to ordering the wrong spare part, the correct spare part in the wrong quantity, or ordering the spare part too late. This phase also concerns the final order problem.

In the fourth phase of the spare parts ordering process, problems of spare part unavailability might be caused by the wrong tactical or strategic decisions on which spare parts to stock, in which location, in what quantity. Further problems may arise with a wrong decision regarding the stock review period, the categorization of spare parts as a consumable or a repairable spare part, or the choice of the supplier of the spare part.

Potential problems regarding the fifth phase of the spare parts ordering process is that, despite the correct spare parts are ordered in the right quantity on time, the wrong part or the wrong quantity is delivered. Furthermore it could be that the spare parts are not delivered on time.

Potential issues of spare part unavailability in the sixth phase of the spare parts ordering process might be caused by spare parts which are not according to specification or drawing (i.e. either the spare part is not correct, or the specifications and drawings are incorrect) or the required certificates for assembling the spare part might be unavailable.

Potential problems regarding spare part unavailability, caused by the seventh phase of the spare parts ordering process, could be because of wrongly installing the spare part which might be due to a lack of knowledge, experience or expertise of the maintenance employees.

Finally, potential problems in the eight phase of the spare parts ordering process are related to the temporarily storage of disassembled spare parts, the unnecessarily scrapping of repairable spare parts, the not correctly registration of scrapped spare parts, and the long and unreliable repair lead times.

6. DECISION TREE OF THE SPARE PARTS ORDERING PROCESS

In this chapter a tool, i.e. decision tree, is designed to be able to determine which phase(s) of the spare parts ordering process cause(s) the most negative economic consequences for SABIC Geleen and therefore provides us with the biggest space for improvement. The decisions and steps of the decision tree are based upon the information provided in chapter 5. First, in this chapter, a decision tree is developed. In chapter 7, the selected work orders are analyzed using the designed decision tree to reveal the most problematic phase(s) of the spare parts ordering process.

Figure 14 shows the designed decision tree, with all steps that should be executed and all decisions that should be made. The content of the phases and decisions are provided below.

6.1. INPUTS AND TAKEN DECISIONS BEFORE ENTERING THE SPARE PARTS ORDERING PROCESS

- **Preventive maintenance activities from a preventive maintenance plan/corrective maintenance activities from a breakdown or malfunction:** The decision tree has a maintenance activity as input, either because the system broke down unexpected (corrective maintenance activities from a breakdown or malfunction) or because a preventive maintenance activity should be executed to prevent the system from breaking down (preventive maintenance activities from a preventive maintenance plan).
- **Decide on the initial priority:** If it is clear that a maintenance activity is planned or needed for the system, an initial priority is assigned to the maintenance activity. This priority indicates a time limit when the maintenance activities have to be finished and the system has to be available for processing (Intranet SABIC Europe, Work Processes, 2010). According to several maintenance and Reliability Engineers of the Site Improvement Polymers department, the determination of the initial priority is sometimes difficult when it is not directly obvious what the scope of the maintenance activity is (e.g. how big the damage is). Deciding a wrong priority to the maintenance activity causes the activity to be not finished within the desired time window with potential negative economic, safety, health and/or environmental effects.
- **Do we need one or more spare part to do maintenance?:** When the priority is assigned to the maintenance activity, it is determined whether a spare part is needed to perform the maintenance activity. If it is not needed, the maintenance activity is performed and the system is available for processing. If we need a spare part to perform the maintenance activity, we enter the first phase of the spare parts ordering process.

6.2. PHASE 1

- **Is it immediately clear what spares, how much, with what priority?:** when it is clear that we need at least one spare part to perform the maintenance activity, ideally it should be immediately clear what spare part in what quantity and with what urgency should be ordered. If it is not immediately clear what part of the system is needed in what quantity, the system has to be opened to inspect what part in what quantity is needed to perform the maintenance activity. The opening of the system, which almost always demands the system to be stopped processing, costs additional time and it is likely that additional costs (e.g. downtime) are made. If it is not immediately clear with what urgency the spare part(s) is/are needed, the moment of ordering the spare parts might not be optimal, which could cost SABIC Geleen additional money (e.g. operational or downtime costs). If it is immediately clear what spare part in what quantity with what priority is needed to perform the maintenance activity, phase one of the spare parts ordering process provides no problems for SABIC Geleen and phase two of the spare parts ordering process is entered.

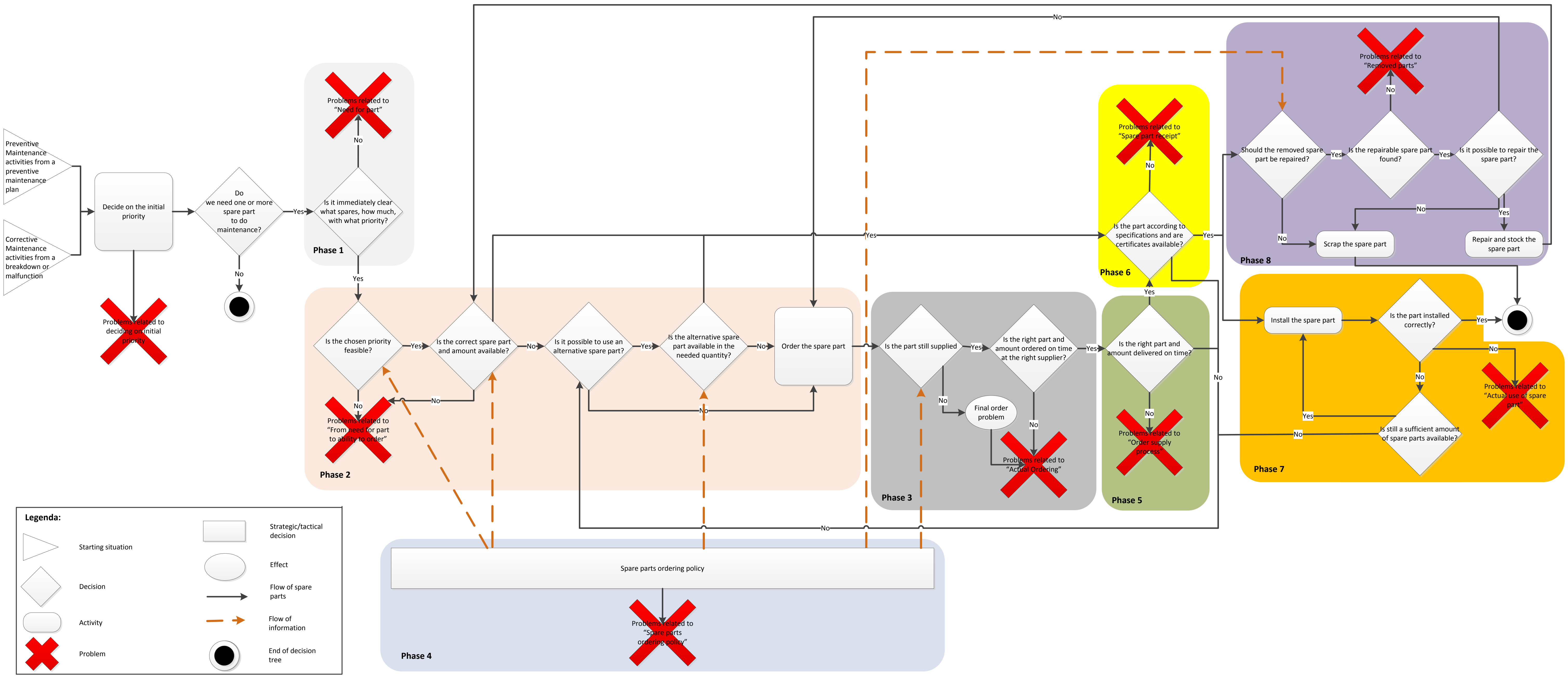

Figure 14: decision tree with steps and decisions to be taken for each phase of the spare parts ordering process

6.3. PHASE 2

- **Is the chosen priority feasible?:** the first decision to be taken in the second phase of the spare parts ordering process is whether the initially determined priority of the maintenance activity is actually feasible. If the spare part needs to be ordered, with a lead time of three weeks for example, and the maintenance activity was desired to be finished within five work days for example, the initially assigned priority is not feasible which could cause problems for SABIC Geleen related to an ineffective maintenance planning which is likely to cost unnecessary additional time and costs. This decision has supplier delivery lead time information from the spare parts ordering policy (phase 4) as input.
- **Is the correct spare part and amount available?:** if the initially determined priority is feasible, it needs to be checked whether the demanded spare part(s) is/are available in the correct quantity. If it was determined in the spare parts ordering policy (phase 4) that the demanded spare part should be kept in stock, it needs to be checked whether it actually is available in the quantity we need to perform the maintenance activity. If the part is available in the needed quantity, we can immediately go to phase 6 of the spare parts ordering process. If not, we need to determine whether we could use an alternative spare part to perform the maintenance activity. Finally, repaired spare parts (phase 8) are stocked again, which influences this decision.
- **Is it possible to use an alternative spare part?:** when the demanded spare part is not available, or the demanded quantity is not available, we could first determine whether it is possible to use an alternative spare part in order to minimize the time and costs lost by ordering a spare part. If it is possible to use an alternative spare part, it needs to be determined whether this spare part is available. If it is not possible to use an alternative spare part, we need to order the initially demanded spare part. The decision to use an alternative spare part should also be made when the wrong part or quantity is delivered (phase 5), when the part is not according to specifications or the required certificates are not available (phase 6) or when the spare part is assembled incorrectly and there is not a sufficient amount of spare parts available to perform the maintenance activity (phase 7).
- **Is the alternative spare part available in the needed quantity?:** when it is determined that an alternative spare part could be used to perform the maintenance activity, this spare part needs to be available in the needed quantity. This decision is similar to the decision whether the initially needed spare part is available in the needed quantity. If the alternative spare part is available, we can immediately go to phase 6 of the spare parts ordering process. If not, we need to order the initially needed spare part.
- **Order the spare part:** if it was decided in the spare parts ordering policy that it is more cost efficient to keep the spare part on stock, it actually should be available. If the part is however not available, one could check for an available alternative spare part. When it is not possible to use an alternative spare part, or when the alternative spare part is also not available, the initially demanded spare part needs to be ordered at the supplier. Finally, if a repairable spare part could not be repaired anymore (e.g. it is too much damaged), a new repairable spare part needs to be ordered at the supplier as well. If the spare part is ordered, we enter the third phase of the spare parts ordering process.

6.4. PHASE 3

- **Is the part still supplied?:** when it is needed to order the spare part because it is not available, it should be investigated whether the supplier still supplies the spare part. There is always a moment in time that the supplier decides to stop supplying the spare parts because of economic reasons, the so-called final order problem. If the supplier stops supplying the spare part, it should be mentioned to SABIC Geleen so that they can place a final order or a new supplier should be found to be able to order the spare parts at this supplier. The choice of supplier is considered in the spare parts ordering policy (phase 4).

- **Is the right part and amount ordered on time at the right supplier?:** if the spare part is still supplied, the needed spare part in the needed quantity with the demanded priority could be ordered at the supplier. It could be because of human error (e.g. a typo) or wrong or missing information in the ordering procedure, that the wrong spare part and/or the wrong quantity is ordered, perhaps at the wrong supplier and maybe not on time. When this is the case, the wrong spare part or the wrong quantity will be delivered after the delivery lead time of the supplier. The initially needed spare part should be ordered again, which costs additional money and time. Also if the wrong supplier is chosen to supply the spare part or the spare part is ordered too late, additional time and costs are made. If the right spare part and amount is ordered on time at the right supplier, the fifth phase of the spare parts ordering process is entered.

6.5. PHASE 4

This phase of the spare parts ordering process is concerned with the ordering policy and serves as information input in decisions in other phases. If such a decision receives wrong information from the spare parts ordering policy, the decision is based upon wrong information and it is likely that the outcome of the decision is not optimal for SABIC Geleen, which costs unnecessary time and money. The following decisions are made in the spare parts ordering policy:

- **Determine the criticality of (part of) the system where the spare part is located and a following Failure Mode and Effect Analysis or Reliability Centered Maintenance study for highly critical (parts of) systems::** SABIC Geleen determines the criticality of (parts of) the system based on what the economic, safety or environmental effects are if (parts of) the system fail(s). The Reliability Engineers of the Site Improvement Polymers department determine the criticality of (parts of) the systems. The criticality of the equipment serves as a basis for determining the urgency of the maintenance activities (PrioOrdr), and indicates how long the equipment may be maximally unavailable for maintenance activities. In parallel, the Reliability Engineers focus on (highly) critical (parts of) systems (i.e. approximately 2,000 pieces of equipment is (highly) critical) by means of an RCM or FMEA study. In the FMEA study, among others, it is determined what spare parts are needed to decrease the effect of failure to the desired level. If (parts of) a system is (highly) critical, the effect of failure could be reduced by either decreasing the likelihood (e.g. by means of a preventive or condition based maintenance policy) of the failure, or decreasing the effect (e.g. by having spare parts on stock (see e.g. Fortuin & Martin, 1999; Van Lith, 2004; Driessen et al., 2010)) of the failure. For non-critical (parts of) systems, preventive maintenance activities (not based on a risk analysis) are performed based on experience of the Maintenance Engineers and historical information.
  For SABIC Geleen, the decision on where to keep the spare part on stock is related to the criticality. Strategic spare parts (highly critical) are stocked in the local warehouses near the plants because these parts should be available within two hours after a demand occurs. Spare parts of critical (parts of) systems (i.e. centrally managed inventory) are stocked in the central warehouse on site in Geleen (see Driessen et al., 2010). For (parts of) systems which are less critical (i.e. non-stock spare parts), it is decided to be stocked at the key supplier because unavailability of these spare parts does not directly affect the functionality of the system (and therefore are not able to decrease the effect of a failure). This information serves as an input for phase 2 of the spare parts ordering process.
- **Decide whether the spare part is categorized as a repairable or a consumable spare part:** the decision to indicate a spare part as a consumable or a repairable spare part mainly influences phase 8 of the spare parts ordering process. If the spare part is indicated as a repairable, it should be sent to an internal or external repair shop after disassembly in order to bring it preferably into an as good as new state, whereas consumable spare parts should be scrapped after disassembly because it is technically impossible or economically inefficient (it is cheaper to order a new spare part then to repair it) to repair them.

- **Decide on the order-up-to-level/order quantity, the reorder point and the stock review period:** when it was determined from the FMEA or RCM study that the effect of a failure could be decreased by stocking spare parts of (highly) critical (parts of) systems, the minimum and maximum stock levels should be determined as well as the replenishment period (i.e. with what frequency the stock levels are checked). The moment of checking the stock levels directly influences the moment on which to order spare parts at the supplier. These decisions serve as an input for the second phase of the spare parts ordering process where it is determined whether the correct spare parts are available in the right quantity.
- **Decide on the supplier:** SABIC Geleen also should decide on the supplier of the spare part, because it has implications on the agreed delivery lead time length and reliability of the lead time (considered in phase 2) and it also could have implications on the final order problem (considered in phase 3).

6.6. PHASE 5

- **Is the right part and amount delivered on time?:** when the correct spare part, in the needed amount with the assigned priority at the predetermined supplier is ordered, it could still be possible that spare parts are unavailable when the maintenance activity is to be performed. It could be that the wrong spare part and/or the wrong quantity is delivered by the supplier. Furthermore, it could be that the spare part(s) is/are delivered too late. These issues could cause unavailability of spare parts with the possibility of loss of production. A potential solution to minimize the negative economic, safety, health and environmental effects is to check whether it is possible to use an alternative spare part (see phase 2). If the correct spare part is delivered in the right quantity on time, the spare part is checked upon specifications and drawings in phase 6.

6.7. PHASE 6

- **Is the part according to specifications and are certificates available?:** before the spare part is handed over to the maintenance employees for use, the part is tested based on the specification and drawings of the spare part at the central warehouse of SABIC Geleen. Delays in this phase of the ordering process could be due to a mismatch in the specification of the delivered part and the reference specification or drawing, used by the central warehouse, which causes the spare part to be disapproved. SABIC Geleen could then decide to check if an alternative spare part could be used to perform the maintenance activity (see phase 2). In parallel, because the spare part was disapproved according to the specification or drawing, it should be determined whether the part is correct and the reference specification or drawings should be adjusted, or whether a new spare part should be ordered. Finally, the required certificates for installing spare parts (e.g. for parts which are assembled in a high steam pressure environment) might be missing which unnecessarily delays the order receipt process and therewith might lengthen the system downtime. If the spare part is according to the specifications and drawings, and the necessary certificates are available, the new spare part is installed (phase 7) and in parallel, the old part is removed from the system (phase 8).

6.8. PHASE 7

- **Install the spare part:** when the ordered spare parts are according to the specifications and drawings, and the required certificates are available, the spare part is accepted to be installed in the system.
- **Is the part installed correctly?:** it might be that the spare part is not correctly installed. In that case, the maintenance activity is not performed correctly and perhaps a new spare part is needed (because the former spare part is damaged because it was installed incorrectly) to perform the maintenance activity correctly. If the spare part is installed correctly, the maintenance activity is ready and the system is available for processing.

- **Is still a sufficient amount of spare parts available?:** if a new spare part is needed to perform the maintenance activity correctly, it is first determined whether there are still enough spare parts on stock to perform the maintenance activity. If that is the case, the new spare part is installed. If it is not, it is checked whether it is possible to use an alternative spare part to perform the maintenance activity (see phase 2).

6.9. PHASE 8

- **Should the removed spare part be repaired?:** when the new spare part is delivered, the old spare part needs to be disassembled from the system. The spare part is either categorized as a consumable or a repairable spare part, based on the information of the spare parts ordering policy (phase 4). The categorization of a spare part affects what should be done with a spare part after disassembly. A consumable spare part should be scrapped, whereas a repairable spare part should be repaired to bring it ideally in an as good as new state.
- **Is the repairable spare part found?:** if the spare part is indicated as a repairable spare part, it is temporarily stored on the floor in the plant before a Maintenance Engineer checks whether it is technically feasible and economically desirable to repair the spare part. If the Maintenance Engineer cannot find the spare part in the plant, he is not able to determine whether the part should be repaired or not, which will cause delays in this phase of the spare part ordering process.
- **Is it possible to repair the spare part?:** when the spare part is indicated as a repairable spare part and the part is found by the Maintenance Engineer, he determines whether it is still technically feasible to repair the spare part. In case a spare part is heavily damaged it might be more efficient to order a new spare part instead of trying to repair the damaged one.
- **Scrap the spare part:** for both consumable spare parts and heavily damaged repairable spare parts, they have to be scrapped and new spare parts have to be ordered to still keep the stock levels between the minimum and maximum levels.
- **Repair and stock the spare part**: if it is possible to repair the repairable spare part, it should be stocked after it returns from the repair shop. The part can then be used for a next maintenance activity.

6.10. CHAPTER SUMMARY

In this chapter we designed a decision tree (see Figure 14) in order to conclude, using the selected work orders as input, which phase(s) of the spare parts ordering process is/are most problematic for SABIC Geleen because the economic consequences were highest in 2012. For each phase in the decision tree, the decisions and steps to be taken are explained. In the next chapter, the selected work orders (i.e. work orders which were delayed because of spare part unavailability and had unnecessary costs related to the spare part unavailability) are analyzed using the decision tree.

7. Determining of the relevance of the phases of the spare parts ordering process of SABIC Geleen

As mentioned earlier in section 2.2.2, about [redacted] could have been maximally saved if we solve (part of) the problem of spare parts unavailability for SABIC Geleen. In order to conclude how much of the money could be saved per phase of the spare parts ordering process, the selected work orders which were delayed because of spare part unavailability and had unnecessary costs (downtime, cost related to safety, health and environmental issues, and unnecessary urgency ordering) are analyzed using the decision tree, designed in chapter 6. Each selected work order is analyzed starting with assigning the initial priority until a problem area in a particular phase of the decision tree.

7.1. Analysis of the selected work orders using the decision tree

In Table 13: delayed work orders of 2012 because of spare part unavailability with a cost indication (in €) and to which phase(s) of the spare parts ordering process the problem is related the delayed work orders because of spare part unavailability which caused negative economic consequences are indicated, together with the amount of lost money and the phase(s) of the spare parts ordering process at which the problems belong.

For work orders which perhaps unnecessarily urgently ordered spare parts at the supplier, the costs are calculated by multiplying the urgency costs of the supplier (see Table 11) with the number of urgently purchase order documents:

$$Unnecessary\ urgency\ costs\ (in\ €) = urgency\ costs\ of\ the\ supplier\ (in\ €) * amount\ of\ purchase\ orders\ (in\ \#) \quad (7.1)$$

For the first work order for example, four purchase orders were perhaps unnecessary urgently ordered at the central warehouse, the costs are then:

Unnecessary urgency costs = [redacted] ∗ 4 = [redacted]

Table 13: delayed work orders of 2012 because of spare part unavailability with a cost indication (in €) and to which phase(s) of the spare parts ordering process the problem is related

Number	Description	Cost lower bound (in €)	Cost higher bound (in €)	Problems related to phase(s)
1.	Broken valves	[redacted]	[redacted]	3
2.	Breakdown extruder HDSS	[redacted]	[redacted]	2,3,4
3.	Viscosity measuring instrument indicates too high pressure during small stop	[redacted]	[redacted]	3,4
4.	Too high level of vibrations to the e-motor	[redacted]	[redacted]	3,4
5.	Cleaning the oil filters	[redacted]	[redacted]	6
6.	Repair of the gland	[redacted]	[redacted]	3
7.	Gearbox vibrates and makes a deviating noise	[redacted]	[redacted]	3,4
8.	Sprocket of the shrinking furnace is bent	[redacted]	[redacted]	4,7
9.	Roll of the roller conveyer is broken down	[redacted]	[redacted]	2,3,4

10.	Furnace fails occasionally	[redacted]	[redacted]	3
11.	Breakdown of the shrinking furnace	[redacted]	[redacted]	2,3,4
12.	The slip-action clutch is loose	[redacted]	[redacted]	2,3,4
13.	Repair of the gearbox	[redacted]	[redacted]	8
14.	Pilot valve leaks at gland nut	[redacted]	[redacted]	3,4
15.	Crack in the pressure safety valve pipe	[redacted]	[redacted]	2,3,4
16.	Crash of a gearbox	[redacted]	[redacted]	2,3,4,8
17.	Spraying machine does not get back	[redacted]	[redacted]	3,4
18.	Pump is broken down	[redacted]	[redacted]	3,4

The lower bound of the costs of a delayed work order is calculated using the actual asset utilization margins of 2012 (which are lower than the long-term average asset utilization margin) and using lower bound of urgently ordering costs and no additional transportation costs. The upper bound of the costs is calculated using the long-term average asset utilization margin of a production loss, the upper bound of the urgently ordering costs and additional transportation costs are included.

For work orders which were (partially) delayed because one or more spare parts were ordered too late (i.e. the Date WFMA was later than the required end date), the costs were calculated by the ratio of the delay caused by ordering the spare parts too late, multiplied with the asset utilization margin (i.e. the asset utilization margin of 2012 is a lower bound, whereas the long-term average asset utilization margin serves as a higher bound):

$$\begin{aligned} &Costs\ because\ of\ a\ delay\ in\ ordering\ the\ spare\ parts\ (in\ €) \\ &\quad = \frac{days\ delay\ caused\ by\ ordering\ too\ late (in\ days)}{total\ delay\ of\ the\ work\ order\ (in\ days)} \\ &\quad * asset\ utilization\ margin\ (in\ €/ton)\ * the\ amount\ of\ lost\ production\ (in\ tons) \end{aligned} \tag{7.2}$$

Note that if it is not exactly clear how much tons of production is lost because of spare part unavailability, we estimated that 10% of the total production loss is caused by the unavailability of spare parts.

For the work orders in Table 13, the costs were assigned per phase of the spare parts ordering process using the decision tree, designed in chapter 6. Note that for work orders which had negative economic consequences which could have been saved when the spare part was on stock while it was not, the complete costs are also referred to phase 4 of the spare parts ordering process.

7.2. CONCLUSION OF THE ANALYSIS

As mentioned in section 6.1, according to several maintenance and Reliability Engineers of the Site Improvement Polymers department, the determination of the initial priority is sometimes difficult when it is not directly obvious what the scope of the maintenance activity is. Despite the feeling of the maintenance and Reliability Engineers of the Site Improvement Polymers department that this could delay the maintenance activity with a potential negative economic, safety, health and/or environmental effect as a consequence, a conclusion, based on the data from the zpm_stat_list and the PROMISE asset utilization database, could not be made because the data did not show these effects. We are therefore not able to support or reject the feeling of the Maintenance and Reliability Engineers and so we cannot focus on this problem area for a further redesign.

We described in section 7.1 how the lower and upper bound of loss of economic value of a work order is calculated and how the costs per phase of the spare parts ordering process are calculated. Now, the costs for the data of SABIC Geleen are calculated for each phase of the spare parts ordering process (see Table 14).

Table 14: lost economic value (in €) in 2012 for SABIC Geleen per phase of the spare parts ordering process

Phase number	Name of the phase of the spare parts ordering process	Cost lower bound (in €)	Cost higher bound (in €)
1.	Need for a spare part	[redacted]	[redacted]
2.	From need for a spare part to the actual ability to order a spare part	[redacted]	[redacted]
3.	Actual ordering of the spare part	[redacted]	[redacted]
4.	Spare parts ordering policy	[redacted]	[redacted]
5.	Order supply process	[redacted]	[redacted]
6.	Order receipt process	[redacted]	[redacted]
7.	Actual use of the spare part	[redacted]	[redacted]
8.	Repair or discard process of a spare part	[redacted]	[redacted]

From the analysis, we see that phase one and phase five of the spare parts ordering process did not cost SABIC Geleen money in 2012. As can be seen from Table 14, SABIC Geleen lost the most economic value in 2012 in the fourth (the spare parts ordering policy) and eight phase (repair or discard process of a spare part) of the spare parts ordering process. As mentioned in section 2.2.2, one failure caused about 76% (about [redacted]) of the total costs, which is perhaps an outlier. These costs are referred to in phase 2, 3, 4 and 8 of the spare parts ordering process. After removal of the work order which caused this failure, the following negative economic effects are found (see Table 15):

Table 15: lost economic value (in €) in 2012 for SABIC Geleen per phase of the spare parts ordering process after deletion of the failure which contributes to 76% of the total costs

Phase number	Name of the phase of the spare parts ordering process	Cost lower bound (in €)	Cost higher bound (in €)
1.	Need for a spare part	[redacted]	[redacted]
2.	From need for a spare part to the actual ability to order a spare part	[redacted]	[redacted]
3.	Actual ordering of the spare part	[redacted]	[redacted]
4.	Spare parts ordering policy	[redacted]	[redacted]
5.	Order supply process	[redacted]	[redacted]
6.	Order receipt process	[redacted]	[redacted]
7.	Actual use of the spare part	[redacted]	[redacted]
8.	Repair or discard process of a spare part	[redacted]	[redacted]

From Table 15, one concludes that phase 4 and phase 8 of the spare parts ordering process cost SABIC Geleen the most in terms of economic value in 2012, even after removing the failure which cause about 76% of the total lost economic value. Because SABIC Geleen does not expect that in the near future (between now and five years) large problems can be expected in other phases of the spare parts ordering process, we will focus on (re)designing phase 4 and phase 8 of the spare parts ordering process.

7.3. CHAPTER SUMMARY

In this chapter it was analyzed in which phase(s) of the spare parts ordering process the most economic value was lost in 2012. This analysis is needed to conclude at which phase(s) of the spare parts ordering process we should focus with the (re)design because in this/these problem area(s) the most can be gained in terms of economic value. We concluded that phase 4 (the spare parts ordering policy) and phase 8 (repair or discard process of a spare part) cost SABIC Geleen the most money in 2012, even when a failure which caused about 76% of the total lost economic value is removed from the dataset. Because SABIC Geleen does not expect large problems in the other phases of the spare parts ordering process in the near future, we decide to focus our resources on (re)designing phase 4 and phase 8 of the spare parts ordering process.

8. Redesign of the spare parts ordering policy of SABIC Geleen

As was discussed in chapter 7, the phases of the spare parts ordering process which were most problematic for SABIC Geleen in 2012 because the most economic value was lost because of spare parts unavailability were phase 4, i.e. problems related to the spare parts ordering policy, and phase 8, i.e. problems related to the repair or discard process of spare parts. For the spare parts ordering policy phase, in section 8.1 a literature review is given on what decisions in what sequence should be included in the ordering policy. In section 8.2, the current decisions and sequence is described, which is then confronted with literature (see section 8.3). In section 8.4, a redesign is given to improve the current decision variables and/or sequence of decisions for SABIC Geleen.

8.1. Literature review on the spare parts ordering policy

According to literature the following decisions should be taken in the spare parts ordering policy in the sequence given below (see e.g. Driessen et al., 2010) (see also Figure 15):

1. The determination of equipment criticality,
2. The determination of parts criticality for critical equipment,
3. Decide whether a spare part is indicated as a repairable or as a consumable spare part,
4. The selection of a supplier of a spare part,
5. The stocking decision of a spare part,
6. The stocking location of a spare part,
7. The selection of the replenishment policy, and
8. The determination of the replenishment policy parameters (i.e. the reorder point, the order-up-to level or order quantity, and the stock review period).

Below, the decision variables are discussed in detail:

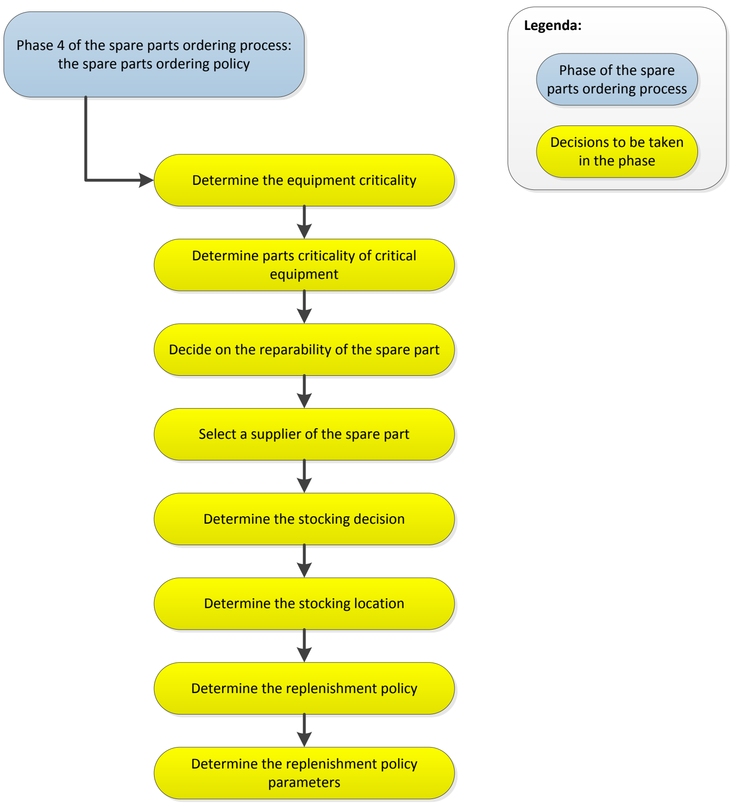

Figure 15: decisions and sequence of spare parts ordering policy (Driessen et al, 2010)

- **The determination of equipment criticality.** When a company has to deal with large installed asset base an analysis has to be done to differentiate the important assets and the less important assets so that the company can focus time and economic resources on the spare parts of the important assets. A method is needed for ensuring efficient expenditure of analysis efforts, which is largest when the effect (i.e. cost savings) of the analysis is maximized (De Groof, 2010).
- **The determination of part criticality for critical equipment.** Once an asset is selected for further analysis, because the asset is critical, it is necessary to identify components in the asset for which it is expected that the yield is highest in terms of savings in the total maintenance costs. A useful technique to identify critical components in an asset is the Failure Mode and Effect Analysis (De Groof, 2010).
- **Decide whether a spare part is indicated as a repairable or as a consumable spare part.** Deciding on the reparability of a spare part is performed with a Level Of Repair Analysis (LORA) (Basten et al., 2011), which consists of non-economic and economic decision criteria. First, it is determined whether it is technically feasible to repair the spare part (non-economic decision criterion). If this is the case it is determined whether it is economically desirable (i.e. cost efficient) to repair the spare part (economic decision criterion). The decision whether a spare part is indicated as a repairable or as a consumable has consequences for the availability of the spare parts. The delivery lead time for a consumable spare part may differ from the repair lead time of a repairable spare part and has implications on the availability of a spare part.
- **The selection of a supplier.** This decision needs to be taken in the spare parts ordering policy to ensure that one or multiple supply sources are available to supply spare parts when they are demanded at any given moment in time with predetermined supplier characteristics (e.g. lead time, price structures and minimum order quantities) (Driessen et al., 2010). Determination of the expected supply lead time (and its probability distribution) is an important decision in the ordering policy (Driessen et al., 2010). Selecting a supplier could be done based on e.g. the expected delivery lead time, delivery lead time reliability, costs of delivery, desired spare part quality, minimum order quantity.
- **The stocking decision of a spare part.** Spare parts are stocked in order to meet desired service levels. Driessen et al. (2010) discuss to only stock spare parts to cover unplanned demand for spare parts, i.e. the demand of a spare part because of unexpected corrective maintenance activities, or planned demand that is not known far enough ahead in time, i.e. when the supply lead time exceeds the delivery lead time of the spare parts. Note that the supply lead time consists of (Driessen et al., 2010):
    1. the repair or delivery lead time,
    2. the time needed to procure the spare part,
    3. picking, transport and storage time, and,
    4. hand in times of failed spare parts, in case of repairable spare parts.

  If the planned demand for spare parts is known in advance, the spare parts should be ordered according to Driessen et al. (2010). However, ordering spare parts with a planned demand at the supplier with high fixed ordering costs may not be cost efficient and should therefore be stocked as well. From literature, it appears to be useful to classify spare parts into different subset so that each subset of spare parts has the same tailored stocking strategy (Driessen et al., 2010). Driessen et al. (2010) propose to classify the spare parts based upon their criticality and price to conclude which stocking strategy fits best. Critical spare parts have to be stocked in order to prevent the possible consequences (large downtime costs) when such a component is needed but unavailable.
- **The stocking location of a spare part.** The decision on where to stock the spare parts is dependent on the target service level. When it is determined that a spare part should be stocked because the service level is not met when delivery to order (e.g. the delivery lead time is too long or unreliable), it should

also be determined where to stock the spare part. For determining the stocking location of a spare part, a multi-criteria decision analysis could be performed (Botter & Fortuin, 2000).

- **The selection of the replenishment policy.** For each spare part at a stocking location, an inventory replenishment policy should be chosen. When determining the inventory control policy, decisions have to be made regarding:
    1. The decision whether to use a fixed order quantity (Q) or a fixed order-up-to level (S), and
    2. The decision whether to periodically (R) or continuously review the stock levels.

  Based on these decisions a replenishment policy is selected.
- **The determination of the replenishment policy parameters.** For the chosen decisions in the selection of a replenishment policy, the parameter values should be determined. De Kok, Fortuin, and Van Donselaar (2007) propose to determine the replenishment policy parameters simultaneously because the determination of the reorder point and order quantity/order-up-to level is dependent on each other.

8.2. CURRENT DECISIONS AND SEQUENCE IN THE SPARE PARTS ORDERING POLICY OF SABIC GELEEN

SABIC Geleen currently performs the following steps and makes decisions in the spare parts ordering policy in the following sequence (see also Figure 16):

1. Determine the criticality of the equipment,
2. Determine the criticality of the spare parts of critical equipment,
3. Decide on which spare parts to stock,
4. Creating an article number where decisions are taken in the following sequence:
    a. Determine the maximum stock level,
    b. Determine the minimum stock level (reorder point),
    c. Decide on the selection of a supplier of spare parts,
    d. Decide on the stocking location of the spare parts, and
    e. Determine whether a spare part is categorized as a repairable or a consumable spare part.

- **Determine the criticality of the equipment.** SABIC Geleen has a large amount of equipment (about [redacted] different types of equipment) and time and economic resources are not sufficient to analyze all assets. Therefore, SABIC Geleen determines, based upon the criticality of the equipment, on which equipment time and economic resources should be focused. A multi-criteria decision analysis is not performed by SABIC Geleen, only the criticality analysis is used to determine at which equipment resources are devoted.
- **Determine the criticality of the parts of critical equipment.** After it is determined on which equipment resources should be focused because they are critical, it should be determined what components of the equipment are critical. SABIC Geleen uses the FMEA technique to determine which components of the equipment are critical. Focusing on critical component gives the highest savings in the maintenance costs.
- **Decide on which spare parts to stock.** SABIC Geleen focuses time and economic resources to critical assets and their critical components. They determine, based on a FMEA study, what the effect of a failure would be, given that no spare parts are available, and no preventive maintenance activities are performed. In order to decrease the effects of a failure, it is determined whether it could be useful to have a spare part on stock. SABIC Geleen incorporates the criticality in the stocking decision, but not the price of a spare part, as was proposed by literature.

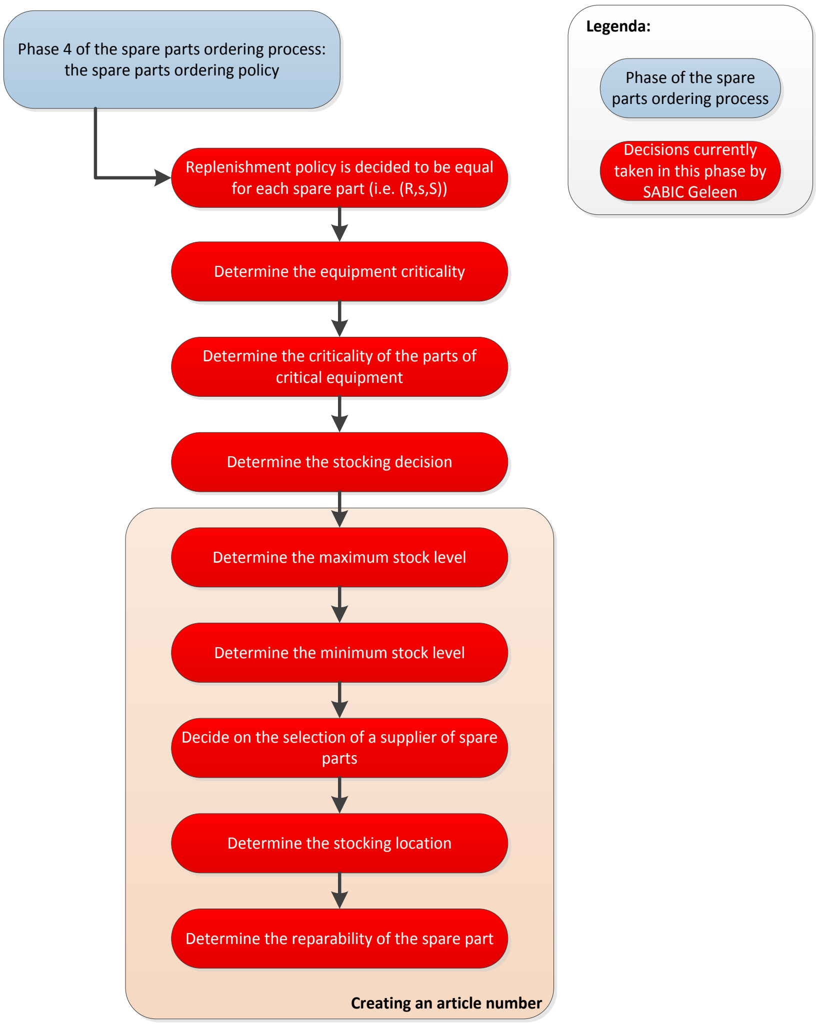

Figure 16: decisions and sequence of spare parts ordering policy as currently done by SABIC Geleen

- **Creating an article number.** When SABIC Geleen proposed to stock a certain spare part in order to reduce the effect of a failure, the Maintenance Engineer demands to create an article number for the spare part. In the creation of an article number, the following aspects need to be determined by the Maintenance Engineer in the following sequence:
    1. The determination of the maximum stock level,
    2. The determination of the minimum stock level (reorder point),
    3. The decision on the selection of a spare parts supplier,
    4. The determination of the stocking location, and
    5. The determination of the reparability of the spare part.

  Currently, the Purchase Schedulers of SABIC Geleen determine the maximum stock level, whereas the minimum stock level is determined by the Maintenance Engineers of the Site Improvement department. The stock levels are determined independently of each other.

  After the stock levels are determined, the Maintenance Engineers determine, if possible, at which supplier the spare part is ordered. For about 80 to 90 percent of the spare parts, the choice of a supplier is limited to the Original Equipment Manufacturer, because this is the only party which is able to supply the spare part with the demanded quality. In the remaining 10 to 20 percent, the Purchasing employees are allowed to determine from which supplier the spare parts are to be ordered based on which qualified supplier proposes to deliver the demanded spare part at the desired quality at the lowest price.

The decision on the stocking location of SABIC Geleen is based upon the desired availability of the spare part.

For determining the reparability of the spare part, non-economic followed by economic decisions are made to determine whether it is technically feasible and economically efficient to repair the spare part (i.e. it costs less to repair the spare part than to order a new one). The repair lead time is not incorporated in the decision to repair the spare part or to order a new spare part, but is incorporated in the stocking decision of the spare part.

8.3. Confrontation of decisions and sequence of the spare parts ordering policy of SABIC Geleen with literature

Comparing the decisions to be taken in the spare parts ordering policy from literature with the current situation of SABIC Geleen shows the following deviations:

- The sequence of the decision steps is wrong, i.e. SABIC Geleen determines the stocking decision before determining the reparability and the supplier of the spare part. The stocking decision should depend on the supply lead time, which is at that moment unknown, and therefore first the reparability decision and supplier selection decision should be taken,
- The decision of the replenishment policy parameters, the selection of a supplier, the stocking location, and the reparability of the spare part is clustered in SABIC Geleen in the described sequence, whereas literatures describes these decisions to be taken sequentially,
- The replenishment policy is not decided for each individual spare part in the current situation of SABIC Geleen (i.e. one single replenishment policy is chosen for all spare parts), and
- The reorder point and order-up-to level or order quantity are not jointly determined, whereas the determination of the stock levels is dependent on each other.

8.3.1. Different sequence of the decision steps

First, SABIC Geleen decides on the stocking decision after they determined the criticality of the equipment and the associated components. The logic behind this is that SABIC Geleen wants to stock critical spare parts, based on the criticality of the equipment and the repair or delivery lead time of the critical spare part, in order to prevent critical spare parts to be unavailable and causing downtime in case of failure of the critical equipment. However, at that moment in time, no information is available on the delivery or repair lead time because this is dependent on the reparability of the component and the selected supplier of the spare part. That is the reason why literature proposes to firstly determine the reparability for critical spare parts because this influences the choice of a supplier and the decision to keep the spare parts on stock. Also the selection of a supplier has an influence on the decision to stock the part or to order the part at the supplier. We agree with the proposal from literature to first determine the reparability of the spare part, then decide on the supplier of the spare part and then decide whether or not to stock the spare part.

SABIC Geleen determines the height of the reorder point (minimum stock level) and the order quantity/order-up-to level before they determine the stocking location. According to literature the stocking location decision should be determined before the height of the replenishment parameters is determined because the stocking location affects the chosen inventory replenishment policy and its parameters.

8.3.2. Clustered decisions of the replenishment parameters, supplier selection decision, stocking location decision, and reparability of the spare part

SABIC Geleen clustered the decision on the height of the replenishment policy parameters, the choice for a supplier, the stocking location, and the reparability of the spare part. In the literature, these decisions are described to be taken sequentially because the decisions are based upon different decision criteria. It is therefore not useful to make decisions for these criteria in the same decision step. SABIC Geleen should make them sequentially.

Describing the spare parts stocking location decision is not relevant for SABIC Geleen because both response time (i.e. the time until demand for the spare part occurs until it is available for use) and the handling, transportation and inventory holding costs are about equal, irrespective of the stocking location (i.e. the local warehouse near the plant or the central warehouse at the site in Geleen). We propose that SABIC Geleen should stock spare parts at the local warehouse when the spare part is associated to critical equipment, the demand rate for the spare part is high (i.e. the spare part fails with a high frequency), and the component can be replaced immediately when a failure occurs (i.e. no other maintenance activities are needed before the defect component could be replaced). In all other cases, we propose to stock the spare part at the central warehouse at the site in Geleen.

8.3.3. Decision on the inventory replenishment policy for the spare parts

SABIC Geleen uses the same replenishment policy for each spare part. Currently SABIC Geleen uses a (R,s,S)-policy for all spare parts to control inventory. Different spare parts may demand for different replenishment policies, so it is proposed to incorporate the decision of determining the spare parts inventory replenishment policy in the spare parts ordering policy (i.e. highly critical spare parts should ideally be always available which implies continuous review, whereas less critical spare parts do not necessarily have to be reviewed continuously).

8.3.4. Jointly determination of the inventory replenishment parameters

Finally, SABIC Geleen does not jointly determine the optimal values for the reorder point and the order-up-to-level. However, the order-up-to level is dependent on the reorder point and the order quantity (De Kok, Fortuin, and Van Donselaar, 2007):

$$order - up - to\ level = reorder\ point + order\ quantity \tag{8.1}$$

If this equation does not hold because the stock levels are not determined jointly (i.e. the reorder point is determined separately from the order-up-to level), it could mean that the order-up-to level is set at an unnecessary high or low level which could lead to unnecessary inventory holding costs (in case the maximum stock level was set too high) or ordering costs (in case the maximum stock level was set too low). Determining an order-up-to level which is too low also increases the probability of stock-out and downtime costs. Therefore, we propose to jointly determine the reorder point and order quantity/order-up-to level.

Based on the above four observed deviations of the current situation of SABIC Geleen with literature, we propose in section 8.4 what decisions should be incorporated in the spare parts ordering policy and in what sequence these decisions should be taken.

8.4. Redesign of current decisions in the spare parts ordering policy

Based on the confrontation between literature and the current decisions and sequence, we proposed to include the following decisions in the following sequence in the spare parts ordering policy (see also Figure 17):

1. Determine the equipment criticality
2. Determine the criticality of the parts of the critical equipment
3. Determine the reparability of the spare part
4. Select a supplier of the spare part
5. Determine the stocking decision
6. Determine the inventory replenishment policy

7. Jointly determine the replenishment policy parameters (review period, reorder point and order-up-to level/order quantity)

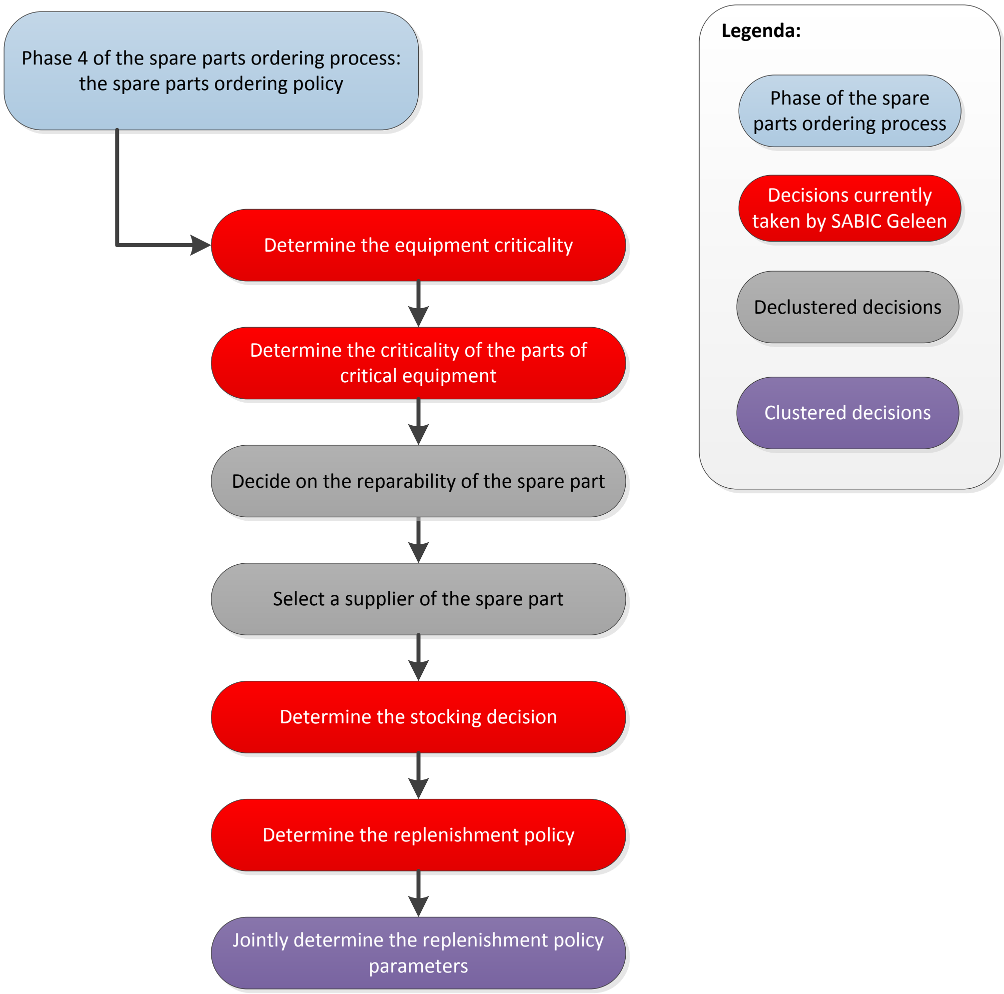

Figure 17: adjustments of the decisions and sequence of the spare parts ordering policy

8.5. Chapter Summary

This chapter evaluated the (sequence of) decisions to be taken in the spare parts ordering policy according to literature (Figure 15). The current (sequence of) decisions of SABIC Geleen is/are described (Figure 16) and based on the difference between the proposed steps and sequence from literature and the current situation of SABIC Geleen, a redesign on the decisions and the sequence is developed (Figure 17) for SABIC Geleen. Because the spare parts stocking location decision is irrelevant for SABIC Geleen because the response time (the time between the failure occurred until it is available for use) and the handling, transport, and inventory holding costs are about equal, irrespective of the stocking location at the site in Geleen.

The redesigned decision steps and sequence is applied in this thesis in the following chapters (chapter 9 until chapter 16) to arrive at a systematic description of the spare parts ordering policy phase, in order to prevent future production losses because of wrong decisions and/or the wrong decision sequence. The redesigned decision steps will be discussed in detail in the following chapters.

9. DECISION ONE IN THE SPARE PARTS ORDERING POLICY PHASE: DETERMINE THE EQUIPMENT CRITICALITY INCLUDING SEVERITY AND LIKELIHOOD OF OCCURRENCE USING A RISK MATRIX

SABIC Geleen firstly determines the criticality of the equipment in order to focus time and economic resources on the most critical equipment. Because of the large amount of equipment (i.e. SABIC Geleen owns about [redacted] different types of equipment) SABIC Geleen does not have the resources (time, money, personnel) to focus on all types of equipment in order to prevent spare part unavailability when a failure occurs.

In this chapter, the first decision of the spare parts ordering policy will be discussed. Section 9.1 will explain the literature review on equipment criticality analyses. In section 9.2 the current methodology used by SABIC Geleen is described. Then the equipment criticality analysis is compared with methodologies described in the literature. A redesign of the equipment risk analysis is made in section 9.4, which is applied to a case study of SABIC Geleen in section 9.5.

9.1. LITERATURE REVIEW OF THE DETERMINATION OF EQUIPMENT CRITICALITY

Since the amount of assets is very large (more than [redacted] assets), time and economic resources are insufficient to analyze all assets. Hence, we need a method so that resources are focused on assets in an efficient way. Effort is spent most efficiently if the impact (i.e. cost savings) of the analysis is maximized. Costs are defined as the downtime costs of a failed asset, the costs related to safety, health or environmental issues (e.g. remediating polluted ground), and urgency ordering costs. The downtime costs are directly related to the criticality of the equipment (i.e. if the equipment is critical and a part fails, downtime costs will be higher than for non-critical equipment). Therefore it is proposed to first determine the criticality of the assets performing an equipment criticality analysis (Carretero et al., 2003). First it is determined on which assets focus should be devoted because the impact of a failure is highest. For these assets, an analysis on component level could be performed.

The criticality of an asset is defined by an asset criticality number:

$$criticality\ number_i = max_j[risk\ number_{ij}] \tag{9.1}$$

where j represents the risk categories: safety, downtime, environment, quality, lost revenues, legal, and related exposure (De Groof, 2010). The $risk\ number_{ij}$ is the risk number of an asset i in risk category j, specified as:

$$risk\ number_{ij} = probability_{ij} * effect_{ij} \tag{9.2}$$

$probability_{ij}$: Probability that the effect defined in category j occurs for asset i
$effect_{ij}$: Effect of asset i for risk category j

The resulting criticality numbers should be compared with a set threshold value (Carretero et al., 2003) determined on the risk acceptable for management. Assets with a criticality number higher than the threshold value are included for further multi-criteria decision analysis (De Groof, 2010). Using a multi-criteria decision analysis provides us with a technique to incorporate more than only the criticality of the asset as a decision to select assets on their importance. De Groof (2010) proposes to first make a selection of assets based on criticality before performing the multi-criteria decision analysis for the complete installed asset base because this saves time and operational costs (e.g. of data gathering).

Visualizing the risk number compared to a set threshold value in a criticality matrix is broadly described in literature (see De Bruijn, 2013). The criticality matrix distinguishes the assets based on their effect on a risk category and the probability that the effect defined in the risk category occurs in important and less important assets. Literature describes that a company is free to choose what risk categories to include in the criticality analysis, but at least safety, environment, health, and total costs (i.e. downtime costs, costs of repair or discard, ordering costs, transport costs, labor costs, and inventory holding costs) (MIL-STD-882D) should be included. Using the MIL-STD-882D for the process industry is allowed, because in both environments the realization of high worker and system safety, low environmental consequences with the lowest economic consequences is the objective. For the determined risk categories, the effect should be defined. The MIL-STD-882D proposes to differentiate the effect of a failure in four classes:

- Very severe,
- Severe,
- Moderate, and
- Low.

The number of classes and the determination of a potential consequence to a particular effect class should be defined by each company because this information is company specific. The likelihood of occurrence, which is defined as the probability that the potential consequences will be experienced, should be estimated. MIL-STD-882D proposes to define four likelihood categories:

- Very high,
- High
- Moderate, and
- Low,

which could be quantified by the company in order to decrease the subjectivity of a qualitative scale.

Also in the likelihood determination, the number of categories and the determination of boundary values (i.e. at what value does the company conclude that the likelihood is very high instead of high) is company specific and should therefore be determined for company specific situations.

MIL-STD-882D proposes the following risk matrix including boundary values for the impact and likelihood, which could serve as a baseline for a risk matrix of companies (see Table 16):

Table 16: risk assessment matrix according to MIL-STD-882D

						Probability/Likelihood			
		Health (worker safety)	Safety	Environment	Economic	< 1 in 1,000 years	1 in 100 years to 1 in 1,000 years	1 in 10 years to 1 in 100 years	> 1 in 10 years
Effect/impact	Low	Reportable or equivalent	None	Limited impact that is readily corrected	10k$ - 100k$	D	D	C	C
	Moderate	Hospitalization or lost-time injury	Minor medical attention	Report to agencies and take remediate action	100k$ - 1M$	D	C	C	B
	Severe	Single disabling injury	Hospitalization or serious injury	Irreversible damage to low quality land, or clean-up of environmentally sensitive areas required	1M$ - 10M$	C	C	B	A
	Very severe	Fatality or multiple serious injuries	Fatality or multiple serious injuries. Massive negative publicity	Months of clean-up work needed in environmentally sensitive areas	≥ 10M$	C	B	A	A

The meaning of the four letters and colors of Table 16 are:

- A (red): very high: this level of risk requires immediate action regardless of the schedule and budget,
- B (orange): high: this level of risk must be reduced, but there is (limited) time to conduct detailed analyses and investigation. If resolving the problem takes longer than the available time, immediate action is needed,
- C (yellow): moderate: the risk is significant but cost and scheduling constraints can be taken into account for determining when action needs to be taken to solve the problem.
- D (green): low: requires a solution, but is of low importance.

9.2. CURRENT EQUIPMENT CRITICALITY DETERMINATION OF SABIC GELEEN

SABIC Geleen currently uses a criticality matrix to assess the risk of a failed asset. Other locations of SABIC also use risk matrices to determine the risk of a failed asset, but because each location of SABIC developed an own risk matrix, no standard format is available which makes it difficult to compare risks between different sites for the management of SABIC in Saudi Arabia. Management of SABIC Saudi Arabia developed a new risk matrix in order to arrive at a standardized format which could be used by all locations of SABIC worldwide. Using a standardized format facilitates managing and comparing risks between different locations of SABIC. Because management of SABIC Saudi Arabia determined to use the newly developed risk matrix from January 1st 2014, we describe this risk matrix for determining the current equipment criticality analysis of SABIC Geleen, instead of the, until now currently used, own developed risk matrix.

SABIC Saudi Arabia defined the following risk categories:

- Financial, which is measured on a corporate and site level (in $). Direct costs (repair costs, replacement costs, downtime costs, ordering costs, labor costs, transport costs,) are considered in this risk category,
- Reputation, which is measured qualitatively. It describes the media activity (both in geographical reach and duration) that might be readily seen if this risk does occur,
- Health and safety is measured on the extent of injury to employees and the public as a consequence of the potential incident. SABIC chose to not estimate the financial value of a human life because it could be perceived as controversial,
- Environmental impact is measured on the amount of release/spillage of hazardous chemicals into the environment with a potential acute or long-term environmental impact or harm to the environment,
- Operational consequences are measured in the amount of equivalent days of lost production. Because SABIC has facilities of different capacities, where different products with different margins are manufactured, the assessment of production loss is measured in the equivalent of calendar days (where it is assumed that the plant produces with its maximum capacity) to make a fair comparison between the sites worldwide. For example, if an incident results in the equivalent of three days of production loss, this could be caused by three complete calendar days of complete shutdown with the maximum capacity or by e.g. six calendar days of partial shutdown were only half of the capacity of the plant could be used.

The consequences of a potential failure to the above mentioned risk categories are defined in five severity classes, ranging from very low to very high and boundary values are determined by SABIC Saudi Arabia based on industry relevant benchmark data and experience of the designers of the matrix.

SABIC Saudi Arabia also defined the likelihood of a potential failure. Two quantitative scales (used for estimating risks with an operational or financial/strategic nature) based on the probability that the failure occurs, and a qualitative scale (based on events occurring within SABIC or its industry or branch within a one year period) are defined to indicate the likelihood of the failure. Also these boundary values are determined using benchmarking data from the chemical industry and experience of the designers of the matrix.

Based on the above defined risk categories, scales, and boundary values, SABIC Saudi Arabia designed the SABIC Risk Matrix (see Table 17). The colors and numbers in the cells of the risk matrix indicate the risk level:

- Risk level 1 (red): indicates a major risk and specific control should be established in the short-term in order to reduce the risk to a lower level as soon as possible,
- Risk level 2 (orange): indicates a significant risk. The risk should be reduced unless it is technically impossible or economically undesirable (i.e. the cost of solving the risk should outweigh the expected benefit of the solution of the risk) to do,
- Risk level 3 (yellow): indicates a minor risk and the risk should be reduced only if a cost efficient solution already exists, and
- Risk level 4 (green): indicates an insignificant risk. The risk is expected to be efficiently managed and therefore it is proposed to continue monitoring and risk mitigating measures in order to keep the risk at this risk level.

SABIC Geleen currently focuses resources to equipment types of risk level 1 and risk level 2 because the impact of an analysis is maximized for these risk levels (i.e. the most costs can be saved).

Table 17: risk matrix to be used by SABIC Geleen from January 2014 (source: Enterprise Risk Management – SABIC Risk Management and Risk Matrix Guideline, 2013)

		Financial (Corporate/Site) Direct Loss (in $)	Reputation	Health and Safety	Environment	Operation (Production Loss in equivalent hours or days)		Likelihood				
								L5	L4	L3	L2	L1
								Probability per year (operational)				
								< 0.01%	0.01% - 0.1%	0.1% - 1%	1% - 10%	> 10%
								Probability per year (financial & strategic)				
								< 1%	1% - 10%	10% - 30%	30% - 60%	> 60%
								Frequency				
								The scenario is not foreseen to occur and is not recorded in the industry/branch	The scenario may occur in exceptional circumstances but has been recorded in similar industry/ branch	The scenario has occurred in SABIC or has happened more than once per year in similar industry/branch	The scenario has happened once before at the location/site or more than once per year in SABIC	The scenario is almost certain to occur and has happened several times per year at the location/site
								Very Unlikely	**Unlikely**	**Possible**	**Likely**	**Very Likely**
Consequence	**C1**	Corporate > 100M Site > 10M	Regional media coverage over multiple days or global media coverage	Multiple fatalities to SABIC employees/ contractors or public fatality	Chemical release of > than 20 times the threshold quantity Release/spillage > 10MT of hazardous chemicals/ substance or hazardous waste	Equivalent to > 5 days	**Very high**	**2**	**2**	**1**	**1**	**1**
	C2	Corporate 10M - 100M Site 1M - 10M	National media coverage over multiple days or single regional media coverage	Fatality or multiple lost workday injuries to SABIC employees/ contractors or public injuries	Chemical release between 9 - 20 times the threshold quantity Release/spillage > 10MT of hazardous chemicals/ substance or hazardous waste	Equivalent to 3 - 5 days	**High**	**3**	**2**	**2**	**1**	**1**
	C3	Corporate 1M - 10M Site 100k - 1M	Local media coverage over multiple days or single national media coverage	Lost workday injuries to SABIC employees/ contractors	Chemical release between 3 - 9 times the threshold quantity Release/spillage between 4 - 10 MT of hazardous chemicals/substance or hazardous waste Release/spillage of > 50MT of non-hazardous chemicals/substance	Equivalent to 1 - 3 days	**Moderate**	**4**	**3**	**2**	**2**	**1**
	C4	Corporate 100k - 1M Site 10k - 100k	Single local media coverage	Medical treatment to SABIC employees/ contractors	Chemical release between 1 - 3 times the threshold quantity Release/spillage between 4 - 10 MT of hazardous chemicals/substance or hazardous waste Release/spillage between 20 - 50 MT of non-hazardous chemicals/substance	Equivalent to 8 - 24 hours	**Low**	**4**	**4**	**3**	**2**	**2**
	C5	Corporate < 100k Site < 10k	Only internal communications	First aid to SABIC employees/ contractors	All other chemical release that does not meet the threshold value Release/spillage < 0.1MT of hazardous chemicals/substance or hazardous waste All other incident release/spillage < 20MT of non-hazardous chemicals/substance	Equivalent to < 8 hours	**Very low**	**4**	**4**	**4**	**3**	**3**

9.3. Confrontation of the determination of equipment criticality of SABIC Geleen with literature

Using a risk matrix for assessing the asset criticality is broadly described in literature (see De Bruijn, 2013). Therefore, the choice of SABIC Geleen to use a risk matrix for determining the equipment criticality is supported in the thesis. For determining whether the matrix of SABIC is useful according to literature, the designed matrix of SABIC should be compared with the proposed matrix from literature on the following six aspects:

1. The risk categories included in the risk assessment,
2. The used scale for measuring the consequences of a potential incident,
3. The used scale for measuring the likelihood of a potential failure,
4. The boundary values for classifying the risk categories on the consequence scale,
5. The boundary values classifying the incident on the likelihood scale, and
6. The accepted risk level.

9.3.1. The included risk categories in the risk matrix

As described in the literature when using a risk matrix to determine the criticality of an asset, at least safety, health, environment, and costs should be included as risk categories but a company is free to include more risk categories as the inclusion of risk categories is company specific. SABIC did incorporate the risk categories as described by literature and extended this with two categories: reputation and operations (production loss). These categories are included in the risk matrix of SABIC because management of SABIC wants to control these risk categories. They want to control reputation because negative publicity caused by an incident could deteriorate customer loyalty and endangers the profitability of SABIC in the long-term. Operations (lost production) is controlled for because lost production caused by an incident could cost SABIC up to about €500,000 per day if a complete plant has to be shut down.

9.3.2. The used scale for measuring the consequences of a potential incident

The military standard for system safety (MIL-STD-882D) proposed to differentiate the consequences of a potential failure in four qualitatively classes, ranging from low to very severe. SABIC uses also a qualitative classification and included one additional class of very low consequences to arrive at five consequence classes (C1 to C5). Although the names of the categories differ (literature proposed to use severe, whereas SABIC uses high), the meaning of the scale is the same. Literature stated that it is company specific what scale to use and how to classify a potential incident on the consequence scale.

9.3.3. The used scale for measuring the likelihood of a potential failure

The military standard for system safety (MIL-STD-882D) proposed to differentiate the likelihood scale in four classes, ranging from low to very high, and quantify the scale if possible to prevent subjectivity. SABIC differentiated their likelihood scale in five classes, ranging from very unlikely to very likely (L1 to L5). Although the names of the classes of the risk matrix used by SABIC are different than the names proposed by the military standard, the meaning is the same. SABIC included one additional likelihood class (very unlikely) that the failure will occur in the coming year. They also quantified the likelihood scale as much as possible, determining the probability of failure per year for risks with an operational or strategic/financial nature, which decreases subjectivity in the risk assessment.

9.3.4. The boundary values for classifying the risk categories on the consequence scale

SABIC has chosen to determine quantitative boundary values for the consequence scale in order to arrive at a more objective determination of the consequence of a potential failure. SABIC quantified the financial consequences (direct loss) for both the corporation as well as the specific site where the failure occurred, the release/spillage of hazardous chemicals/substance above a threshold quantity, and the days of production lost because of the incident. SABIC Saudi Arabia deliberately chose not to quantify financial value of human life because it could be perceived as controversial.

The boundary values are determined by SABIC Saudi Arabia based on industry benchmark data and experience of the designers of the risk matrix.

9.3.5. THE BOUNDARY VALUES FOR CLASSIFYING THE INCIDENT ON THE LIKELIHOOD SCALE

SABIC has chosen to determine quantitative boundary values for the likelihood scale in order to arrive at a more objective determination of the likelihood of a potential failure in the coming year. SABIC quantified the probability of a risk with an operational and a strategic/financial nature. Also these values are determined by SABIC Saudi Arabia based on industry benchmark data and experience of the designers of the risk matrix.

9.3.6. THE ACCEPTED RISK LEVEL

The military standard proposed a guideline for companies to see what level of risk could be accepted and what risks could be identified as unacceptable. The process of determining the maximum acceptable risk level is company specific. Comparing the proposed solution of the military standard and the developed risk matrix of SABIC shows only small deviations with respect to the categorization of risk level 2 (significant or high risk) and risk level 3 (minor or moderate risk). The designed risk matrix of SABIC accepts slightly lower risk levels than proposed by the military standard.

9.4. REDESIGN OF CURRENT DETERMINATION OF EQUIPMENT CRITICALITY OF SABIC GELEEN

From the comparison between literature and the designed matrix of SABIC it appeared that the matrix of SABIC fulfilled all proposed requirements from literature. SABIC designed additional risk categories, consequence and likelihood classes for their company-specific situation, which is supported by literature. The quantification of the classes is specific for SABIC and they based the values on industry benchmarking data. Finally, SABIC determined the acceptable risk levels based upon their own specific situation, which is also supported by literature.

Because the risk matrix fulfills all proposed requirements of literature and is systematically adjusted to the specific situation of SABIC, we propose to use the risk matrix of SABIC. Designing a new risk matrix would raise operational costs (labor cost) while the result of a newly designed risk matrix will be about the same as the currently designed risk matrix. Therefore, no new risk matrix is designed and we propose to use the currently designed risk matrix of SABIC to determine the criticality of the equipment. Furthermore, SABIC Saudi Arabia wants to introduce a generic risk assessment method for all worldwide sites, which means that we are not able to redesign the risk matrix of SABIC Geleen

9.5. CASE STUDY: EQUIPMENT CRITICALITY ANALYSIS APPLIED USING THE REDESIGNED SOLUTION

In order to explain SABIC Geleen how to use the risk matrix, an equipment type related to delayed work orders of 2012 is selected. The matrix is applied for this type of equipment to determine the criticality (risk level) of the equipment. We examine a nitrogen compressor on its criticality to explain how the new risk matrix should be used.

The estimated failure probability of the compressor with an operational nature lies between once a year and once per ten years, which indicates a failure probability of > 10% or a classification in the very likely likelihood class of the SABIC risk matrix. Then the consequences of the failure are estimated for each risk category:

- Financial loss: the financial loss of the site is estimated by the Maintenance Engineers, based on their experience or supplier data, to be between 10k€ and 100k€ which equals between around 13k$ and 130k$ which is categorized as a low impact. Combined with the very high likelihood, the risk level according to the financial loss risk category would be significant (risk level 2).
- Reputation: the impact of reputation is estimated by the Maintenance Engineers to be almost close to zero, which is categorized in the very low consequence class. Combined with the very high likelihood, the risk level according to the reputation risk category would be minor (risk level 3).
- Health and safety: the effects on health or safety are estimated, based on experience, feeling, or supplier data, to be very small, which is categorized in the very low consequence class. Also this risk category would lead to a risk level 3 (minor risk).
- Environment: it is estimated by the Maintenance Engineers that failure of the nitrogen compressor will not affect the environment, which is categorized in the very low consequence class. Concluding, based on the environment risk category, the equipment has a risk level 3 (minor risk).
- Operations: the incident of failure of the nitrogen compressor is estimated, based on experience, feeling or supplier data, to lose less than 8 equivalent hours of production because the nitrogen compressor is designed with redundancy (i.e. if one nitrogen compressor fails, the other can take over the complete production process without production loss) , which is categorized in the very low consequence class. Combined with the very likely possibility of failure this leads to a minor risk (risk level 3).

The criticality number of the equipment is determined by the minimum of the risk numbers for the risk categories. Note that a lower risk level number depicts a higher risk level. For the nitrogen compressor, this means that the criticality number will be 2 $(\min(2,3,3,3,3) = 2)$, which indicates a significant risk of failure.

9.6. CHAPTER SUMMARY

In this chapter, the equipment criticality analysis was explained. Based on the military standard (MIL-STD-882D) a risk matrix is proposed included what risk categories should be minimally included in the risk matrix. Literature emphasizes that the risk matrix should be designed by the company using the company-specific situation as a guide for the inclusion of risk categories, classification scales of the consequence and likelihood scale, determination of boundary values, and maximum accepted risk level.

SABIC Saudi Arabia designed a new risk matrix (see Table 17) which is planned to be used from 2014 in all sites of SABIC worldwide to simplify the comparison of risks and their consequences between different production locations. This matrix is compared with the proposed solution of literature. Because the deviations, caused by the specific situation of SABIC, of the currently designed risk matrix are small compared to the proposed solution by literature, and the boundary values are determined using industry benchmarking data, we propose to use the developed risk matrix of SABIC to determine the criticality of equipment.

Finally, we applied the matrix to a case study in order to explain SABIC Geleen how the matrix should be used from 2014 onwards. Better equipment criticality estimations could be made which decrease the negative economic effects of downtime because of focusing on critical equipment.

10. DECISION TWO IN THE SPARE PARTS ORDERING POLICY PHASE: DETERMINE THE CRITICALITY OF THE PARTS OF CRITICAL EQUIPMENT

SABIC Geleen wants to focus time and economic resources on critical equipment because the resources are not sufficient to analyze all equipment. When SABIC Geleen indicates a type of equipment as critical, further resources are devoted to this equipment. For critical equipment, SABIC Geleen wants to determine what components are critical so that the highest yield in saving costs could be realized.

Section 10.1 describes a literature review of the spare part criticality determination. Then, the current spare part criticality determination of SABIC Geleen is described, which is compared with the proposed technique by literature in section 10.3. Based on the difference between the two techniques, a redesign is made.

10.1. LITERATURE REVIEW OF THE PART CRITICALITY DETERMINATION

Before optimizing the spare parts ordering policy for critical equipment, it is necessary to identify components in the asset for which it is expected that high yields in terms of cost savings, i.e. critical components, can be realized because time and economic resources of SABIC Geleen are insufficient to optimize the spare parts ordering policy of all components for all critical equipment. SABIC Geleen therefore needs a technique to identify the critical components of an asset. McDermott et al. (2009) propose to use the Failure Mode and Effect Analysis technique in order to reveal what components of an asset are critical.

Because maintenance data, and therefore the demand of spare parts, is registered on equipment level, it is not immediately clear which component needed a maintenance action. To reveal maintenance information on a component level takes additional effort by identifying which component failed or needed a maintenance action. Assets of SABIC Geleen mostly contain at least ten components (small, elementary equipment like a pump) or up to more than several hundred components (larger, complex equipment like a gearbox). Identifying the components belonging to the maintenance activity data for all components of critical equipment will cost a lot of time and economic resources. In order to save resources, it is proposed to use the FMEA technique. The advantage of using FMEA is that time resources are saved while it could still be decided which components are critical based on multiple criteria.

FMEA studies are a subjective technique to determine which components of an asset are critical. In order to decrease the subjectivity of the technique, a multifunctional team of employees from different departments participate in the FMEA study to achieve a greater scope and depth of information.

Before the group session starts, a decomposition of the asset is made at the first indenture level. The decomposed assemblies of the equipment, i.e. functional locations, are again decomposed into components (second indenture level). The resulting list of components is used in the FMEA study to reveal potential failure mode(s) for each component of the asset. After the possible failure modes were determined, a severity (the impact of the effect caused by a failure mode), occurrence (the frequency of occurrence) and detection (to what extent could a failure mode be detected before failure occurs) ranking is assigned to each failure mode using ten-point scales. The criticality of a component is now determined using a risk priority number (RPN) which is calculated in the following way (McDermott et al., 2009):

$$Risk\ Priority\ Number = severity * occurrence * detection \tag{10.1}$$

The final step in the FMEA study is to take action to reduce the highest risk priority numbers, by monitoring the condition of the component, by performing periodical maintenance activities or by stocking spare parts.

10.2. CURRENT PART CRITICALITY DETERMINATION OF SABIC GELEEN

Currently, SABIC Geleen uses the FMEA study to reveal the failure mode(s) for components of critical equipment as was described by literature. SABIC Geleen also calculates risk priority numbers, based upon the multiplication of severity, occurrence and detection, but not on ten-point scales. SABIC Geleen chose to link the severity and occurrence score to the five dimensions of the risk matrix (described in chapter 9), whereas the detection is scored on a ten-point scale.

10.3. CONFRONTATION OF THE PART CRITICALITY DETERMINATION OF SABIC GELEEN WITH LITERATURE

Using a FMEA study for assessing the criticality of a component is broadly described in literature (see e.g. McDermott et al., 2009). Therefore, the choice of SABIC Geleen to use a FMEA study for determining the part criticality is supported in the thesis. For determining whether the FMEA study of SABIC is useful according to literature, the currently used FMEA technique should be compared with the proposed FMEA technique from literature. Only three small deviations were revealed when comparing the FMEA studies:

1. SABIC Geleen currently measures severity on a five-point scale instead of ten-point because they coupled severity to the impact dimension of the risk matrix
2. SABIC Geleen currently measures occurrence on a five-point scale instead of ten-point because they coupled occurrence to the likelihood dimension of the risk matrix
3. SABIC Geleen uses different rating scales for expressing the scores on severity, occurrence, and detectability

Literature discusses that rating scales usually range from five-point to ten-point scales where a higher number indicates a higher severity, occurrence rate, or detectability. It is described by literature that the levels of the rating scales are company-specific and should be determined by the organization, instead of using a generic determined scale not applicable for the specific situation of SABIC Geleen. Therefore we propose to keep the five-point ranking scales of the severity and occurrence components unchanged.

Literature also discusses that the same rating scale should be applied to all the components of severity, occurrence and detection to avoid the appearance of skewing the resulting RPN. Because the ranking scales of the severity and occurrence components are linked to the risk matrix, we propose to decrease the levels of the detectability ranking scale to five-points. It is discussed by literature that using nonconsecutive numbers are more useful than consecutive numbers because it allows for more distinction between the ratings and less debate among the FMEA team members. Therefore we propose to retain the odd numbers of the ten-point detectability scale as currently used by SABIC Geleen.

10.4. REDESIGN PART CRITICALITY DETERMINATION

From the comparison between literature and the designed FMEA technique of SABIC it appeared that the technique of SABIC was almost the same as proposed by literature. The only differences between the proposed technique from literature and the currently used FMEA study of SABIC Geleen which is redesigned is that not all ranking scales have the same amount of levels. We propose to give all scales the same dimension in order to prevent the RPN from becoming skewed which increases the probability of focusing resources on non-critical spare parts. Because SABIC Geleen decided to relate the severity and occurrence scales to the risk matrix designed by SABIC Saudi Arabia, we are not able to redesign these scales. The only option left to give all scales an equal dimension is to decrease the amount of levels of the detectability scale from ten to five points. SABIC Geleen currently uses the following dimensions for the detectability scale (see Table 18):

Table 18: currently used detectability scale of SABIC Geleen (Source: FMEA study SABIC Geleen, 2013)

Detectability score	Detectability
1	Detection is possible by elimination or alarm
2	Detection is possible by an operator during the inspection round
3	Detection is possible by indirect measurements
4	Detection is possible by maintenance inspection rounds
5	Detection is possible by periodical condition monitoring
6	Detection is possible by specific maintenance inspections or monitoring activities
7	Detection is possible by specific maintenance inspections or plant shutdown actions
8	Detection is possible by random inspections or plant shutdown actions
9	Detection is only possible by extraordinary coincidence
10	Detection is impossible

Based on literature to use nonconsecutive numbers, we propose to keep score 1, 3, 5, 7, and 9 of the currently used detectability scale (see Table 18) and provided them with new scores (see Table 19). Note that score 2 (detection is possible by an operator during the inspection round) is chosen instead of score 3 (detection is possible by indirect measurements) because it was not clear for the Maintenance or Reliability Engineers of SABIC Geleen what the definition of indirect measurements is.

Table 19: proposed detectability scale of SABIC Geleen (Source: FMEA study SABIC Geleen, 2013)

Detectability Score	Detectability
1	Detection is possible by elimination or alarm
2	Detection is possible by an operator during the inspection round
3	Detection is possible by periodical condition monitoring
4	Detection is possible by specific maintenance inspections or plant shutdown actions
5	Detection is only possible by extraordinary coincidence

10.5. CHAPTER SUMMARY

In this chapter the spare parts criticality analysis was explained. Based on literature (McDermott et al., 2009) a FMEA technique is proposed to identify the critical components in an asset while minimizing needed resources.

SABIC Geleen currently uses the FMEA technique in order to determine which components of an asset are critical. Comparing the technique proposed by literature and the currently used technique of SABIC Geleen revealed only subtle differences. The choice of the amount of levels in the ranking scales is company-specific. SABIC Geleen chose to couple the severity and occurrence scale to the risk matrix (described in chapter 9). Literature emphasizes that the amount of levels of the ranking scales, used for calculating the Risk Priority Number (see formula 10.1) should be the same. Literature also discusses to use nonconsecutive numbers in order to increase the distinction between the dimensions which decreases the debate among the FMEA team members.

Because SABIC Geleen currently uses a higher amount of levels in the detectability scale we propose to keep only the odd numbers of the currently used detectability scale of SABIC Geleen in order to have equally dimensioned ranking scales and inserting nonconsecutive numbers to prevent the RPN outcome to be skewed (see Table 19) and minimize debate among the FMEA team members.

11. DECISION THREE IN THE SPARE PARTS ORDERING POLICY PHASE: DECIDE ON THE REPARABILITY OF THE SPARE PART

After it is determined what the critical components of the critical assets are, SABIC Geleen should determine the reparability of the spare part. The repair (in case of repairable spare parts) or delivery (in case of consumable spare parts) lead time influences the decision on the supplier selection and the stocking decision and therefore the decision of the reparability of the spare part is taken early in the spare parts ordering policy.

In section 11.1 literature is reviewed on the reparability of the spare part. Then the current reparability decision of SABIC Geleen is described and the proposed techniques from literature are compared with the current method used by SABIC Geleen. Based on the difference between the proposed and currently used method, a redesign is made in section 11.4. A case study of SABIC Geleen is described to explain the employees of SABIC Geleen how to use the redesign in practice.

11.1. LITERATURE REVIEW OF THE REPARABILITY OF A SPARE PART

To prevent critical assets from downtime, assets are generally repaired by replacement, i.e. a defective component is removed and replaced by a functioning spare part which is located in the local warehouse to reduce replacement times, or at the central warehouse to achieve risk pooling effects (i.e. maximum system availability at minimum inventory holding costs). Defective components can be only discarded and replaced with a newly purchased component, or they could be both repaired or discarded. The decision on the reparability of a spare part is divided into a decision based on non-economic criteria, and an analysis based on cost models (i.e. economic criteria).

11.1.1. NON-ECONOMIC CRITERIA TO DETERMINE THE REPAIR DECISION

In this step of the reparability decision, non-economic criteria are used to determine whether it is technically possible to repair the spare part. If that is the case, an analysis based on cost models is performed to determine whether it is cost efficient to repair the component.

11.1.2. ECONOMIC CRITERIA TO DETERMINE THE REPAIR DECISION

The economic decision whether to repair or discard the component upon failure is referred to as the first decision of the Level Of Repair Analysis problem, which is also known as the repair/discard decision (Basten et al., 2011). The repair/discard decision in the LORA problem is purely based on the costs to perform a repair or discard, disregarding the fact that the delivery lead time for a spare part might differ from the repair lead time. If the delivery lead time for replacing the defective component by buying a new one is much higher than the lead time for repairing the part, choosing the discard option (i.e. replacing the defective component by buying a new one and discarding the defective component), because of lower costs, leads to higher stock levels of the spare part to achieve the same availability of the asset (Basten et al., 2011). Therefore, Basten et al. (2011) propose to incorporate stocking decision aspects (asset availability and supply lead time) in the minimization model. The standard LORA minimization model also incorporates at which locations the repairs and discards should be performed and at which locations the resources should be deployed, but we are only interested in determining which components should be repaired upon a failure and which components should be discarded. We are therefore able to simplify the minimization model of Basten et al. (2011). The following variables are included in the minimization model (see Table 20):

Table 20: description of used variables in the LORA minimization problem

Variable	Description
$A(S)$	Realized availability given the stock level of the component
A_0	Target availability
c_d	Variable costs when making decision d. The variable costs consist of ordering costs, transport costs, downtime costs, labor costs, and costs of decision d (i.e. either repair or discard costs)
D	Decision to repair or discard the component after failure
h	Annual costs of holding one spare of the component
λ	Total failure rate of the component, which is assumed to fail according to a Poisson process and is assumed to be constant
L_d	Lead time when making decision d
S_d	The order-up-to level when making decision d
X_d	Binary decision variable indicating the choice of a decision d

The assumption of a Poisson distributed constant annual failure rate is valid for modeling demand of spare parts (Louit, Pascual, Banjevic, and Jardine, 2011).

The variables and assumptions result in the following minimization model:

$$minimize \sum_{d \in D} c_d * \lambda * X_d + h * S_d \tag{11.1}$$

subject to:

$$\sum_{d \in D} X_d = 1 \tag{11.2}$$

$$A(S_d) \geq A_0 \tag{11.3}$$

$$X_d \in \{0,1\} \tag{11.4}$$

$$S_d \in \mathbb{N}_0 \tag{11.5}$$

The minimization formula (11.1) indicates that the decision to repair or discard the spare part should be decided based on which decision minimizes the total costs (repair vs. discard costs, ordering costs, transport, downtime costs, labor costs and inventory holding costs). Constraint 11.2 indicates that for each component a decision upon repair or discard is made. Constraint 11.3 assures that the target availability is met, which takes into account the various lead times. Constraint 11.4 describes that the decision variable is binary, and constraint 11.5 indicates that the stock levels are a set of all natural numbers.

Because the availability constraint (11.3) is a linear function of a repair/discard decision and the inventory of the spare part, we have a linear integer optimization problem which could be solved using standard optimization software. An Excel tool is developed for SABIC Geleen to calculate the stock levels and corresponding costs for both the repair and discard option, which makes it easier for the Maintenance Engineers to determine what option is cheaper given the desired target availability. For both decisions, either to repair or discard the component, the following calculations need to be executed:

$$Compute\ E[D(0, L_d + 1)] = \lambda * (E[L_d] + 1)$$

$$Compute\ A(S_d) = \sum_{x=0}^{S_d} \frac{\left(\lambda * (E[L_d] + 1)\right)^x * e^{-(\lambda * (E[L_d]+1))}}{x!}, for\ x \in \{0,1,2, \dots\}$$

$$Compute\ \hat{C} := c_d S_d$$

$If\ A(S_d) < A_0$

$then$

$S_d = S_d + 1$

$Compute\ A(S_d) and\ \hat{C}$

$else\ stop$

Of each option, an availability-investment curve can be plotted where it is seen what option (i.e. discard or repair) achieves the target availability at minimum costs ($\hat{C}$). This option should be chosen for the component of the asset in order to achieve maximum asset availability at minimum costs.

11.2. CURRENT SPARE PART REPARABILITY DECISION AT SABIC GELEEN

Currently, SABIC Geleen divides the decision whether a component should be repaired after failure or should be discarded into a decision based on non-economic criteria and an analysis based on cost models.

11.2.1. NON-ECONOMIC CRITERIA TO DETERMINE THE REPAIR DECISION

The Maintenance Engineers of the Site Improvement Departments determine whether it is technically possible to repair the spare part, which is based on information from the supplier of the spare part (in case of new components) or on the experience of the Maintenance Engineer. When the Maintenance Engineer decided that the component is indicated as a repairable, every time the repairable spare part fails it is determined whether it is still technically possible to repair the spare part or that it is so heavily damaged that a repair activity is impossible.

11.2.2. ECONOMIC CRITERIA TO DETERMINE THE REPAIR DECISION

If the maintenance employees determined that it is (still) possible to repair the component, SABIC Geleen compares the costs of repair (consisting of purchasing costs to make the order, costs to receive the materials and test them, costs to process the invoice, costs of transporting the spare parts, and costs of repairing the spare part) with the costs of buying a new item (consisting of the purchasing costs to make the order, costs to receive the materials and test them, costs to process the invoice, costs to transport the new purchased spare part, and the selling price of the supplier). Because the purchasing costs, receiving costs, testing costs, invoice costs, and transport costs are almost equal, irrespective whether a spare part is indicated as a repairable or as a consumable, the spare part will be repaired when the costs of repair are lower than the selling price of the item. If the price of buying a new component is less than the costs of repairing the spare part, the component will be scrapped and a new spare part will be ordered.

Because of uncertainty in the successfulness of a repair activity of a component (e.g. it was predetermined that the spare part could be repaired but during repair it appears that it is impossible), SABIC Geleen does not repair spare parts when the price of repair is close to the price of buying a new component. To determine the maximum price SABIC accepts to pay for repairing a spare part is dependent on the state the spare part is repaired, i.e. as good as new, or with minimal repair, and is determined by the Maintenance Engineer based on his experience. Repairs of components in an as good as new state are allowed to have a higher price than minimal repair activities, i.e. the repair of a failed system is just enough to get the system operation again. The amount of costs accepted to repair the component instead of purchasing a new one is based on the experience and insights of the Maintenance Engineer.

If SABIC Geleen decides to buy a new part for replenishing the defective spare part (i.e. because it is technically infeasible or economically undesirable) the damaged spare part is minimally repaired so that it could be used in emergency situations (e.g. as a back-up when the installed spare part fails within the delivery lead time of the new spare part). The disassembled failed component is not immediately scrapped in order to cover unexpected breakdown of the new assembled spare part during the delivery lead time of the new spare part to minimize the probability of spare part unavailability and downtime effects. As soon as the new spare part is delivered, the old, minimally repaired component is scrapped.

11.3. Confrontation of spare part reparability decision of SABIC Geleen with literature

Comparing the proposed technique for deciding whether a spare part should be indicated as a repairable or consumable component with the current practice of SABIC Geleen shows that both techniques distinct between non-economic and economic criteria to base the reparability decision on. Basten et al. (2011) propose to firstly determine whether it is technically feasible to repair the component. This proposal of literature is currently included in the reparability decision of SABIC Geleen.

After it is determined that it is technically feasible to repair the spare part, economic criteria should be evaluated to determine whether it is economically efficient to repair the spare part. Literature proposes to take into account both the lead time and the costs to base the repair/discard decision on (Basten et al., 2011). Taking into account the lead time of a repair compared with the delivery lead time of a new purchased component is important because it affects spare part availability (i.e. a longer lead time increases downtime effects and therefore demands for higher stock levels to cover unexpected spare part demand during the lead time). Therefore, literature proposes to incorporate stocking decision aspects (asset availability and supply lead time) in the reparability decision (Basten et al., 2011). Currently, SABIC Geleen only decides on the costs of repair compared to costs of purchasing a new component and does not take into account the lead time to determine the reparability of the component.

11.4. Redesigned spare part reparability decision

In section 11.3 it is described that it is useful to incorporate the lead time when deciding upon the reparability of a spare part. Because SABIC Geleen does not take the lead time into account in the reparability decision, a redesign is made to be able to incorporate the lead time.

We propose to use the simplified minimization model of the LORA problem of Basten et al. (2011), and the greedy heuristic developed by Rustenburg (2000), as discussed in section 11.1.2, to determine whether a spare part should be indicated as a repairable or as a consumable component.

11.5. Case study: spare part reparability decision applied using redesigned solution

In order to explain SABIC Geleen how to use the simplified minimization model, and to show the benefits of using the redesigned technique for determining the reparability of a spare part, a critical component from critical equipment is selected to determine the reparability decision based on the redesigned solution. We examine the reparability decision of a gear of the gearbox of the extruder which has a damaged tooth. Currently SABIC Geleen decided that the gear is indicated as a repairable spare part, but Maintenance and Reliability Engineers had doubts whether the right decision was made.

11.5.1. Current reparability decision of SABIC Geleen

The gear with damage to the tooth could be repaired in an as good as new state. The exact price what SABIC Geleen accepts to repair the gear is unknown because it is based on the experience of the Maintenance Engineer, but a price below [redacted] is likely to be accepted. Because the repair costs are lower (i.e. [redacted]), SABIC Geleen decided to repair the component after failure.

11.5.2. Redesigned reparability decision

In order to determine whether the gear should be indicated as a repairable or a consumable spare part, we need the following inputs (see Table 21):

- The failure rate (λ) of the gear (in times of failure/week),
- The mean delivery lead time (L_p) of the gear in case the gear is purchased after failure (in weeks),
- The mean repair lead time (L_r) of the gear in case the gear is repaired after failure (in weeks),
- The costs of purchasing (c_p) a new gear after failure (in €), and
- The costs of repairing (c_r) the gear after failure (in €).

Table 21: input variables and their parameter values for determining the repair/discard decision of the gear

Symbol	Input variable	Parameter value for the gear
λ	Annual failure rate (in failures/week)	0.00096 (once in 20 years)
L_p	Mean delivery lead time (in weeks)	19
L_r	Mean repair lead time (in weeks)	2
c_p	Purchase costs (in €)	55,000
c_r	Repair costs (in €)	10,000

We are then able to calculate the demand during $L_d + 1$ periods for both the discard and the repair option and use this as an input for the calculation of the availability:

$\boldsymbol{Option\ 1: repair\ the\ component}$

$$Compute\ E[D(0, L_r + 1)] = \lambda * (E[L_r] + 1)$$

$$= 0.00096 * (19 + 1)$$

$$= 0.00096 * 20$$

$$= 0.01923$$

$$Compute\ A(S_r) = \sum_{x=0}^{S_r} \frac{(\lambda * (E[L_r] + 1))^x * e^{-(\lambda * (E[L_r]+1))}}{x!}, for\ x \in \{0,1,2, \dots\}$$

$$Compute\ \hat{C} := c_r S_r$$

$$If\ A(S_r) < A_0$$

$$then$$

$$S_r = S_r + 1$$

$$Compute\ A(S_r) and\ \hat{C}$$

$$else\ stop$$

$\boldsymbol{Option\ 2: discard\ the\ component}$

$$Compute\ E[D(0, L_p + 1)] = \lambda * (E[L_p] + 1)$$

$$= 0.00096 * (2 + 1)$$

$$= 0.00096 * 3$$

$= 0.00288$

$$Compute\ A(S_p) = \sum_{x=0}^{S_p} \frac{\left(\lambda * \left(E\left[L_p\right] + 1\right)\right)^x * e^{-\left(\lambda * \left(E\left[L_p\right]+1\right)\right)}}{x!}, for\ x \in \{0,1,2, \dots\}$$

$Compute\ \hat{C} := c_p S_p$

$If\ A\left(S_p\right) < A_0$

$then$

$S_p = S_p + 1$

$Compute\ A\left(S_p\right) and\ \hat{C}$

$else\ stop$

The option which achieves the target availability at the lowest costs is chosen to perform on the gear. See Table 22 for the calculation in case of the gear of the gearbox of the extruder.

Table 22: stock levels, availability, and investment values for the case study of the gear of the gearbox of the extruder

S_p	S_r	$A(S_p)$	$A(S_r)$	$Inv(S_p)$	$Inv(S_r)$
0	0	0.9810	0.9971	0	0
1	1	0.9998	1.000	55,000	10,000
2	2	1.000	1.000	110,000	20,000

Suppose that SABIC Geleen demands for a target system availability of 99% (i.e. in 99% of the time, the equipment should be operational for producing products). When choosing to repair the spare part after failure, this availability is achieved without having one spare part on stock, so the investment is €0, whereas for the purchase option, one spare part should be kept on stock to achieve the availability, which demands for an investment of €55,000. In this case the target system availability is met at the lowest costs when deciding to repair the spare part, instead of purchasing it after failure.

11.6. Chapter summary

In this chapter the spare parts reparability decision was explained. Based on literature (Basten et al., 2011) it is proposed to base the decision on both non-economic and economic criteria. The non-economic criteria should be used for determining whether it is technically feasible to repair the spare part, whereas the economic criteria need to be used for determining whether it is cost efficient to repair the spare part. Literature proposes to base the economic decision on both the lead time and the costs to base the repair/discard decision on (Basten et al., 2011). Taking into account the lead time of a repair compared with the delivery lead time of a new purchased component is important because it affects spare part availability (i.e. a longer lead time demands for higher stock levels to cover unexpected spare part demand during the lead time).

Currently, SABIC Geleen only decides on the costs of repair compared to costs of purchasing a new component and does not take into account the lead time to determine the reparability of the component.

A redesign is made to be able to incorporate the lead time. We use the simplified minimization model of the LORA problem of Basten et al. (2011), and the greedy heuristic developed by Rustenburg (2000), as discussed in section 11.1.2, to determine whether a spare part should be indicated as a repairable or as a consumable component. The greedy heuristic is explained using a practical example regarding the gear of a gearbox of the extruder where it was concluded, using the redesigned solution, that the gear should be repaired after failure. SABIC Geleen currently decided that the gear should be repaired after failure, so they made the right decision for this case study.

12. DECISION FOUR IN THE SPARE PARTS ORDERING POLICY PHASE: SELECT A SUPPLIER FOR THE SPARE PART

After SABIC Geleen determined what equipment is critical, based on the risk assessment described in chapter 9, they should select at which supplier the spare parts of the equipment should be ordered. The selection of a supplier precedes the stocking decision because supply availability has a direct effect on the stocking decision (i.e. if a supplier cannot supply the critical spare part, SABIC Geleen could perhaps stock the spare part to reduce the risk of failure).

In the first section of this chapter, section 12.1, literature is reviewed on the selection of a supplier. In section 12.2, the current supplier selection decision of SABIC Geleen is described, and this is compared with literature in section 12.3. Based upon the gap between the proposed and the actual supplier selection decision, a redesign is made, which is applied to a case study of SABIC Geleen (see section 12.5).

12.1. LITERATURE REVIEW OF THE SELECTION OF A SUPPLIER

According to literature (Ghodsypour & O'Brien, 1996) the selection decision of a supplier is a multi-criteria decision problem which includes qualitative and quantitative factors. In order to select the best supplier it is necessary to make a trade-off between the potentially conflicting factors, i.e. all suppliers are able to only partially satisfy the buyer's requirements of demand, quality, and delivery within preset constraints (e.g. budget, quality of the spare part).

Ghodsypour and O'Brien (1996) assume that more than one supplier is always available for supplying the demanded parts. If this assumption does not hold, i.e. there is only one supplier available for delivering the demanded parts, the buyer party has no choice in choosing what supplier is able to deliver the spare parts best.

Ghodsypour and O'Brien (1996) propose to use an Analytical Hierarchy Process (AHP) for the supplier selection problem in order to trade-off the potentially conflicting factors to be able to choose the best supplier because it is an accurate scoring method, compared to e.g. the linear weighted point, categorical method, or cost ratio method.

The main steps of the AHP algorithm are (Ghodsypour & O'Brien, 1996) (see also Figure 18):

1. Define the criteria for supplier selection,
2. Calculate the weights of the criteria,
3. Rate the alternative suppliers, and
4. Compute the overall score of each supplier and select the supplier with the highest overall score.

See Appendix F – Explanation of the main steps of the Analytical Hierarchy Process when selecting a supplier for a detailed description of the main steps of the AHP algorithm.

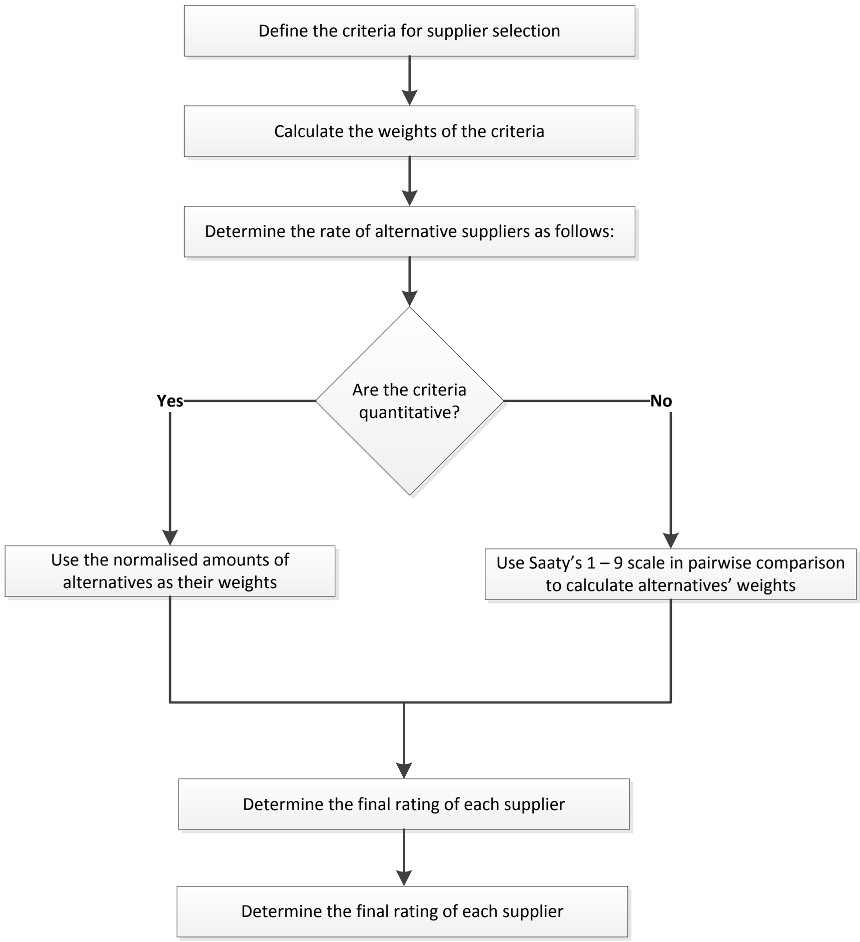

Figure 18: supplier selection algorithm
(Source: Ghodsypour & O'Brien (1996))

12.2. CURRENT SELECTION DECISION OF A SUPPLIER OF SABIC GELEEN

For selecting a supplier, SABIC Geleen firstly determines whether more than one supplier is able to deliver the demanded spare part. If that is not the case, the Procurement Department of SABIC Geleen has no choice in selecting a supplier and is forced to demand spare parts at that supplier because he is the only party to be able to deliver the spare part. If more than one supplier is available for supplying the demanded spare parts, SABIC Geleen uses the vendor qualification process to determine which supplier is qualified for delivering the demanded spare parts. In the vendor qualification process, SABIC Geleen scores vendors on a number of criteria for which weights are determined (based on the perceived importance of management on the criteria) to determine which supplier is suitable for delivering the spare parts. SABIC Geleen scores vendors on twelve criteria (Vendor Qualification Questionnaire of SABIC Geleen, 2011):

1. Stability: questions regarding the stability of the supplier are asked (e.g. what are the annual operating revenues and profits before taxes),
2. Presence: questions regarding the presence of the supplier in the market (e.g. in which countries in Europe do you have production facilities/service organizations),
3. Dependence: question regarding how dependent the supplier is of SABIC Geleen (e.g. how much money (in €) has SABIC Europe been spending with your company over the last three years),
4. Quality: questions regarding the quality of the delivered products (e.g. How is your company certified),

5. Capability: questions regarding the short-term and long-term continuity of conducting business (e.g. how is your short-term capability and long-term vision in terms of number of own employees or equipment),
6. Insurance: question regarding the insured delivery when agreed (e.g. provide a general overview of your insurance policy),
7. Experience/references: questions regarding the experience of the supplier in the manufacturing and delivery of the demanded material (e.g. do you have any relevant experience with the manufacturing and delivery of the demanded material),
8. Credentials: questions regarding the performance measurement system of the supplier (e.g. what is your company's score on a performance review),
9. Analysis: questions regarding analyses and improvements within the supplier's organization (e.g. do you use assessment tools, do you use industry benchmarking data),
10. Costs/value: question regarding the costs and value of the delivered product (e.g. is the supplier prepared to give full cost price transparency),
11. Safety, Health and Environment: questions regarding the safety, health, and environment policy and procedures of the supplying party (e.g. what SHE management procedures are in place to ensure safety and health of your employees and to protect the environment), and
12. Miscellaneous: questions regarding using ICT technology and e-commerce (e.g. describe your experience with e-commerce).

For all above mentioned questions, an integer score between zero (the lowest possible score) and three (the highest possible score) is assigned by SABIC Geleen. Scores of questions regarding the same criterion are averaged. SABIC Geleen currently determines the weight factors for the criteria based on experience and/or focus of management. For every supplier which is going to be qualified, the weight factors are determined again, because other factors might be important for delivering different types of spare parts. Finally, multiplying the weights of the criteria with the average scores gives a weighted average score of the supplier on the criteria of SABIC Geleen. SABIC Geleen determined the threshold value to be at least 2.0 (the maximum possible score is 3.0), i.e. if a supplier receives at least a weighted average score of 2.0, the vendor is qualified to deliver to SABIC Geleen. All qualified vendors for the demanded material are then compared on price where the vendor with the lowest price is ultimately selected to deliver the spare part to SABIC Geleen. Note that SABIC Geleen requires that all delivered parts are according to specification.

12.3. Confrontation of the supplier selection decision of SABIC Geleen with literature

When comparing the proposed technique for selecting a supplier from literature with the current situation of SABIC Geleen we see the following deviations:

- SABIC Geleen explicitly takes into account the amount of suppliers which is able to deliver the demanded material,
- SABIC Geleen explicitly obliges the supplier, before it is even qualified, to deliver the parts exactly according to specifications,
- SABIC Geleen currently uses a linear weighted average method to qualify the suppliers, instead of the proposed Analytical Hierarchy Process by literature, and
- The final selection of a supplier is currently based upon costs (i.e. the supplier with the lowest price of delivery is selected), whereas literature proposes to base this decision on the benefit-cost ratio.

The first step SABIC Geleen takes into account to select a supplier is to determine how many suppliers are possible to deliver the spare part. If the spare part is specific and only one supplier (e.g. the Original Equipment Manufacturer) is able to deliver the spare part (in around 80% - 90% of the demanded spare parts), no selection decision could be made and the available supplier is selected for delivering the spare parts. Then SABIC Geleen obliges the potential supplier(s) to deliver the spare part according to specifications. If a potential supplier cannot guarantee that the delivered parts are according to specifications, the potential supplier will not be qualified for delivering spare parts to SABIC Geleen.

These go/no-go decisions are not described in the supplier selection methodology proposed from literature because Ghodsypour and O'Brien (1996) assume that more than one supplier is available for delivering the demanded spare parts. The go/no-go decision of SABIC Geleen regarding the specification is in the model of Ghodsypour and O'Brien (1996) incorporated as a constraint in the Linear Programming model. The decision is of such vital importance (i.e. SABIC Geleen does not want additional risk of failure because of a part that is not according to specifications) for SABIC Geleen that the management has chosen to take this decision explicitly and early in the supplier selection process. Because of possible downtime effects by using spare parts that are not according to specification (e.g. the spare part does not fit exactly or is made of inferior quality) we support the decision of the management of SABIC Geleen to explicitly take into account that the spare part should be according to specification as a go/no-go early in the supplier selection process.

According to literature (Ghodsypour & O'Brien, 1996) the use of an Analytical Hierarch Process is preferred over the linear weighted point method that SABIC Geleen currently uses because it is a more accurate method for selecting the best supplier. We propose to use the AHP method, as described by Ghodsypour and O'Brien (1996), for SABIC Geleen in order to increase the accuracy of the supplier selection process.

Once a vendor is qualified, it could be chosen to give a tender for delivering the demanded part of SABIC Geleen. The tender should be pairwise compared on cost/value, quality, and lead time because these three criteria are the most important for guaranteeing that the correct spare part (quality) is delivered on time (lead time) at minimum price (cost/value) in order to achieve maximum system availability.

Finally, Haas and Meixner (2006) proposed to base the final selection on the benefit-cost ratio instead of only costs, as is currently done by SABIC Geleen. Using a benefit-cost ratio shows the largest benefits compared to the costs, instead of only taking into account the costs. Only taking into account the costs of a solution poses the risk that the cheapest, and not the best supplier is selected. Therefore, we propose to base the final supplier selection decision on the benefit-cost ratio.

12.4. Redesign of the supplier selection decision

Based upon the deviations from the current supplier selection process of SABIC Geleen, described in section 12.3, we make a redesign of the supplier selection process. We propose to use the supplier selection process as described by Ghodsypour and O'Brien (1996) but explicitly incorporating the number of available suppliers, and the decision whether or not the supplier guarantees that he is able to deliver the spare part according to the specifications (see Figure 19).

After it is determined that more than one supplier is able to deliver the spare part according to specifications, the criteria on which the suppliers will be judged have to be determined. SABIC Geleen currently determines the performance of a supplier on twelve criteria. The amount and what criteria are included in the supply selection process is a company-specific choice. We propose to keep the twelve criteria in the redesigned supplier selection process. From the comparison of the current process of SABIC Geleen with literature, an important criterion seems to be missing; the delivery lead time. This criterion is added in the redesigned supplier selection process.

The weights are calculated by pairwise comparison of the thirteen criteria using complex mathematical steps (see Appendix F – Explanation of the main steps of the Analytical Hierarchy Process when selecting a supplier). The aim is to arrive at weight factors for the criteria which indicate the relative importance of the criterion compared to the other criteria. In order to compare the criteria with each other, it is useful to express the weight factors as a fraction of one as it is immediately clear what criterion has a higher score, and thus is more important, compared to other criteria. Additionally, the summed weight factors of all criteria should add up to one. The calculation of the criterion weights is an iterative process and should be stopped if the difference of the newly calculated weight factor compared with the previously calculated weight factor is below a preset threshold value.

When a demand for the spare part occurs, the qualified suppliers are selected and they are asked for a tender. Based upon the pairwise comparison of the suppliers on price and lead time, the rating of a supplier is calculated which results in a final rating of the suppliers after multiplying the criterion weights of the variables cost/value and lead time with the scores of the supplier on these variables. Cost/value is defined as all costs for acquiring the product, i.e. ordering costs, purchasing costs, inventory holding costs, labor costs, and transport costs. Lead time is defined as the time between the moment in time a purchasing order is placed and the moment in time when the demanded part is delivered and ready for use for SABIC Geleen. Finally, the benefit-cost ratio is calculated and the supplier with the highest benefit-cost ratio is selected for delivering the demanded spare parts, where the benefit-cost ratio is defined as the shortest delivery lead time at the lowest costs.

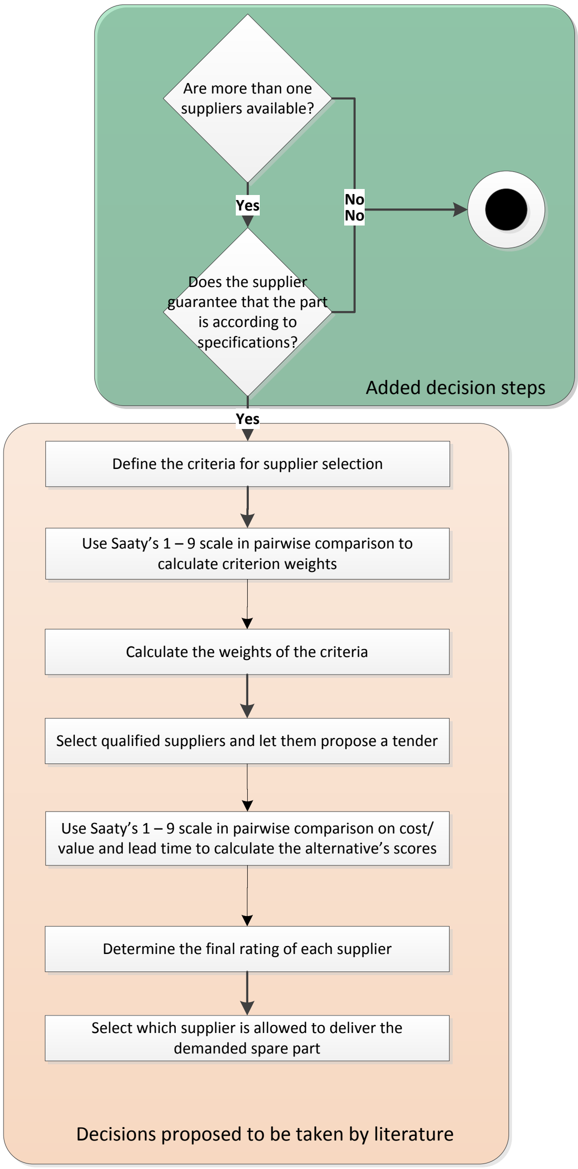

Figure 19: redesigned supplier selection process

12.5. CASE STUDY: SUPPLIER SELECTION DECISION APPLIED USING THE REDESIGNED SOLUTION

In order to explain to the employees of SABIC Geleen how to use the redesigned supplier selection process, a case study is presented. We examine the selection of a supplier for furnace pipes.

The furnace pipes could be delivered with the demanded quality by three possible suppliers, which were qualified using the vendor qualification questionnaire of SABIC Geleen; M, S & C, and P. See Table 23 and Table 24 for the pairwise comparison matrix and the resulting criterion weight factors for the suppliers of the furnace pipes (see Appendix F – Explanation of the main steps of the Analytical Hierarchy Process when selecting a supplier for the mathematical procedure how to arrive at the result).

Table 23: pairwise comparison matrix of SABIC Geleen for the furnace pipes

	Stability	Presence	Dependence	Quality	Capability	Insurance	Experience/ references	Credentials	Analysis	Cost/value	Safety, Health, and Environment	Lead time	Miscellaneous
Stability	1.00	1.00	2.00	0.50	1.00	2.00	2.00	2.00	2.00	0.50	1.00	0.50	2.00
Presence	1.00	1.00	2.00	0.50	1.00	2.00	2.00	2.00	2.00	0.50	1.00	0.50	2.00
Dependence	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Quality	2.00	2.00	4.00	1.00	2.00	4.00	4.00	4.00	4.00	1.00	2.00	1.00	4.00
Capability	1.00	1.00	2.00	0.50	1.00	2.00	2.00	2.00	2.00	0.50	1.00	0.50	2.00
Insurance	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Experience/ references	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Credentials	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Analysis	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Cost/value	2.00	2.00	4.00	1.00	2.00	4.00	4.00	4.00	4.00	1.00	2.00	1.00	4.00
Safety, Health, and Environment	1.00	1.00	2.00	0.50	1.00	2.00	2.00	2.00	2.00	0.50	1.00	0.50	2.00
Lead time	2.00	2.00	4.00	1.00	2.00	4.00	4.00	4.00	4.00	1.00	2.00	1.00	4.00
Miscellaneous	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00

Table 24: criterion weight factors of SABIC Geleen

Criterion	Criterion weight factor
Stability	0.0769
Presence	0.0769
Dependence	0.0384
Quality	0.1538
Capability	0.0769
Insurance	0.0384
Experience/references	0.0384
Credentials	0.0384
Analysis	0.0384
Cost/value	0.1538
Safety, Health, and Environment	0.0769
Lead time	0.1538
Miscellaneous	0.0384

The criterion weights of cost/value and lead time and quality are all equal. However, because SABIC Geleen does not make concessions regarding the quality of the demanded components, this factor is not incorporated in the analysis.

12.5.1. Current supplier selection decision applied

Currently, SABIC Geleen chooses a supplier for delivering the demanded parts purely based on the lowest costs. See Table 25 for the costs of ordering a furnace pipe at each supplier.

Table 25: costs (in €) of ordering at the supplier of furnace pipes for SABIC Geleen

Supplier	Costs (in €)
M	[redacted]
S & C	[redacted]
P	[redacted]

Because P delivers the demanded furnace pipes at the lowest cost, SABIC Geleen currently has chosen P as the supplier for the furnace pipes.

12.5.2. Redesigned supplier selection decision applied

For each criterion (cost/value and lead time) a pairwise comparison matrix is determined using experience and input of Purchasing employees. Also here, the AHP procedure (see Appendix F – Explanation of the main steps of the Analytical Hierarchy Process when selecting a supplier for a detailed explanation of the Analytical Hierarch Process and how to calculate the scores) is followed to calculate the score of each supplier on both the lead time and the cost/value criterion in order to determine which supplier is the best choice for SABIC Geleen (see Table 26 and Table 27):

Table 26: cost/value criterion pairwise comparison for case study furnace pipes of SABIC Geleen

	Cost/value		
	M	*S & C*	*P*
M	1.00	1.10	0.90
S & C	0.90	1.00	0.80
P	1.10	1.25	1.00

Table 27: lead time criterion pairwise comparison for case study furnace pipes of SABIC Geleen

	Lead time		
	Mr	*S & C*	*P*
M	1.00	0.75	1.50
S & C	1.33	1.00	3.00
P	0.75	0.33	1.00

Also now, the same complex mathematical procedures have to be followed in order to calculate the relative score of the suppliers. The relative scores of the suppliers should add up to one and indicate the relative performance of the supplier compared to the other suppliers. The process of calculating the weight factors for the suppliers is iterative and the value of the weight factors might change. As soon as the difference from the last with the former iteration is below a preset threshold value, the final weight factors of the suppliers are found. The weights of the alternative suppliers for the cost criterion are after two iterations (see Table 28):

Table 28: cost/value criterion weight scores for case study furnace pipes of SABIC Geleen

Cost/value	
Supplier	*Cost/value weight factor*
M	0.3317
S & C	0.2983
P	0.3701

The weights of the alternative supplier for the lead time criterion are after three iterations (see Table 29):

Table 29: lead time criterion weight scores for case study furnace pipes of SABIC Geleen

Lead time	
Supplier	*Lead time weight factor*
M	0.3185
S & C	0.4876
P	0.1939

An Excel tool is developed for SABIC Geleen to calculate the relative importance of the weight factors, using the pairwise comparison values as input.

The score of the suppliers is then calculated using the following formula:

$$\begin{aligned} &score\ for\ supplier \\ &\quad = cost/value\ criterion\ weight\ factor * cost/value\ weight\ factor\ of\ supplier \\ &\quad + lead\ time\ criterion\ weight\ factor * lead\ time\ weight\ factor\ of\ supplier \end{aligned} \tag{12.1}$$

See Table 30 for the scores of the suppliers of furnace pipes in this case study.

Table 30: scores for the suppliers for delivering a furnace pipe to SABIC Geleen

Supplier	Final normalized score
M	0.6502
S & C	0.7859
P	0.5640

Finally, the benefit-cost ratio, i.e. the lowest delivery lead time relative to the lowest costs, is to be calculated to determine the supplier which offers the best solution. The costs were already provided in Table 25**Error! Reference source not found.**. However in order to compare the costs with the relative benefit scores, the costs should also be expressed in a relative number, where the sum of all scores is one.

The final solution of the supplier selection follows by dividing the relative benefit score with the relative costs score for each supplier. The supplier with the highest value provides the highest benefits compared to the costs and should therefore be chosen as the supplier for the furnace pipes (see Table 31). From the benefit-cost ratio, supplier S & C provides the highest benefits compared to the costs and should therefore be chosen to supply SABIC Geleen with the demanded furnace pipes.

Based on the costs, the only criterion SABIC Geleen considers now, P should be the preferred supplier of the furnace pipes for SABIC Geleen. Also taking into account the lead time shows that S & C is preferred over P, as the benefits compared to the costs are highest (i.e. a fast lead time at relatively low costs). Currently SABIC Geleen orders the furnace pipes at S & C because of delivery problems encountered at P, which underpins the importance of incorporating supply lead time for choosing a supplier.

Table 31: benefit-cost ratio of the suppliers of furnace pipes for SABIC Geleen

Supplier	Benefit-cost ratio
M	1.9508
S & C	2.1218
P	1.9035

12.6. CHAPTER SUMMARY

In this chapter, the supplier selection process was explained. Based on the paper of Ghodsypour and O'Brien (1996) an Analytical Hierarch Process is proposed instead of the linear weighted point method as is currently used by SABIC Geleen. Using the AHP, based upon pairwise comparisons, increases the accuracy of the decision making process. Haas and Meixner (2006) proposed to base the final supplier selection decision upon the benefit-cost ratio instead of only taking into account the costs like SABIC Geleen currently does.

Literature assumes that ample supply sources with the demanded spare parts quality are available, which is not a realistic assumption for SABIC Geleen. We proposed to take explicitly into account in an early phase of the supplier selection process the amount of available suppliers and the guarantee that the demanded spare part quality can be delivered (see Figure 19), before the weights of the criteria are determined. The qualified suppliers for the demanded spare parts are then judged upon costs, currently applied by SABIC Geleen, and the delivery lead time, proposed from literature.

13. DECISION FIVE IN THE SPARE PARTS ORDERING POLICY PHASE: DECIDE ON THE STOCKING DECISION

After SABIC Geleen has selected a supplier for delivering the critical spare parts of critical equipment they should decide whether or not the spare part is kept on stock. This decision is needed to guarantee a quick repair of an asset that has failed in order to achieve maximum system availability at minimum costs. Literature is reviewed in section 13.1 to determine what methodology could be used to determine the stocking decision. This is compared with the current decision methodology of SABIC Geleen in section 13.3. Because we concluded that the current stocking decision of SABIC Geleen includes the criteria to base the decision upon, we propose to keep using the current stocking decision methodology of SABIC Geleen and a redesign is not made.

13.1. LITERATURE REVIEW OF THE SPARE PARTS STOCKING DECISION

In order to achieve a short repair time, enough spare parts have to be stocked at appropriate locations in the supply chain to guarantee a high service level (Botter & Fortuin, 2000). Because most of these spare parts are expensive it is not cost efficient to stock all spare parts. A selection of what spare parts to stock is needed to determine which spare parts should be stocked and which spare parts could be ordered at the supplier, in order to achieve maximum system availability in a cost efficient way.

Literature (Botter & Fortuin (2000) and Driessen et al. (2010)) emphasize the use of criticality of the spare part to base the stocking decision on. Driessen et al. (2010) distinguish subsets of spare parts based on (partially) critical spare parts and non-critical spare parts (see Figure 20). Availability of (partially) critical spare parts is essential to reduce system downtime in case the equipment failed, whereas unavailability of non-critical spare parts does not directly cause downtime of the equipment. Also Huiskonen (2001) proposes to relate spare part criticality to the maximum repair time (i.e. the maximum desired time, based on the acceptable risk of failure, in which the failure has to be corrected).

Literature proposes however to incorporate more criteria than spare part criticality only, because the criticality classification alone does not discriminate all the control requirements of different types of spare parts. Huiskonen (2001) proposes to also take into account the price of the spare part. Price is an important criterion to base the stocking decision on, because it is undesirable to stock very expensive service parts in every local warehouse. High priced spare parts should be stored only in a central warehouse or even shared among different production locations or companies. Also Driessen et al. (2010) use price as a criterion to determine the stocking decision on and they emphasize that a higher spare parts price makes the stocking of the part less attractive.

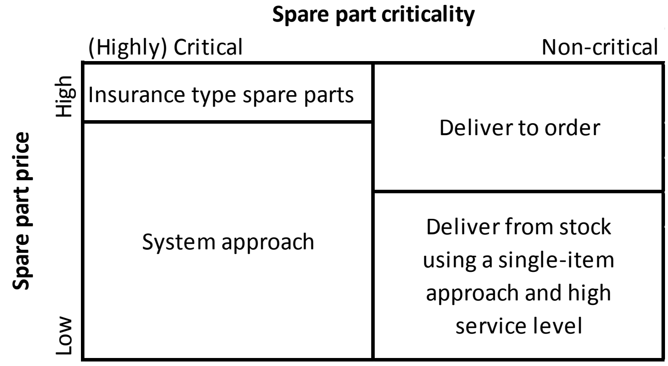

Figure 20: spare part stocking decision framework proposed by Driessen et al. (2010)

They propose to stock critical spare parts (both low and high price) and the low price non-critical spare parts. High value non-critical spare parts are ideally delivered to order. (Highly) critical spare parts with a high price (insurance spare parts) should be stocked as insurance for minimizing downtime effects. Insurance spare parts are known to have a high price (at SABIC Geleen the price is set at more than [redacted] determined by the management of SABIC) and a very long delivery lead time (i.e. more than [redacted] calendar days, based on the maximum desired repair time). The spare parts almost never fail, but if they do, the downtime effects are very large because the system is not able to function (i.e. around [redacted] per day is lost if a complete system is shut down). Companies should stock, according to Driessen et al. (2010) at least one component of a spare part to be able to minimize the downtime effects if the failure occurs. Because the high price of the spare part, the yearly inventory costs will be very high. A strategy for decreasing inventory costs of insurance spare parts while achieving the desired availability is by stock pooling these spare parts (see Karsten and Basten, 2012).

(Highly) critical spare parts with a lower price should be available because unavailability of the spare parts directly influences the functionality of the system. Therefore a system approach is proposed to control the inventory for this class of spare parts in order to achieve maximum system availability at minimum costs. It guarantees the desired availability of the system at lower inventory holding costs (see Appendix I – Explanation of the Multi-Echelon Technique for Recoverable Item Control (METRIC) model for the explanation of the system availability approach).

Non-critical spare parts should be available to support an efficient flow of maintenance activities (i.e. the maintenance employees are able to perform the maintenance activities because they do not have to wait for spare parts). Availability of these spare parts does not have a direct effect on the functionality of the system so the more complicated system approach is unnecessary to use. Because the spare parts are non-critical for the system an item approach is sufficient to control the inventory for this class of spare parts. Note that non-critical spare parts with high prices are not stocked because high inventory holding costs for non-critical spare parts are not justified. Spare parts that have a short delivery lead time are also not stocked. They are procured when needed because the short and reliable delivery lead time guarantees availability of the spare part when it is needed.

Botter and Fortuin (2000) also classify the demand of the spare parts in their decision to stock a spare part or not. They distinguish the demand in units into three different classes:

1. Fast moving,
2. Slow moving, and
3. Intermediate moving (spare parts which are neither fast moving nor slow moving),

which results in the following classification framework (see Figure 21):

		Consumption of spare parts		
		Fast moving	Intermediate moving	Slow moving
Functionality of the spare part	Desirable	Do not stock	Do not stock	Do not stock
	Essential	Stock if maximum 90% of the consumption of spare parts should be covered	Stock if between 90% and 99% of the consumption of spare parts should be covered	Stock if at least 99% of the consumption of spare parts should be covered

Figure 21: spare part stocking decision framework proposed by Botter and Fortuin (2000)

Each segment of spare parts, indicated by a cell in the framework of Botter and Fortuin (2000) (see Figure 21) is based on the decisions management of the company makes. It might be possible to decide not to stock the desirable spare parts, which seems to be a logic decision as unavailability of these spare parts during a failure does not immediately influence the functionality of the asset. Then only the essential spare parts remain as candidates to be stocked. A distinction between the consumption of the spare part is based on the cumulative consumption of the spare part. In common practice, boundaries of 90% and 99% are taken to distinguish the consumption, i.e. when management decided that 90 percent of the cumulative consumption needs to be covered, only fast moving spare parts need to be stocked, whereas if management wants at least 99% of the cumulative consumption to be covered, also the intermediate and slow moving spare parts need to be stocked.

Unfortunately, Botter and Fortuin (2000) do not discuss how they define the demand classes. Also Huiskonen (2001) proposes to use demand as a criterion to determine whether a spare part should be stocked or not. He states that, if large amount of spare parts have a very low and irregular demand, an increased amount of safety stock is needed to cover unpredictable situations (Huiskonen, 2001). Furthermore, low demand volumes of spare parts do not attract suppliers to stock the parts at their own location, and therefore end-users are forced to stock the spare parts, which contradicts with logistics theories. Huiskonen (2001) distinguishes spare part demand streams in “high and smooth demand”, and “low and irregular demand”, but also here, the definition is not discussed. In order to classify the demand pattern using defined boundaries, the demand pattern classification scheme could be used as described by Syntetos, Boylan, and Croston (2005) (see Figure 22).

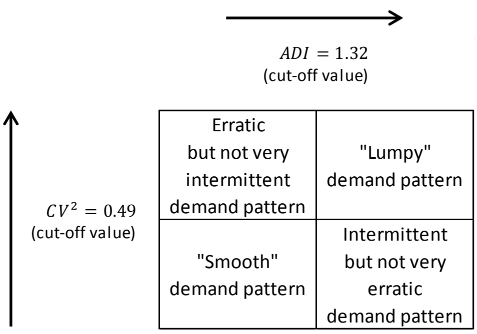

Figure 22: demand pattern classification scheme (Source: Syntetos, Boylan & Croston, 2005)

The demand is classified both upon the average inter-demand interval (ADI) and the variability of the demand sized, expressed by the squared coefficient of variation of the demand sizes (CV^2). Based upon the cut-off values determined by Syntetos et al. (2005), the following four classes of demand can be defined:

- Erratic demand: (highly) variable demand size at relatively certain moments in time,
- Lumpy demand: both the demand size and the moments in time in which the demand occurs are uncertain,
- Smooth demand: bot the demand size and the moments in time in which the demand occurs are certain, and
- Intermittent demand: uncertain moments in time of spare parts demand, but the quantity is relatively certain,

where the smooth demand class is also defined as fast moving demand, and the intermittent demand class as slow moving demand. The framework of Syntetos et al. (2005) could be used to define the boundaries of the consumption of spare parts in the framework of Botter and Fortuin (2000).

Finally, Huiskonen (2001) incorporates spare part specificity, i.e. whether a spare part is able to be used widely by many users (standard parts) or it is specifically tailored for and used by a particular user only (specific parts) in his framework. Specificity of the spare part affects the decision whether to stock a spare part or not because standard parts usually have a better availability because there are stocks of these parts at different levels in the supply chain and suppliers are willing to cooperate with the users because of economies of scale advantages.

For user-specific parts, suppliers are unwilling to stock the special, low volume spare parts and therefore the end-user is forced to keep the spare parts on stock if he wants to achieve his target system availability. Concluding, the framework of Huiskonen (2001) includes spare part specificity, price, criticality, and demand pattern. See Table 32 for the stocking strategies proposed by Huiskonen (2001) for each class of spare parts:

- **User-specific spare parts:** the stocking strategy the company should use is either accepting spare part unavailability or safety stocking, where the last option incurs considerable inventory holding costs (because of the relatively high price). Safety stocking is necessary for all spare parts for which the supply lead time is longer than the maximum desired downtime of a system. Ideally, an end-user should therefore try to shorten the lead time, e.g. by searching a reliable supplier.
- **Standard, high value, (highly) critical spare parts:** the end-user must hold a small amount of safety stock in a local warehouse to guarantee spare part availability. Because the spare part is standard, i.e. used by several other customers, suppliers are more willingly to stock the spare part and offer special services (e.g. 24-hour or faster delivery). In case of extremely low demand volumes, a cooperative stocking pool may be a useful strategy.
- **Standard, low value, (highly) critical spare parts:** having an own safety stock is desirable in this case because working capital is not tied significantly due to the lower value of the spare part.

Table 32: spare part stocking decision framework proposed by Huiskonen (2001)

<table>
<tr><td colspan="3"></td><td colspan="2">Spare parts criticality</td></tr>
<tr><td colspan="3"></td><td>Low</td><td>High</td></tr>
<tr><td rowspan="3">Specificity of the spare parts</td><td rowspan="2">Standard spare parts</td><td>Low price</td><td>• Order processing simplified (e.g. by automated orders)
• Outsourcing of inventory control to a supplier</td><td>• User’s decentralized safety stocks and high replenishment lot-sizes</td></tr>
<tr><td>High price</td><td>• Stock pushed back to the supplier</td><td>• Optimized user’s safety stock (with high and smooth demand)
• Time-guaranteed supplies from established service company (for low and irregular demand)
• Several users’ cooperative stock pools (for very low demand)</td></tr>
<tr><td>User-specific spare parts</td><td></td><td colspan="2">• User’s own safety stock and partnership with local supplier to shorten lead times, to increase dependability and get priorities in emergency situations.
• In the long run, standardization of parts when possible.</td></tr>
</table>

- **Standard, high value, non-critical spare parts:** the need for holding local stocks for guaranteeing spare parts availability is reduced and a useful option for the end-user could be to push all the stock to the supplier or service provider in the supply chain.
- **Standard, low value, non-critical spare parts:** the need for a simple replenishment practice is emphasized (e.g. automatically generated purchase orders), or the supplier takes the complete responsibility of controlling the whole replenishment process (e.g. Vendor Managed Inventory practices).

13.2. Current spare parts stocking decision of SABIC Geleen

As discussed in chapter 10, SABIC Geleen performs a FMEA or RCM study for (highly) risky equipment where it is estimated by the FMEA team what spare parts are needed in order to reduce the impact of a failure. The procedure for determining which spare parts need to be stocked is based on information of the supplier regarding failure modes and frequencies and experience, and feeling of the Maintenance Engineers.

Based on the equipment criticality (using the risk matrix as proposed in section 9.2 and the estimated supply lead time of the spare part, SABIC Geleen indicates which spare parts to stock (see Table 33).

Table 33: matrix used to make a decision which spare parts to stock, based on the equipment criticality and the expected supply lead time (Source: Approved Best Practice 133, SABIC Europe Intranet, 2009)

		Equipment criticality			
		A	B	C	D
Spare parts expected supply lead time	≥ 180 days	red	red	red	red
	20 ≤ days < 180	red	orange	orange	green
	5 < days < 20	red	orange	yellow	green
	≤ 5 days	red	orange	green	green

Note that the red cells in the matrix indicate situations when a spare part should be stocked because either the equipment should be repaired as quick as possible (the equipment is A-critical), or the supply lead time of the spare part is very long (i.e. more than 180 calendar days). The orange cells in the matrix indicate spare parts which also should be stocked, but they are not critical for the functionality of the equipment. The green cells indicate spare parts which do not have to be stocked, because of the low equipment criticality and short supply lead time (less than five calendar days). Finally, the yellow cell indicates situations in which the spare parts are critical for producing a particular production run, but not for another production run (e.g. pump X with spare part Y is critical to produce product type A, but not for producing product type B). The Maintenance Engineer makes the final decision, based on his experience and feeling, whether the spare part needs to be stocked or not, where he takes into account the frequency of the production runs and the criticality of the equipment during a production run for determining the stocking decision of the component.

The boundary values of the spare parts supply time are related to the priority of a work order, which is in turn related to the criticality of the equipment:

- Maintenance orders of A-critical equipment should be repaired as soon as possible (i.e. the maximum desired repair time should also be as fast as possible) (Approved Best Practice 014, SABIC Europe Intranet, 2010). Therefore, irrespective of the supply lead time of the spare part, it should be kept on stock because for such an urgent maintenance activity, spare parts should be immediately available.
- Maintenance orders of B-critical equipment are determined by the management of SABIC Geleen to be repaired within five work days (Approved Best Practice 014, SABIC Europe Intranet, 2010). Spare parts with a supply lead time longer than five working days should be kept on stock. SABIC Geleen also keeps spare parts with a supply lead time of less than five work days on stock because of possible uncertainty in the supply lead time.
- Maintenance orders of C-critical equipment should be repaired within twenty work days (Approved Best Practice 014, SABIC Europe Intranet, 2010). Therefore, components with an expected supply lead time longer than twenty work days should be kept on stock to guarantee spare part availability. If the supply lead time is expected or promised to be shorter than twenty work days, SABIC Geleen is allowed to not stock the spare part. For incorporating uncertainty of the supply lead time, spare parts with an expected supply lead time shorter than twenty work days also are stocked, but this is decided, based on his feeling and experience, by the Maintenance Engineer.
- Maintenance orders of D-critical equipment should be repaired within 180 calendar days (Approved Best Practice 014, SABIC Europe Intranet, 2010). If components have a supply lead time of at least 180 calendar days, the spare part should be kept on stock to guarantee spare part availability. If the supply lead time is less than 180 calendar days, SABIC Geleen does not have to stock the spare part, but it is delivered to order.

13.3. CONFRONTATION OF THE SPARE PARTS STOCKING DECISION OF SABIC GELEEN WITH LITERATURE

We propose to base the stocking decision on the criticality of the equipment, which was determined using the risk matrix of SABIC Geleen (see chapter 9), where lower equipment criticality has a lower need for stocking spare parts. According to Huiskonen (2001) the equipment criticality should be related to the desired maximum supply lead time, which is currently done by SABIC Geleen. SABIC Geleen determined in the risk matrix the maximum amount of equivalent hours or days of production loss which directly indicates the maximum allowed supply lead time of the component.

Price, demand pattern, and spare part specificity affect the height of the stock levels. Spare parts with a higher price have lower stock levels because of high inventory holding costs, spare parts with high demand values have higher stock levels to prevent spare part unavailability, and specific spare parts have higher stock levels because of a longer supply lead time. Because the price, demand, and specificity of a spare parts are incorporated in the determination of the stock levels, there is no need to incorporate them in the decision of whether to stock a spare part or not.

SABIC Geleen currently determines the stocking decision based upon equipment criticality and supply lead time (see section 13.2). The boundary values of the supply lead time are company-specific and should be determined on the maximum accepted time a spare part may be unavailable. Currently, the boundary values are determined by the management of SABIC Geleen based on what maximum supply lead time is accepted for each equipment criticality number. However, because SABIC Geleen is going to use a new risk matrix from 2014 on, the boundary values of the stocking decision tool should also be adjusted. Therefore, we propose to use the stocking decision methodology as is currently used by SABIC Geleen to determine whether a spare part should be stocked or not, and adjust the boundary values to make it compliant with the newly designed risk matrix.

13.4. REDESIGN OF THE SPARE PARTS STOCKING DECISION

SABIC Saudi Arabia decided to distinct the criticality of equipment, using the risk matrix, in four classes (i.e. 1, 2, 3, 4, where 1 indicates the highest equipment criticality and 4 the lowest). SABIC Saudi Arabia also determined the boundary values of the maximum equivalent hours or days of production loss because of a maintenance activity. This directly indicates the period in which a spare part should be available. If the expected supply lead time of a spare part exceeds the maximum allowed production loss, the spare part should be stocked, else it is not necessarily to stock the spare part to guarantee spare part availability. See Table 34: newly designed matrix used to make a decision which spare parts to stock, based on the equipment criticality and the expected supply lead time for the stocking decision tool.

Table 34: newly designed matrix used to make a decision which spare parts to stock, based on the equipment criticality and the expected supply lead time

		Equipment criticality			
		1	2	3	4
Spare parts expected supply lead time	> 5 days				
	3 < days ≤ 5				
	1 < days ≤ 3				
	8 ≤ hours ≤ 24				
	< 8 hours				

The red cells in the matrix indicate situations when a spare part should be stocked because either the equipment should be repaired as quick as possible (the equipment is highly critical), or the supply lead time of the spare part is very long (i.e. more than five equivalent days of lost production). The orange cells in the matrix indicate spare parts which also should be stocked, but they are less critical for the functionality of the equipment. The green cells indicate spare parts which do not have to be stocked, because of the low equipment criticality and short supply lead time (less or equal than five calendar days). Finally, the yellow cells indicates situations in which the spare parts are critical for producing a particular production run, but not for another production run (e.g. pump X with spare part Y is critical to produce product type A, but not for producing product type B). The Maintenance Engineer makes the final decision, based on his experience and feeling, whether the spare part needs to be stocked or not, where he takes into account the frequency of the production runs and the criticality of the equipment during a production run for determining the stocking decision of the component.

13.5. CHAPTER SUMMARY

SABIC Geleen currently holds spare parts in stock in order to decrease the consequences of failure. If the expected supply lead time of the spare part is longer than the maximum allowed equivalent time of lost production, the spare part is kept on stock to decrease the probability of spare part unavailability and therewith downtime costs. When the expected supply lead time of a spare part is equal to the maximum allowed equivalent hours or days of production loss, the spare part is also kept on stock because of variability in the supply lead time. Finally, if the expected supply lead time of a spare part is less than the desired maximum allowed time of lost production, the spare part is not kept on stock but is delivered to order when SABIC Geleen demands the component.

Literature describes to determine the spare parts stocking decision on costs, demand pattern and specificity, besides the criticality of the equipment. We do not agree with literature as these variables have an effect on the height on the stock levels and the stocking location, e.g. spare parts with high costs should be kept on stock centrally because of high inventory holding costs with an as low as possible reorder level, spare parts with high demand values should have a higher reorder point, and user-specific spare parts have a longer lead time and therefore should have a higher reorder level to cover the demand of the spare part during the lead time, but not on the spare parts stocking decision.

We propose to incorporate equipment criticality and the expected supply lead time of the spare part as criteria to determine the stocking decision upon, which are also the included criteria in the spare parts stocking decision of SABIC Geleen (see Table 34). Because the boundary values of the expected spare parts supply lead time are determined for the company-specific situation of SABIC Geleen we propose to keep using the developed methodology of SABIC Geleen to determine which spare parts should be stocked and which could be delivered to order. Because the stocking decision tool is related to the risk matrix of SABIC Geleen, and SABIC Geleen is going to use a new risk matrix from 2014, we adjusted the boundary values of the stocking decision tool to keep the relation between the risk matrix and the stocking decision tool.

14. DECISION SIX IN THE SPARE PARTS ORDERING POLICY PHASE: DECIDE ON THE SPARE PARTS REPLENISHMENT POLICY

After it is determined what spare parts should be stocked, a decision should be taken on the replenishment policy to achieve the desired availability of the system at minimum costs. First literature is reviewed on what replenishment policies are optimal in terms of maximizing the availability of the spare parts at minimum costs (see section 14.1). Then the current replenishment policies of SABIC Geleen are described in section 14.2. Based upon the differences between the proposed optimal replenishment policies from literature and the current used replenishment policies, a proposition for the replenishment policy is given in section 14.3.

14.1. LITERATURE REVIEW OF THE SPARE PARTS REPLENISHMENT POLICY

In literature, the use of a continuous base-stock policy ((S-1,S)-policy), which is also known as a continuous one-for-one replenishment policy for controlling the inventory of spare parts is widely described (Kranenburg, 2006). Driessen et al. (2010) propose to also use the (R,S)-policy, which would result in a continuous base-stock policy if the review period is small compared to the delivery lead time. Tai and Ching (2006) stated that the use of a continuous base-stock policy is the optimal replenishment policy, especially for more expensive spare parts with low demand values, e.g. spare parts of complex systems (Bacchetti et al., 2011 and Sherbrooke, 1968).

The total inventory position (i.e. $stock\ on\ hand + outstanding\ orders - backorders$) of a component is determined by the order-up-to level, which is called the base-stock level in case of the continuous base-stock replenishment policy. Once a spare part is used because of a system breakdown, the spare part is removed from stock and the inventory position is below the base-stock level. Immediately a new component is ordered to replenish the stock in the warehouse (see Figure 23 for a graphical depiction of the continuous base-stock replenishment policy).

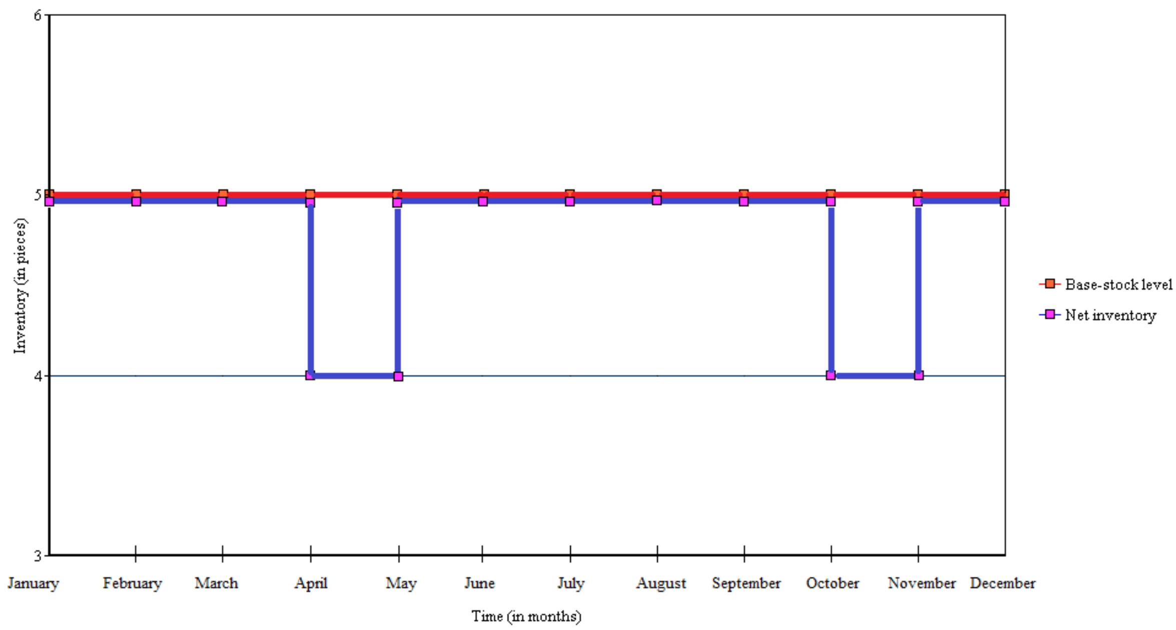

Figure 23: example of the inventory level using a continuous base-stock replenishment policy.

Other types of inventory control policies (e.g. (s,Q)-policy) could be used for managing inventory of spare parts, but it is widely recognized in literature that the continuous base-stock policy is well-suited for controlling inventory of spare parts (Kranenburg, 2006).

Using the continuous base-stock policy for optimally managing inventory of spare parts, needs the following assumptions to be fulfilled:

- Demand occurs continuously over time according to a Poisson process,
- Times between consecutive orders are stochastic but independent and identically distributed,
- Inventory is reviewed continuously,
- Supply lead time is a fixed constant,
- There is no fixed cost associated with placing an order,
- Orders that cannot be fulfilled immediately from on-hand inventory are backordered, and
- The demand pattern of the spare part is stationary over the lifetime of the component (e.g. no seasonal patterns, lumpy demand patterns, or end of use demand effects may be present).

If one of the assumptions is not met, using the continuous base-stock policy is not optimal. Assuming Poisson demand for spare parts often advises more stock than considered really necessary, especially if spare parts are installed in only a few machines (Smith and Dekker, 1997). The failure process of equipment, which often follows a Poisson process, does not necessarily have to lead to a Poisson process at component level. The failure process may be better described by a renewal process, where the interarrival distribution has an increasing failure rate (Smith and Dekker, 1997). The continuous base-stock policy is in that case not optimal but a complex policy could be used which delays the ordering of spares. More research is needed which replenishment policy is optimal when the assumption of Poisson distributed demand is not valid. It is not considered in this master thesis because of limited time.

In case the demand is non-stationary, Graves (1999) proposes to use an adaptive base-stock policy for controlling the inventory. The experience of the manager Reliability & Integrity of the Site Improvement Polymers department is that only for small amounts of spare parts of SABIC Geleen the demand is non-stationary. Therefore, we have chosen to focus on spare parts with stationary demand patterns. Determining the optimal inventory control for spare parts with a non-stationary demand pattern needs more research, which is outside the scope of this thesis because of limited time.

14.2. CURRENT SPARE PARTS REPLENISHMENT POLICY OF SABIC GELEEN

SABIC Geleen uses a (R,s,S)-replenishment policy to control the inventory of all stocked spare parts at the site in Geleen, both in the local and central warehouses. The non-stock spare parts and free format text spare parts are not controlled for with an inventory control policy; these spare parts are delivered to order when they are demanded by SABIC Geleen.

Strategic, part of insurance, and floor stock spare parts are currently stocked in the local warehouses at the site in Geleen. For the strategic and (part of) the insurance spare parts stocked in the local warehouse, the review period of the (R,s,S)-policy is half an hour. SABIC Geleen has chosen for a short review period because strategic spare parts are (highly) critical for the functionality of the system. Because the review period is small compared to the supply lead time, which was about 33 calendar days for the maintenance order with spare part unavailability, the inventory control policy can be described as a (s,S)-policy. See Figure 24 for a graphical depiction of the (s,S)-inventory control policy.

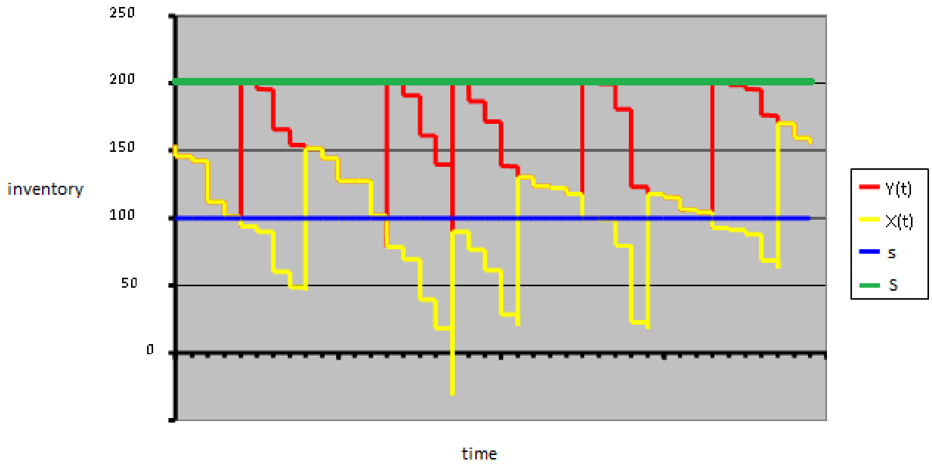

Figure 24: example of the (s,S)-replenishment policy.

Note that Y(t) indicates the inventory position at time t, X(t) indicates the net inventory at time t, s indicates the reorder point, and S indicates the order-up-to-level. If the net inventory (yellow line) falls below the minimum stock level (the blue line) a replenishment order is issued to increase the stock to the maximum stock level (green line). The inventory position immediately increases towards the maximum stock level. Physically the components are not yet received because of the delivery lead time. After the delivery lead time, the net inventory is increased with the ordered quantity.

Floor stock spare parts consist of consumable materials like work wear and disposable cloths which are obtained contractually from suppliers with a usual lead time of one to two days. These components are not critical for the functionality of the equipment. Because of the non-criticality of these items, planning and control of these items are the responsibility of the warehouse administrator (and not of the Maintenance Engineers of the Site Improvement department) and are not recorded within the SAP system because of their non-criticality. Because the inventory control of these spare parts is not the responsibility of the Maintenance Engineers, no exact inventory control policy is determined. Currently, a warehouse operator checks the inventory periodically (how often is unclear). If he observes that the stock level is low (the exact level is unclear), he issues a replenishment order to bring up the inventory level (by how much is unclear) so that he believes that the inventory level is sufficient to cover the demand for spare parts. The inventory control of floor stock spare parts also consist of a review period, a reorder point, and an order-up-to level, so the control can be modeled using the (R,s,S)-inventory policy (see Figure 25).

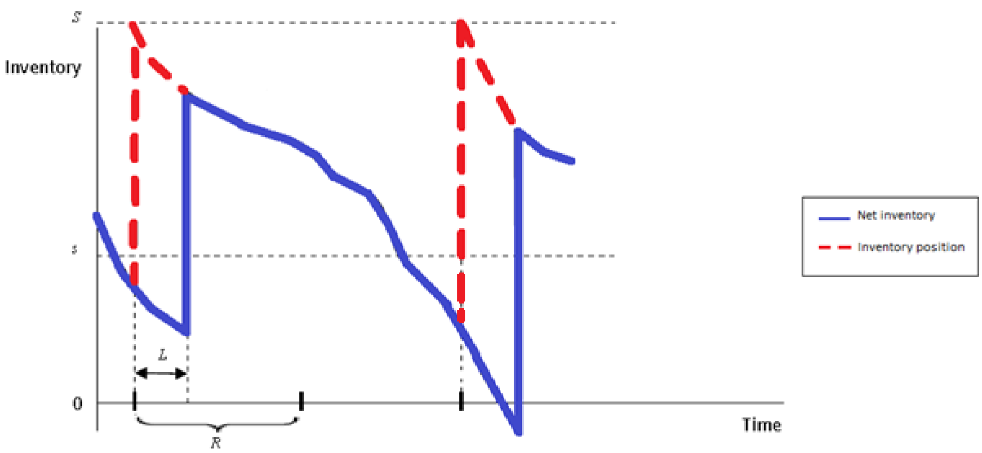

Figure 25: example of the (R,s,S)-replenishment policy

At each review point in time, the stock levels are checked. If the net inventory is below the minimum order point (s), a replenishment order is issued to increase the stock to the maximum stock level (S).

The review period for the Centrally Managed Inventory and (the other part of) the insurance spare parts, which are stocked in the central warehouse, is one calendar week (i.e. every Monday morning at 8.00AM, the replenishment proposals are issued). As soon as the inventory level is below the reorder point at the review moment, a replenishment proposal is issued by the SAP information system to increase the inventory to the order-up-to level.

Note that during the period before a purchase order is issued, new consumptions cannot be made and the consumption is placed on a backorder list. This list is checked daily by the Purchase Schedulers and the replenishment proposal is issued manually (i.e. the Purchase Schedulers will not wait until the information system has issued the purchase order at Monday morning 8.00AM but issue the purchase order by hand) if another demand for the component occurred during stock-out. If no consumption of the spare part arose during the stock-out period, the purchase order will be issued via the information system at Monday morning 8.00AM. Also here, the review period (maximum 7 calendar days) is short compared to the supply lead time (on average [redacted] calendar days), so therefore the control of inventory at the central warehouse can be modeled using the (s,S)-replenishment policy.

SABIC Geleen currently controls all spare parts, both at the local and central warehouses with a (R,s,S)-replenishment policy. For all but floor stock spare parts, the review period is small compared to the supply lead time and continuous review may be assumed. Therefore, for all spare parts, except floor stock, the inventory could be controlled using the (s,S)-replenishment policy. For the floor stock spare parts, the inventory is controlled using the (R,s,S) replenishment policy.

14.3. Confrontation of the spare parts replenishment policy of SABIC Geleen with literature

Currently, SABIC Geleen uses other replenishment policies to control inventory of spare parts than the described optimal policy from literature. This means that the current inventory control of spare parts could be improved by implementing another inventory control policy. From literature the optimal replenishment policy, with respect to maximum spare part availability at minimum costs, for spare parts with a stationary Poisson demand pattern is the continuous base-stock policy, whereas SABIC Geleen currently controls inventory using the (R,s,S)-replenishment policy. Because the review period is small compared to the supply lead time, continuous review is assumed, which results in control of the inventory of spare parts with the (s,S)-replenishment policy. We propose that SABIC Geleen should implement the continuous base-stock replenishment policy for all spare parts with a stationary Poisson demand pattern, except the floor stock spare parts. Because the control of floor stock parts is not implemented in the information system, continuous review is not possible and it is not cost efficient to implement the planning of these non-critical spare parts in the information system. For floor stock spare parts, we propose that SABIC Geleen keeps using the (R,s,S)-replenishment policy. Determining the optimal inventory policy for spare parts with a non-stationary demand pattern is outside the scope of this master thesis because of limited time and the amount of spare parts with nonstationary demand is perceived to be low.

14.4. Chapter summary

In this chapter, the spare parts replenishment policy of SABIC Geleen is reviewed. Literature proposes to control inventory of spare parts using the continuous base-stock replenishment policy because it is an optimal policy to control inventory of especially high price spare parts with a stationary demand pattern (Tai and Ching, 2006). Currently SABIC Geleen uses the (R,s,S)-replenishment policy for controlling inventory of all their spare parts, where literature (Driessen et al., 2010) emphasized that if the review period is small compared to the supply lead time, which is the case for all but the floor stock spare parts, continuous review of the stock levels could be used.

We proposed to control inventory of all spare parts, except the floor stock components, using the continuous base-stock replenishment policy because of its optimality for spare parts with a stationary Poisson demand pattern. A significant amount of total inventory costs could be gained by using a base-stock policy instead of other inventory control policies (e.g. Tai and Ching, 2006). For the floor stock spare parts, it is not possible to review them continuously because the inventory control is not integrated in the SAP information system. It is not cost efficient, because of the non-criticality of these components, to include the control of these components in the information system. Therefore, we propose to use the (R,s,S)-replenishment policy that SABIC Geleen currently uses for controlling inventory of the floor stock spare parts.

15. DECISION SEVEN IN THE SPARE PARTS ORDERING POLICY PHASE: DECIDE ON THE VALUE OF THE SPARE PART REPLENISHMENT POLICY PARAMETERS

In this chapter, the decision needs to be taken how to determine the values of the parameters of the spare parts replenishment policy. The determination of the policy parameters includes the determination of the review period, the reorder point (i.e. at what inventory level it is decided to issue a replenishment order), and the order-up-to level or order quantity. Because we determined in chapter 14 that the continuous base-stock replenishment policy is optimal for components with a stationary demand pattern, which is perceived to be the case for most of the spare parts of SABIC Geleen, we only need to determine the order-up-to level, as the reorder point is equal to the order-up-to level minus one, and the review period is continuous.

In section 15.1, literature is reviewed on how to determine the order-up-to level of the continuous base-stock replenishment policy. Then, it is described how SABIC Geleen currently determines the order-up-to level. Based on the difference between the proposed methodology from literature and the currently used methodology, a redesign is made in section 15.4, which is applied to a case study of SABIC Geleen to increase the understandability of the new designed solution.

15.1. LITERATURE REVIEW OF THE SPARE PARTS REPLENISHMENT ORDER-UP-TO LEVEL

Calculating the order-up-to level for a component is normally done, using the item approach. Under an item approach, inventory levels for each individual component are set independently, based on simple formulas that balance the costs of holding inventory, ordering and stock-out. The decision on the number of spare parts to stock is determined independently of other components in the same equipment (Sherbrooke, 2004). Because the feeling of the Manager Reliability & Integrity of the Site Improvement Polymers department is that most spare parts of SABIC Geleen have a stationary demand pattern, using a Poisson distribution to model the demand of spare parts is justified.

For critical equipment with a very high price, i.e. insurance spare parts, it is discussed by Driessen et al. (2010) that they should be stocked because of large negative consequences of unavailability when demanded. Insurance spare parts are known to be very expensive (i.e. more than [redacted] for SABIC Geleen) and have a very long delivery lead time (i.e. more than [redacted] months for SABIC Geleen). It is also known that the parts will almost never fail, but if they do, downtime effects are very large in case of unavailability because of the long delivery lead time. A strategy that could be used to achieve the target service level at minimum costs for insurance spare parts is stock pooling (see Karsten & Basten, 2012).

The proposed methodology for stocking spare parts of non-critical equipment is not discussed in this thesis, because management of SABIC Geleen determined to focus resources on critical equipment.

15.2. CURRENT DETERMINATION OF THE SPARE PARTS REPLENISHMENT POLICY PARAMETERS OF SABIC GELEEN

The Purchase Scheduler determines the maximum stock level, based on the item approach for all equipment, irrespective of the criticality. According to Approved Best Practice 133 of SABIC Geleen (SABIC Europe Intranet, 2009), the maximum stock level is calculated taking into account both the ordering costs and the costs of holding inventory (in 2009 the yearly inventory holding costs were [redacted]% of the price of the spare part). SABIC Geleen uses the economic order quantity (EOQ) lot sizing rule to determine the optimal order quantity which minimizes total yearly costs. The formula of the EOQ lot sizing rule is:

$$EOQ = \sqrt{\frac{2 * ordering\ costs * average\ demand\ per\ year}{price\ of\ a\ spare\ part * annual\ inventory\ holding\ cost\ rate}} \quad (15.1)$$

Note that SABIC Geleen stated two requirements for the optimal order quantity:

- The economic order quantity should never be higher than the average consumption of one year (e.g. because of ageing issues)
- The minimum economic order quantity is one, and the quantity is always rounded towards the nearest integer.

Note that the consumption of materials which are not ordered at the central warehouse is not tracked in the SAP system. Therefore, special care is needed when analyzing and using historical consumption data, as the consumption levels shown in the SAP system may not accurately reflect the real historical spare part consumption.

The order-up-to level is then determined by SABIC Geleen using the following formula:

$$Order - up - to\ level = minimum\ stock\ level + EOQ - 1 \quad (15.2)$$

where the order-up-to level should be at least one. See Appendix H – Explanation of the current determination of the reorder point for the calculation method of the minimum stock level as currently used by SABIC Geleen.

In practice however, the Purchase Scheduler estimates the maximum stock level based on his experience because the Economic Order Quantity formula does not incorporate the variations in demand caused by different production runs (e.g. knife blades wear faster when producing harder pellets, but the EOQ formula assumes constant demand). First, he sets the maximum stock level to be equal to the minimum stock level. If he then experiences that a lot of replenishment orders for the spare part are issued, he increases the maximum stock level. If he sees that the consumption of the spare part is zero for quite a period of time (based on the average consumption and his experience), he will propose to decrease the maximum stock level.

For insurance spare parts, SABIC Geleen decides to stock one spare part, despite the above mentioned EOQ-formula will arrive at a rounded value of zero (because of the very low average demand per year and the very high selling price of the component). This spare part is stock pooled among the sites of SABIC Europe or all sites of SABIC worldwide.

15.3. CONFRONTATION OF THE DETERMINATION OF THE SPARE PARTS REPLENISHMENT POLICY PARAMETERS OF SABIC GELEEN WITH LITERATURE

As described in section 15.2, SABIC Geleen currently calculates the stock levels using the Economic Order Quantity formula and the minimum stock level. Using the Economic Order Quantity for determining the stock level has the following disadvantages:

- The demand is assumed to be constant and deterministic,
- All parameters (demand, order quantity, costs, and lead time) will continue at the same values for a long time,
- Delivery of the spare part is assumed to be instantaneous after demanding the part, i.e. the lead time is zero,
- The model is only useful for single products because it treats items entirely independent of other components, and
- The model is not able to incorporate quantity discounts (scale advantages when ordering more parts).

For SABIC Geleen, these assumptions are not realistic in their everyday situation. The demand rate of a spare part is not constant (e.g. knife blades wear faster when producing harder pellets) and stochastic (it is not always known when a failure of a component occurs). Furthermore, the supply lead time of a component has a positive value for all spare parts of SABIC Geleen. Concluding, the unrealistic assumptions of the Economic Order Quantity model cause the model to be not useful for SABIC Geleen for ordering spare parts.

In order to overcome the, in real-life sometimes unrealistic, assumptions of the Economic Order Quantity model, one could use the item approach to calculate the order-up-to level of the continuous base-stock policy. Using the item approach assumes the demand to be Poisson distributed and stationary over the lifetime of the component. We explained in chapter 14 why this assumption is justified for SABIC Geleen. Therefore, we propose for SABIC Geleen to use the item approach to calculate the order-up-to level of the components.

For the insurance spare parts, SABIC Geleen currently uses the technique of stock pooling, as is described by literature (Karsten & Basten, 2012). Therefore, no redesign is made for the insurance spare parts as the currently used technique is a good strategy according to literature.

15.4. Redesign of the determination of the spare parts replenishment policy parameters

As we have stated in section 15.3, we propose to use the item approach at SABIC Geleen to make a better decision regarding the spare part replenishment policy parameters. The algorithm we propose to use at SABIC Geleen to determine the height of the base-stock level for components with a stationary demand pattern is the following greedy heuristic:

Step 1: Set $S = 0$

$$Compute\ P(DI = x) := (mET)^x/(x!))\exp\{-mET\}, for\ x \in \{0,1,2,\ldots\}$$

$$Compute\ \beta_i(S_i) := \sum_{x=0}^{S_i-1} P(DI_i = x)$$

$$Compute\ \hat{C} := cS$$

Step 2: $If\ \beta_i(S_i) < \beta_0$

$then$

$S_i := S_i + 1$

$Compute\ \beta_i(S_i) := \sum_{x=0}^{S_i-1} P(DI_i = x)$

$Compute\ \hat{C} := c_i S_i$

$else\ stop$

For a detailed explanation of the item approach, including the underlying assumptions of the model, we refer to Appendix G – Explanation of the item approach and greedy algorithm.

15.5. Case study: the determination of the spare parts replenishment policy parameters applied using the redesigned solution

In order to explain SABIC Geleen how to use the greedy heuristic of the item approach, critical equipment is selected to determine the base-stock level for its associated components. A comparison is made between the previously used Economic Order Quantity model and the newly proposed item approach to determine how much spare parts of the equipment should be stocked. We examine a compressor of the Low Density Poly Ethylene plant 17, i.e. S17, on its stock level decision. Note that from Table 5, the target availability of S17 in 2012 was [redacted]%

The compressor exists of a lot of components, but for the sake of simplicity, we assume only the following three components:

1. Repair kit for high pressure packing,
2. Oil injector, and a
3. Lens ring.

15.5.1. Calculating the order-up-to level with the current Economic Order Quantity model of SABIC Geleen

Determining the order-up-to level using the current methodology of SABIC Geleen, i.e. the Economic Order Quantity formula, the following parameters and their values should be determined (see Table 35):

Table 35: parameters and their values for determining the order-up-to level using the EOQ-formula for the case study of SABIC Geleen

Symbol of the parameter	Parameter	Parameter value
A_i	Ordering costs (in €)	[redacted] for the repair kit, [redacted] for the oil injector, and [redacted] for the lens ring
D_i	Annual constant demand of the component (in items/year)	[redacted] item/year for the repair kit, [redacted] items/year for the oil injector, and [redacted] items/year for the lens ring
p_i	Selling price of the component (in €)	[redacted] for the repair kit, [redacted] for the oil injector, and [redacted] for the lens ring
r	Annual inventory holding cost rate (in % of the selling price)	[redacted] (yearly average holding costs of 2009)

Using the parameter values for inserting them in the EOQ-formula (see formula 15.1), the following optimal order quantities are found (see Table 36):

Table 36: optimal economic order quantities for the components of the compressor in the case study of SABIC Geleen

Component of the compressor	Optimal Economic Order Quantity	Rounded EOQ
Repair kit for high pressure packing	1.30	1
Oil injector	2.66	3
Lens ring	38.16	38

According to formula 15.2, the order-up-to level is dependent on the reorder point (see Appendix H – Explanation of the current determination of the reorder point how SABIC Geleen currently determines the value of the reorder point).

For the components of the compressor, the following reorder points are determined (see Table 37):

Table 37: reorder points for the components of the compressor in the case study of SABIC Geleen

Component of the compressor	Reorder point
Repair kit for high pressure packing	1
Oil injector	0
Lens ring	0

The order-up-to level is determined using formula 15.2 (see Table 38), and the investment is determined by multiplying the costs of a component with the order-up-to level of the component (see Table 39).

Table 38: order-up-to level for the components of the compressor in the case study of SABIC Geleen

Component of the compressor	Order-up-to level
Repair kit for high pressure packing	1
Oil injector	2
Lens ring	37

Table 39: investment for the components of the compressor in the case study of SABIC Geleen

Component of the compressor	Investment
Repair kit for high pressure packing	[redacted]
Oil injector	[redacted]
Lens ring	[redacted]

The total investment in spare parts using the item approach will then be [redacted].

The fill rates of the items with a stationary demand pattern is calculated using the cumulative Poisson distribution:

$$\beta_i(S_i) = \sum_{x=0}^{S_i-1} P(DI_i = x) \quad (15.3)$$

where

$$P(DI_i = x) = \frac{e^{-m_i ET_i} * (m_i ET_i)^x}{x!} \quad (15.4)$$

The following fill rates of the items are found (see Table 40):

Table 40: fill rates of the components of the compressor of SABIC Geleen

Component of the compressor	Availability
Repair kit for high pressure packing	0.8411
Oil injector	0.9523
Lens ring	1.000

which would result in an availability of the compressor of:

$$A(\underline{S}) = 0.8411 * 0.9523 * 1.000 = 0.8009$$

which is below the target availability of the system of [redacted]% (see Table 5).

15.5.2. Calculating the base-stock levels with the proposed item approach

For determining the base-stock levels using the item approach, the following parameters with their values for the three components need to be determined (see Table 41):

Table 41: parameters and their values for determining the base-stock level using the system approach for the case study of SABIC Geleen

Symbol of the parameter	Parameter	Parameter value
m_i	Number of failures per year (in items/year)	[redacted] a year for the repair kit, [redacted] a year for the oil injector, and [redacted] times per year for the lens ring
ET_i	The mean supply lead time (in years)	[redacted] year for the repair kit, [redacted] year for the oil injector, and [redacted] year for the lens ring
c_i	Selling price of the component (in €)	[redacted] for the repair kit, [redacted] for the oil injector, and [redacted] for the lens ring

We can then use the parameter values to calculate the base-stock levels for components with a stationary demand pattern, which is perceived to be the case for the majority of the spare parts of SABIC Geleen, using the algorithm:

Step 1: Set $S_1 = 0$

Set $S_2 = 0$

Set $S_3 = 0$

$Compute\ P(DI_i = x) := (m_i ET_i)^x/(x!))\exp\{-m_i ET_i\}, for\ x \in \{0,1,2,\dots\}$

$$Compute\ \beta_i(S_i) := \sum_{x=0}^{S_i-1} P(DI_i = x)$$

$Compute\ \hat{C} := c_i S_i$

Step 2: $If\ \beta_i(S_i) < \beta_0$

$then$

$S_i := S_i + 1$

$$Compute\ \beta_i(S_i) := \sum_{x=0}^{S_i-1} P(DI_i = x)$$

$Compute\ \hat{C} := c_i S_i$

$else\ stop$

See Table 42 for the base-stock levels to meet the target item fill rate (which is [redacted]%) for the case study of SABIC Geleen.

Table 42: item approach for determining the availability of the components for the case study of SABIC Geleen

x	$P(DI_1 = x)$	$P(DI_2 = x)$	$P(DI_3 = x)$	$\beta_1(S_1)$	$\beta_2(S_2)$	$\beta_3(S_3)$
0	0.8411	0.7074	0.7939	0	0	0
1	0.1456	0.2449	0.1832	0.8411	0.7074	0.7939
2	0.0126	0.0424	0.0211	0.9866	0.9523	0.9771
3	0.0007	0.0049	0.0016	0.9992	0.9947	0.9983
4	$3.15 * 10^{-5}$	0.0004	$9.38 * 10^{-5}$	1.0000	0.9995	0.9999
5	$1.09 * 10^{-6}$	$2.93 * 10^{-5}$	$4.33 * 10^{-6}$	1.0000	1.0000	1.0000
6	$3.14 * 10^{-8}$	$1.69 * 10^{-6}$	$1.67 * 10^{-7}$	1.0000	1.0000	1.0000

From Table 42 we can conclude that SABIC Geleen needs to stock two components of the repair kit, the oil injector, and the lens ring in order to meet the target item availability of [redacted]. The needed investment is then: $\hat{C} =$ [redacted]. The availability of the compressor is then:

$$A(\underline{S}) = 0.9866 * 0.9523 * 0.9771$$

$$= 0.9181$$

which exceeds the target availability of the compressor (which was [redacted]).

SABIC Geleen currently achieves, using the item approach an availability of the compressor of 91.8% by stocking two repair kits, two oil injectors and two lens rings. The total needed investment is [redacted], which is higher than the solution of the currently used Economic Order Quantity model, where an investment of [redacted] was needed. However, the Economic Order Quantity model does not incorporate the target availability and only considers the optimum ordering quantity based on costs.

15.6. Chapter Summary

In this chapter, the decision of how to determine the replenishment policy parameter is redesigned. It is proposed by literature to use the item approach for determining the stock levels of critical equipment in order to achieve the target availability of the components at minimum costs (see Appendix G – Explanation of the item approach and greedy algorithm for a detailed explanation of the item approach. Currently, SABIC Geleen however uses the Economic Order Quantity model which is discussed to be non-optimal and based on assumptions which are not valid in real-life. Using the Economic Order Quantity model for determining stock levels of critical equipment does not take into account the target fill rate of the components, but solely bases the order quantity of a component on cost considerations. To include the target fill rate of a component, the item approach is useful to calculate the stock levels.

For calculating stock levels of insurance spare parts (i.e. critical spare parts with a very high price (i.e. more than [redacted] for SABIC Geleen) and very long supply lead times (i.e. more than [redacted] calendar months for SABIC Geleen)) SABIC Geleen currently uses the stock pooling strategy which is also proposed by literature for these type of spare parts. Therefore we did not make a redesign for these parts.

Finally, we focused on critical equipment only to determine what strategy is optimal for determining the stock levels, which is in line with the focus of management of SABIC Geleen. Therefore, no redesign is made for determining base-stock levels of non-critical equipment of SABIC Geleen.

16. The use of the system approach to determine the replenishment policy parameters

Using the item approach for determining the stock levels of critical equipment does not take into account the effects on the availability of and the investment in the system when determining the stock levels, which may ultimately lead to not meeting the target system availability or exceeding maintenance budgets. In this chapter, it is proposed to use the system approach for determining the base-stock levels of critical equipment of SABIC Geleen.

In section 16.1, literature is reviewed why the use of a system approach regarding the determination of the replenishment parameters is more optimal than the discussed item approach of chapter 15. SABIC Geleen currently does not use the system approach. The model is designed in section 16.3 and applied to a case study (the nitrogen compressor) of SABIC Geleen.

16.1. Literature review of the system approach for determining replenishment policy parameters

The use of a system approach for critical equipment, instead of the item approach, for determining the spare parts replenishment policy parameters is broadly discussed in literature.

A disadvantage of using the item approach for determining stock levels is that the effects on the availability of and the investment in the system are not controlled for when determining the stock levels. Although high individual service levels of the items are realized, the overall system availability of the system may still be relatively low, despite the considerable total inventory investments. Also, there is no clear relationship between the overall system availability and the amount of money spent (Rustenburg et al., 2001). The disadvantages could lead to the failure to meet the target system availability or the exceeding of the maintenance budget. Therefore, it is proposed to integrate the availability and investment budget in the decision process of determining the stock levels, which is incorporated in the system approach (Sherbrooke, 2004).

In the system approach all associated components of the system are evaluated when making inventory-level decisions. Using the system approach may lead to large reductions in inventory holding costs, of up to 20 to maximally 50% (e.g. Sherbrooke, 1992, Thonemann et al., 2002, and Rustenburg et al., 2003) while achieving the desired availability of the equipment, compared with the item approach. The main idea behind using a multi-item service level is to have less stock of very expensive items and more stock of cheaper items, which is realized using the Multi-Echelon Technique for Recoverable Item Control (METRIC) (see Appendix I – Explanation of the Multi-Echelon Technique for Recoverable Item Control (METRIC) model for the explanation of the METRIC methodology). Compared to the single-item model, one is able to obtain the same desired system service level at lower costs.

16.2. Current determination of the system approach for determining replenishment policy parameters

Currently, SABIC Geleen does not use the system approach, but the Economic Order Quantity model to determine the order-up-to level of the spare parts. Using an item approach is not optimal, because it does not incorporate target system availabilities and budgets. Therefore, we propose to use the system approach for determining the order-up-to levels of components of critical equipment.

16.3. DESIGN OF THE SYSTEM APPROACH FOR DETERMINING REPLENISHMENT POLICY PARAMETERS

We propose to use the system approach for SABIC Geleen for critical equipment because it includes availability and investments in the system which leads to a better decision on the parameter values of the replenishment policy. The following algorithm should be used (see also Appendix I – Explanation of the Multi-Echelon Technique for Recoverable Item Control (METRIC) model) to calculate the order-up-to levels of the components, given the target system availability at minimum costs:

Step 1: Set $S_i := \max\{\lceil m_i ET_i - 2\rceil, 0\}\ for\ all\ i = 1, \ldots, I$

$Compute\ PBO_i(S_i) := 1 - \sum_{x=0}^{S_i} P(DI_i = x), where$

$P(DI_i = x) := (m_i ET_i)^x/(x!))\exp\{-m_i ET_i\}, for\ x \in \{0,1,2, \ldots\}$

$$Compute\ A(\underline{S}) := \sum_{x=0}^{S_i} P(DI_i = x)$$

$$Compute\ \hat{C} := \sum_{i=1}^{I} c_i S_i$$

Step 2: $\Delta_i := \big(PBO_i(S_i) - PBO_i(S_i + 1)\big)/c_i\ for\ all\ i = 1, \ldots, I$

$k = argmax\ \Delta_i\ for\ all\ i = 1, \ldots, I$

Step 3: $If\ A(\underline{S}) < A_0$

$then$

$S_k := S_k + 1$

$Compute\ A(\underline{S}) := \sum_{x=0}^{S_i} P(DI_i = x)$

$$Compute\ \hat{C} := \sum_{i=1}^{I} c_i S_i$$

$else\ stop$

16.4. CASE STUDY: THE SYSTEM APPROACH FOR DETERMINING REPLENISHMENT POLICY PARAMETERS APPLIED USING THE DESIGNED SOLUTION

In order to determine the benefits (i.e. lower investment in spare parts while achieving the target system availability) of the system approach as compared to the item approach, the same case study is considered, i.e. we examine a compressor of the Low Density Poly Ethylene plant 17, i.e. S17, on its stock level decision. The algorithm as described in section 16.3 is used.

Step 1: $S_1 = \max\{\lceil$[redacted]$- 2\rceil, 0\} = 0$

$S_2 = \max\{\lceil$[redacted]$- 2\rceil, 0\} = 0$

$S_3 = \max\{\lceil$[redacted]$- 2\rceil, 0\} = 0$

From this information it is clear that the backorder probability function is decreasing and convex at base-stock levels of zero components, which is needed to guarantee that there exists only one minimum for the optimization problem. Then the initial backorder probabilities, the system availability, and the investment could be calculated, using the determined base-stock levels.

$$PBO_1(S_1) = 1 - \sum_{x=0}^{0} P(DI_1 = x) = 1 - P(DI_1 = 0), where$$

$$P(DI_1 = 0) = (m_1 ET_1)^0/(0!))\exp\{-m_i ET_i\}$$

= ([redacted])^0/(0!))exp{−[redacted]}

$$= 0.8411$$

Therefore, $PBO_1(S_1) = 1 - 0.8411 = 0.1589$.

In the same way, the backorder probabilities for component two and three are calculated:

$$PBO_2(S_2) = 0.2926$$

$$PBO_3(S_3) = 0.2061$$

The availability of the system is calculated by:

$$A(\underline{S}) = \prod_{i=1}^{3} \left(1 - PBO_i(S_i)\right)$$

$$= (1 - 0.1589) * (1 - 0.2926) * (1 - 0.2061)$$

$$= 0.4724$$

Finally, the investment is calculated by multiplying the base-stock levels of the components with the cost of a component:

$$\hat{C} = c_1 * S_1 + c_2 * S_2 + c_3 * S_3$$

= [redacted] ∗ 0 + [redacted] ∗ 0 + [redacted] ∗ 0

= €0

Because the system availability does not meet the target system availability of [redacted]%, we need to increase the stock level of the components.

Step 2: We want to calculate for which component it is most beneficial to stock an additional item, so that the increase in system availability is maximized at minimum costs, i.e. the "biggest bang for the buck" until the target system availability is reached. Several iterations may be needed to eventually meet the target system availability. For each component, the benefit-cost ratio (the increase in system availability compared with the increase in investment costs) is calculated by dividing the decrease in backorder probability by the price of the component:

$$\Delta_1 := \left(PBO_1(S_1) - PBO_1(S_1 + 1)\right)/c_1$$

$$\Delta_2 := \left(PBO_2(S_2) - PBO_2(S_2 + 1)\right)/c_2$$

$$\Delta_3 := \left(PBO_3(S_3) - PBO_3(S_3 + 1)\right)/c_3$$

For the first iteration step the following ratios are found:

$$PBO_1(S_1+1) = 1 - \sum_{x=0}^{1} P(DI_1 = x) = 1 - P(DI_1 = 0) - P(DI_1 = 1)$$

$$= 1 - 0.8411 - (([redacted])^1/(1!))\exp\{-[redacted]\}$$

$$= 1 - 0.8411 - 0.1456 = 0.0134$$

$$\Delta_1 = (0.1589 - 0.0134)/[redacted] = 2.80 * 10^{-5}$$

$$\Delta_2 = 1.74 * 10^{-4}$$

$$\Delta_3 = 1.07 * 10^{-2}$$

The largest benefit-cost ratio is selected and for this component, an additional spare part is stocked to increase the availability of the system against minimum costs (see step 3).

Step 3: For the component with the highest benefit-cost ratio, an additional spare part is stocked. Then the availability of the system is calculated, together with the investment. For our case study, the benefit cost ratio of the third component, i.e. the lens ring, is the largest, so one item of the lens ring is stocked. The new availability of the system will be:

$$A(\underline{S}) = (1 - 0.1589) * (1 - 0.2926) * (1 - 0.0229) = 0.5814$$

The corresponding investment will be:

$$\hat{C} = c_1 * S_1 + c_2 * S_2 + c_3 * S_3$$

[redacted] $* 0 +$ [redacted] $* 0 +$ [redacted] $* 1$

$=$ [redacted]

Because the system availability is still below the target system availability, again the benefit-cost ratios are calculated and an additional component is stocked with the highest ratio, until the availability of the system at least meets the target system availability. See Table 43 for the algorithm applied to the case study of SABIC Geleen.

Table 43: greedy algorithm applied to the components of the compressor of SABIC Geleen

Iteration	Δ_1	Δ_2	Δ_3	S_1	S_2	S_3	$PBO_1(S_1)$	$PBO_2(S_2)$	$PBO_3(S_3)$	$A(\underline{S})$	$\hat{C}$
0	-	-	-	0	0	0	0.1589	0.2926	0.2061	0.4724	[redacted]
1	$2.80 * 10^{-5}$	$1.74 * 10^{-4}$	$1.07 * 10^{-2}$	0	0	1	0.1589	0.2926	0.0229	0.5814	[redacted]
2	$2.80 * 10^{-5}$	$1.74 * 10^{-4}$	$1.23 * 10^{-3}$	0	0	2	0.1589	0.2926	0.0017	0.5940	[redacted]
3	$2.80 * 10^{-5}$	$1.74 * 10^{-4}$	$9.47 * 10^{-5}$	0	1	2	0.1589	0.0477	0.0017	0.7996	[redacted]
4	$2.80 * 10^{-5}$	$3.01 * 10^{-5}$	$9.47 * 10^{-5}$	0	1	3	0.1589	0.0477	$9.83 * 10^{-5}$	0.8009	[redacted]
5	$2.80 * 10^{-5}$	$3.01 * 10^{-5}$	$5.46 * 10^{-6}$	0	2	3	0.1589	0.0053	$9.83 * 10^{-5}$	0.8365	[redacted]
6	$2.80 * 10^{-5}$	$3.47 * 10^{-6}$	$5.46 * 10^{-6}$	1	2	3	0.0134	0.0053	$9.83 * 10^{-5}$	0.9813	[redacted]

Using the proposed system approach from literature to determine the stock levels achieves the target system availability of [redacted]% for S17 when stocking one repair kit, two oil injectors, and three lens rings. The actual achieved system availability is 98.13% and a total investment of [redacted] is needed. Recall that, using the proposed item approach, as discussed in chapter 15, the system availability achieved was 91.8% (which exceeds the target system availability of [redacted]%) at an investment of [redacted] (two units of the repair kit, two units of the oil injector, and two lens rings are needed, according to the item approach).

16.5. Chapter summary

In this chapter, we discussed the use of the system approach, compared to the item approach, for calculating the order-up-to levels for components of critical equipment. The benefits of using a system approach is that the target system availability and investment budget is directly incorporated in the model, which helps to identify the base-stock levels of the components to achieve the target system availability at minimum investment costs.

Using the system approach, compared with the item approach, for the case study of SABIC Geleen meets the target system availability with a decrease in costs of almost 40%, which is in line of the expected gains, according to literature.

17. Redesign of the repair or discard process of spare parts of SABIC Geleen

When the maintenance activity is finished, several components may have been removed from the system. Either, the component is indicated as a repairable spare part, i.e. the component is repaired after damage, or the component is indicated as a consumable spare part, i.e. the component is disposed after damage and a new part is bought. As was indicated in chapter 7, problems related to this phase of the spare parts ordering process caused significant problems in 2012 in terms of lost money (around [redacted]) because of spare part unavailability. Discussions with the Reliability and Maintenance Engineers of the Site Improvement department and the Purchase Schedulers from the Purchasing department revealed the currently encountered problems with disassembled defective components of SABIC Geleen:

- A disassembled defective repairable spare part is not directly sent to the repair shop,
- The repairable spare parts are not tracked and traced,
- The Maintenance Field Planners do not check the availability of the spare part and do not differentiate on spare part categories before making a maintenance activity planning, causing the planning of maintenance activities to be unrealistic, which increases the probability of downtime and costs,
- The discard procedure of a defective repairable spare part is not followed or even forgotten by the Maintenance Engineers, causing the value of the spare part to remain on the suspense account,
- Stock levels increase if a new spare part is already ordered before the defective repairable spare part is scrapped, which causes inventory holding costs to increase, and
- Supply lead times and prices are not updated in the SAP information system, which means that SABIC Geleen bases decisions on invalid lead time and cost data, possibly increasing downtime and costs.

Each above mentioned problem of a disassembled defective spare part is discussed in the sections below. Each section provides a detailed problem description and a possible solution to reduce the negative effects of the problem.

17.1. Problem that a disassembled defective repairable spare part is not directly sent to the repair shop

The problem that a disassembled defective repairable spare part is unnecessary delayed before it is sent to the repair shop could be caused by three issues:

1. The Maintenance Engineer does not know that technical support for a maintenance activity is necessary and the Maintenance Field Planner is waiting for technical support before the component is sent to the repair shop,
2. It is not clear for the Maintenance Engineer where the defective repairable component is temporarily stored in the plant before a Technical Mission Statement can be developed, and
3. The defective component is sent later to the repair shop than it was possible.

17.1.1. It is unknown that technical support for a maintenance activity is necessary

When the maintenance employees, either internal employees of SABIC Geleen or employees from an external maintenance party, disassemble the defective repairable spare part, the Maintenance Field Planner should decide, using the Technical Mission Statement developed for the failure of the equipment, whether or not the defective repairable component is transported to the repair shop for repair. In 2012, the Maintenance Engineers estimated that in approximately 10% of the cases of a defective repairable spare part, no Technical Mission Statement was available for the equipment while the Maintenance Field Planner needed technical support. The Maintenance Field Planner indicates in the notification that technical support is necessary by applying the status Technical Support Necessary (TSNE). However, not all Maintenance Engineers track these notifications to see if they have to provide technical support. A solution could be that the Maintenance Field Planner alerts the Maintenance Engineer of the Site Improvement department, who then could, in corporation with the Maintenance Engineer of the Running Business department, develop a Technical Mission Statement for the failure of the equipment. Maintenance Engineers of the Site Improvement mentioned that the Maintenance Field Planners do not always contact them that they would like technical support before they send the component to the repair shop. In that case, the work is unnecessary delayed, because the Maintenance Field Planner is waiting for technical support, but the Maintenance Engineer is not aware that he should technically support the Maintenance Field Planner. The unnecessary delay in the supply lead time because the Maintenance Engineers are not alerted that technical support is necessary, increases the backorder probability and decreases the availability of the system.

We propose that the Maintenance Engineers of the Site Improvement department daily filter the notifications on the status Technical Support Necessary. In this way the Maintenance Engineers have an overview of maintenance activities where technical support is necessary. If the Maintenance Engineers discover notifications with this status which were until then unknown to them, they can contact the Maintenance Field Planner and discuss actions which should be taken in order to prevent unnecessary delay in the maintenance activity.

17.1.2. THE TEMPORARY STOCKING LOCATION OF THE DEFECTIVE COMPONENT IS UNKNOWN

When a defective repairable component is disassembled from the system, it is either sent to the repair shop (in case a Technical Mission Statement was available and it is clear for the Maintenance Field Planner what actions should be taken), or it is temporarily stored somewhere in the plant before it is sent to the repair shop so that the Maintenance Engineers are able to investigate the component before developing the Technical Mission Statement. It is mentioned by the Maintenance Engineers of the Site Improvement department that sometimes, it is not communicated to them where the spare part is stored after disassembly from the system. The Maintenance Engineer needs to search the location of the component before he is able to investigate the component, which takes additional unnecessary time, increasing the probability of a backorder (because of a longer supply lead time) and decreasing the availability of the system.

Because it is not formally described (e.g. in a work process) what actions should be taken with defective repairable spare parts, the Maintenance Engineers and Maintenance Field Planners do not exactly know what actions should be taken at what moments in time to prevent delays in the repair process of SABIC Geleen. Our proposal is that the Maintenance Engineers describe in the Technical Mission Statement what actions should be taken regarding the defective component which is disassembled from the system, e.g. where it should be temporarily stored. Then it is known for both the Maintenance Engineer and the Maintenance Field Planner what actions should be taken regarding the defective repairable component in order to minimize the supply lead time and therefore increasing the availability of the system at minimum costs.

17.1.3. THE COMPONENT IS SENT LATER TO THE REPAIR SHOP THAN IT WAS POSSIBLE

Another complaint of the Maintenance Engineers of the Site Improvement department is that disassembled repairable components are sent later to the repair shop. The delay in sending the defective spare part to the repair shop could be planned because no budget is available at that moment to repair the defective spare part, but it could also be unplanned, i.e. the Maintenance Field Planner has forgotten to send the repairable component to the repair shop for revision, which increases the supply lead time of the component. A longer expected supply lead time leads to lower availability of the system and thus increases the possibility of downtime of the equipment.

When a demand for a new component arises, because a repairable spare part is defective, automatically a replenishment proposal is sent to the Maintenance Engineer of the Site Improvement department. The Maintenance Engineer should firstly determine whether the repairable spare part could still be repaired before he orders a new spare part, by sending the part to a repair shop. As soon as the Maintenance Engineer receives the replenishment proposal, he should contact the Maintenance Field Planner in order to agree in which time aspect the component is sent to the repair shop as an additional reminder for the Maintenance Field Planner to send the spare part to the repair shop. Another proposal to decrease the effects of delayed delivery of the component to the repair shop is to issue the replenishment proposal to the Maintenance Engineer of the Running Business department instead of the Site Improvement department. The Maintenance Engineer of the Running Business department is responsible for the daily corrective maintenance activities and therefore knows better the current progress of the delivery of damaged repairable spare parts to repair shops than the Maintenance Engineer of the Site Improvement department. The Maintenance Engineer of the Running Business department is able to remind the Maintenance Field Planner more easily, because he is working in the plant almost daily, whereas the Maintenance Engineer of the Site Improvement department is on average only once per week working in the plant. Reminding the Maintenance Field Planner that the repairable component should be transported to the repair shop could lead to a smaller supply lead time and therefore a higher availability of the asset.

17.2. Problem that the spare parts are not tracked and traced

As soon as the Maintenance Field Planner has sent the component to the repair shop, it is not tracked and traced anymore. The problem when not tracking and tracing the spare part when it is sent to the repair shop is that SABIC Geleen wrongly assumes that the promised supply lead time will be met.

SABIC Geleen currently employed a dedicated job leader who is responsible for tracking and tracing all work orders to external parties (e.g. repair shop) in order to solve the problem. We propose to accommodate the spare part with a track and trace system so that SABIC Geleen is able to check what the status of the component is, and whether the current status of the part is according to schedule. When this is not the case, SABIC Geleen can then contact the repair shop in order to achieve the promised supply lead time.

17.3. Problem that the Maintenance Field Planners do not check availability of the spare part and do not differentiate on spare part categories

Because the Maintenance Field Planners do not differentiate on the different spare part categories, i.e. strategic, CMI, non-stock, or floor stock, they are also not able to control for the availability and supply lead time of the components. Currently, the Maintenance Field Planners of SABIC Geleen do not check the availability of the needed components when they make the planning of the maintenance activities. Furthermore, the Maintenance Field Planners assume that all components which are unavailable could be ordered and delivered with about the same supply lead time. This is not a realistic assumption as critical user-specific components have a longer lead time than standard non-critical components. Not incorporating the availability and the supply lead time of the components in the planning of the maintenance activities causes the maintenance planning to be based on wrongly assumptions which increases the probability that the maintenance activities cannot be finished on the planned due date. Maintenance activities which exceed the planned due date when the system is down, cause the length of the downtime and the downtime costs to increase.

We propose that, before the planning is made by the Maintenance Field Planner, he should contact the Purchase Scheduler and consult whether the needed spare parts are available and if not, what the expected supply lead time of the component will be. Then a more realistic maintenance planning could be made which decreases the backorder probability and increases the availability of the system at minimum costs.

17.4. Problem that the discard and repair procedures are not followed or even forgotten by the Maintenance Engineers

When a repairable spare part is disassembled from the system, the value of the spare part is booked temporarily on a suspense account. The value of the spare part remains on the suspense account as long as the repairable spare part is disassembled from the system and no dispose command is issued by the Maintenance Engineer. As soon as the Maintenance Engineer issues a dispose command, e.g. because the spare part is irreparably damaged, the value of the component is deleted from the suspense account. The Maintenance Engineers sometimes forget to issue a dispose command while the component is physically scrapped (e.g. because it was technically impossible to repair the spare part, or because the maintenance employee which disassembled the component was not aware that the component was repairable and scrapped it). The Maintenance Engineers then buy a new item, but they forget to issue the dispose command of the defective spare part, which causes the value of the component to remain on the suspense account.

We propose to solve the problem making it impossible for the Maintenance Engineers to buy a new repairable component while the dispose command is not yet issued. Every Monday morning, the replenishment proposals are issued automatically by the SAP information system, which are collected by the Purchase Schedulers. If the Purchase Schedulers see that the replenishment proposal concerns a repairable component, a reminder should be send to the Maintenance Engineer that, before a new repairable component can be purchased, the dispose command should be issued.

17.5. Problem that stock levels increase if a new spare part is already ordered before the defective repairable spare part is scrapped

When a defective repairable component is disassembled from the system, it is replaced as soon as possible to minimize the downtime of the system. Currently, if the inventory level drops below the reorder level, a replenishment order is issued for orders below [redacted] and a replenishment proposal is issued for orders with a price higher than [redacted]. If a new repairable component would be purchased immediately before it is clear whether or not the defective component could be repaired and return to stock, the stock level increases because both a new repaired component is stocked, together with the repaired component from the repair shop. This is undesirable because it increases inventory holding costs.

We propose that for repairable spare parts, no automatic replenishment order should be issued when a demand for a component occurred, but only a replenishment proposal to be issued. The replenishment proposal functions as a reminder to the Maintenance Engineer that the replenishment concerns a repairable spare part and that he should first determine whether the defective spare part could be repaired before a new spare part is purchased in order to prevent the increase of stock. In fact, the proposed solution is the same solution for the problem described in section 17.4.

17.6. Problem that supply lead times and prices are not updated in the SAP-information system

Currently SABIC Geleen records for each supplier the expected supply lead time, and the price of the component. The determination of the lead times and price is static, i.e. the lead time and price is determined once and used for years and is not changed after the initial determination. SABIC Geleen thus assumes that the supply lead time and price of the component will remain constant over the years. This assumption is not valid as in recent years the worldwide demand for complex equipment increased because of higher demand in the emerging markets (e.g. Brazil, Russia, India, and China). Because the demand of complex equipment increased the last few years while the supply remained relatively constant, the price increases, based on market forces. Furthermore, if the demand for equipment increases while the supply remains relatively constant, suppliers need to increase their stock levels to guarantee the supply lead time as promised to SABIC Geleen. However, because of the credit crunch, suppliers tend to hold fewer components on inventory. Therefore, also the supply lead time increased the last years, while SABIC Geleen assumed that it would be constant and equal to the values determined when the supplier was classified. Assuming a shorter supply lead time than is actually realized causes SABIC Geleen to underestimate the probability of a backorder and thus to overestimate the availability of the equipment than it really is, which could lead to downtime and high costs. Wrongly assuming that costs remain equal over the years could lead to wrongly determined stock levels (i.e. the wrong components are stocked in the wrong quantity) and eventually increases downtime effects.

We propose to update the expected supply lead times and prices of the components using a feedback loop. Determining the review period of the supply lead times and prices of the components is dependent on the amount of resources needed to update the values compared with the benefit by using updated information in the reparability decision, the supplier selection decision, the stocking decision, and the replenishment policy parameter decision, to achieve a cost efficient solution. Ideally, the suppliers should inform SABIC Geleen when changes in the supply lead time and costs appear, but this is not always the case. In those cases, SABIC Geleen should invest resources to update supplier information. To determine for which components with what frequency the supplier information should be updated, an analysis should be made which is outside the scope of this master thesis because of limited time.

17.7. Chapter summary

In this chapter, we discussed the main problems of SABIC Geleen and we proposed solutions for these problems regarding the repair process of defective repairable spare parts. The main problem areas and their respective designed solutions of SABIC Geleen are:

1. **Problem that a disassembled defective repairable spare part is not directly sent to the repair shop**
    a) *It is unknown that technical support is necessary*
    The Maintenance Engineers should daily filter the notifications based on the status Technical Support Necessary and contact the Maintenance Field Planners to discuss previously unknown notifications.
    b) *The temporary stocking location of the defective component is unknown*
    Describe in the Technical Mission Statement what actions need to be taken at what moment in time regarding the defective repairable spare part (e.g. where to temporarily stock it before it could be determined whether or not to send the defective component to the repair shop)
    c) *The component is unnecessary delivered later to the repair shop*
    Use the replenishment proposal of the Maintenance Engineers as a reminder to discuss with the Maintenance Field Planner when the component is sent to the repair shop. Furthermore, provide the Maintenance Engineer of the Running Business department, instead of the Maintenance Engineer of the Site Improvement department, with the replenishment proposals because they know better the current progress of the delivery of damaged repairable spare parts to the repair shop.
2. **Problem that the repairable spare parts are not tracked and traced**
    A dedicated job leader is currently employed by SABIC Geleen to track and trace all work orders to external parties. Furthermore, we propose to use a track and trace system to check the status of the component and take necessary precautions (e.g. contact the supplier) if he scheduled supply lead time cannot be met.

3. **Problem that the Maintenance Field Planners do not check the availability of the spare part and do not differentiate on spare part categories**
   Contact the Purchase Schedulers before a maintenance planning is made to determine what spare parts are available, and if not, what the expected supply lead time of the certain type of component is. We propose to take into account the category of spare parts because each category (i.e. strategic, CMI, non-stock, and floor stock) has its own expected supply lead time.
4. **Problem that the discard procedure of a defective repairable spare part is not followed or even forgotten by the Maintenance Engineer**
   Make it impossible for the Maintenance Engineers to purchase a new repairable spare part before the dispose command is issued. Furthermore we propose to issue a replenishment proposal as a reminder that the component only can be purchased when the defective repairable spare part is scrapped.
5. **Problem that stock levels increase if a new spare part is already ordered before the defective repairable spare part is scrapped**
   The same solution which is used for problem four is proposed.
6. **Problem that supply lead times and prices are not updated in the SAP information system**
   Make a feedback loop to update the supply lead times and prices. Ideally SABIC Geleen should be contacted by the suppliers in case of changes in the supply lead time or price, but this is not always the case. When the suppliers do not contact SABIC Geleen, resources should be devoted to reveal the changes in supplier information. Additional research is needed to determine the update frequency and for which components the updating of information is the most cost efficient.

18. Conclusions and Recommendations

This final chapter will provide the conclusions and recommendations of this master thesis. Additionally, the academic relevance is described in section 18.3.

18.1. Conclusions

In this master thesis new decision making tools regarding the spare parts ordering policy and the reparability process have been developed, in order to answer the main research question as provided in the research design (see section 3.2):

> ***"Can SABIC Geleen increase the actual utilization rate of its plants, through reduction of the losses related to maintenance, caused by spare part unavailability, by improving the relevant phase(s) of the spare parts ordering process, within the given maintenance budget of SABIC Geleen?"***

In section 1.3 we pointed out that the actual utilization rate of 2012 was on average [redacted]% below the target utilization rate and almost all (14 of the 16) production plants did not meet the target utilization rate. A large portion (on average [redacted]% of the total capacity to produce) is due to maintenance and could be caused by unavailability of spare parts. About [redacted] was lost in 2012 because of spare parts unavailability, which is about 9.7% of the total maintenance budget of SABIC Geleen in 2012. This indicates that there is room for improving the actual utilization rate by decreasing the losses in maintenance by reducing spare parts unavailability. The research question is answered in chapters 9 until 16 (the spare parts ordering policy) and chapter 17 (the repair process)

In order to be able to answer the main research question, five research questions are investigated. Those are focused on the general method of the development of the spare parts ordering policy and the repair process: frameworks and tools that prescribe how to develop the spare parts ordering policy and repair process.

18.1.1. Of what phases does the spare parts ordering process exists, based on the literature review?

Currently, SABIC Geleen has limited knowledge and no general process that determines of what phases the spare parts ordering process of SABIC Geleen exists. We developed the spare parts ordering process of SABIC Geleen, shown in Figure 26. The spare parts ordering process consists of the following eight phases (see chapter 4):

- Need for a spare part,
- From need for a spare part to actual ability to order the spare part,
- Actual ordering of the spare part,
- The spare parts ordering policy,
- Order supply process,
- Order receipt process,
- Actual use of the spare part, and
- Repair or discard process of spare parts.

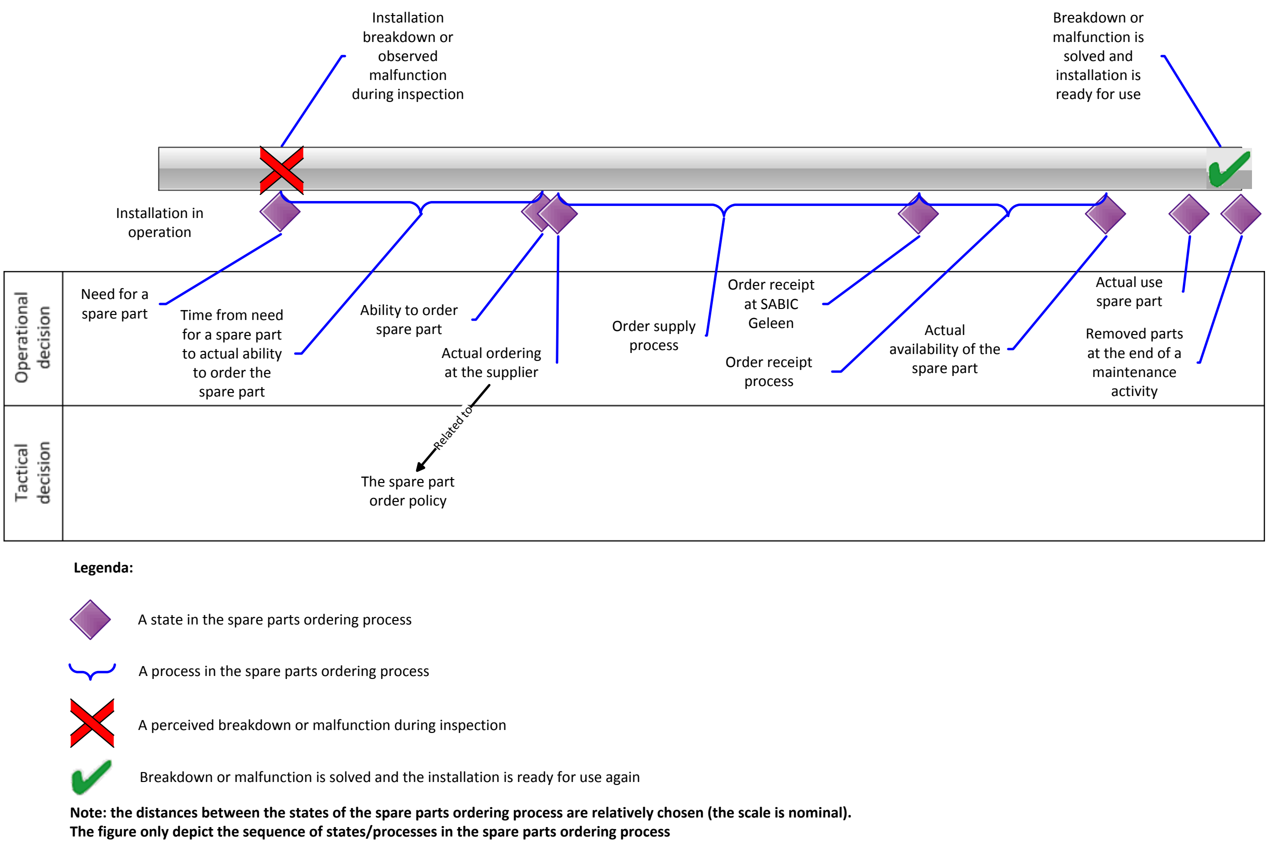

Figure 26: graphical depiction of the spare parts ordering process (copy of Figure 9)

18.1.2. FOR EACH PHASE IN THE SPARE PARTS ORDERING PROCESS, WHAT ARE THE POTENTIAL PROBLEMS THAT COULD CAUSE SPARE PART UNAVAILABILITY, BASED ON THE LITERATURE REVIEW AND PRACTICAL SITUATION AT SABIC GELEEN?

This master thesis investigated the potential problems of each phase in the spare parts ordering process. The current problems of SABIC Geleen are combined with potential problems as described in literature. Summarized, the following problem areas are discovered (see chapter 5 for a detailed description):

Phase 1 – Need for a spare part:

a. It is not immediately clear which spare part in what quantity, with what priority, from which supplier is needed to perform the corrective maintenance activity
b. The determination of the urgency of the needed spare part is difficult for the problem discoverer

Phase 2 – From need for a spare part to actual ability to order the spare part:

a. Maintenance activities receive an unnecessary high priority to speed up the work or because of limited knowledge and experience of the problem discoverer
b. The Gatekeepers do not discriminate between the four different spare part categories and they do not address whether spare parts are actually available when the planning is made
c. The ordered spare parts are not expedited

Phase 3 – Actual ordering of the spare part:

a. The wrong spare part is ordered too late in the wrong quantity
b. The final order problem

Phase 4 – Spare parts ordering policy:

a. Spare parts are classified in the wrong category
b. Minimum stock levels are chosen at a too low level
c. The calculation of the minimum stock level does not incorporate the wear rate of components
d. Wrongly classified spare parts are too little or too often reviewed
e. Wrong decision on the reparability of the spare part
f. The wrong supplier is selected for delivering the spare part

Phase 5 – Order supply process:

a. Badly specified ordering procedures
b. Not following correctly specified ordering procedures
c. Missing values in the data

Phase 6 – Order receipt process:

a. Mismatch in the specification of the delivered part and the reference specification or drawing
b. Required certificates for assembling the spare part are missing

Phase 7 – Actual use of the spare part:

a. Skills and expertise of maintenance employees decrease because maintenance activities are postponed
b. Lower knowledge and experience of newly hired personnel
c. The wrong spare part is installed or the correct spare part is installed incorrectly

Phase 8 – Repair or discard process of spare parts:

a. The location of the temporarily stored disassembled repairable spare parts is unknown to the Maintenance Engineer
b. Maintenance personnel have limited knowledge of the reparability of a component
c. The dispose command is not issued when a repairable spare part is scrapped
d. Change in the reparability of the spare part is not communicated to the Maintenance Engineer and maintenance personnel
e. Long and unreliable repair lead times

18.1.3. In what phase(s) of the spare parts ordering process is/are the impact of spare parts unavailability the largest for SABIC Geleen?

In chapter 7, the impact of the phases of the spare parts ordering process is determined. The costs of downtime, cost related to safety, health and environmental issues, and unnecessary urgency ordering are included in the determination of the impact. In Table 44 it can be seen that particularly phase 4, i.e. the spare parts ordering policy, and phase 8, i.e. the repair or discard process of spare parts, had the highest negative consequences in 2012. SABIC Geleen does not expect that in the future other phases of the spare parts ordering process will become problematic, so we focus our redesigns on the spare parts ordering policy phase and the repair process phase.

Table 44: lost economic value (in €) in 2012 for SABIC Geleen per phase of the spare parts ordering process (copy of Table 14)

Phase number	Name of the phase of the spare parts ordering process	Cost lower bound (in €)	Cost higher bound (in €)
1.	Need for a spare part	[redacted]	[redacted]
2.	From need for a spare part to the actual ability to order a spare part	[redacted]	[redacted]
3.	Actual ordering of the spare part	[redacted]	[redacted]
4.	Spare parts ordering policy	[redacted]	[redacted]
5.	Order supply process	[redacted]	[redacted]
6.	Order receipt process	[redacted]	[redacted]
7.	Actual use of the spare part	[redacted]	[redacted]
8.	Repair or discard process of spare parts	[redacted]	[redacted]

18.1.4. HOW CAN WE IMPROVE THE PROBLEMS OF SPARE PART UNAVAILABILITY WHEN SABIC GELEEN WANTS TO DO MAINTENANCE AT MINIMUM COSTS, BASED ON THE LITERATURE REVIEW?

We developed redesigns for both the spare parts ordering policy and the repair process in order to (partially) solve the problems related to these phases of the spare parts ordering process. In section 18.1.4.1 we discuss the redesigns of the spare parts ordering policy. In section 18.1.4.2 we discuss the redesigns of the repair or discard process of SABIC Geleen.

18.1.4.1. REDESIGNS OF THE SPARE PARTS ORDERING PROCESS

a. The decisions and the sequence of the decisions to be taken in the spare parts ordering policy

This research investigated the current decisions and sequence of the decisions taken in the spare parts ordering policy of SABIC Geleen. Based on this literature, knowledge and experience at SABIC Geleen, the framework has been redesigned (see Figure 27).

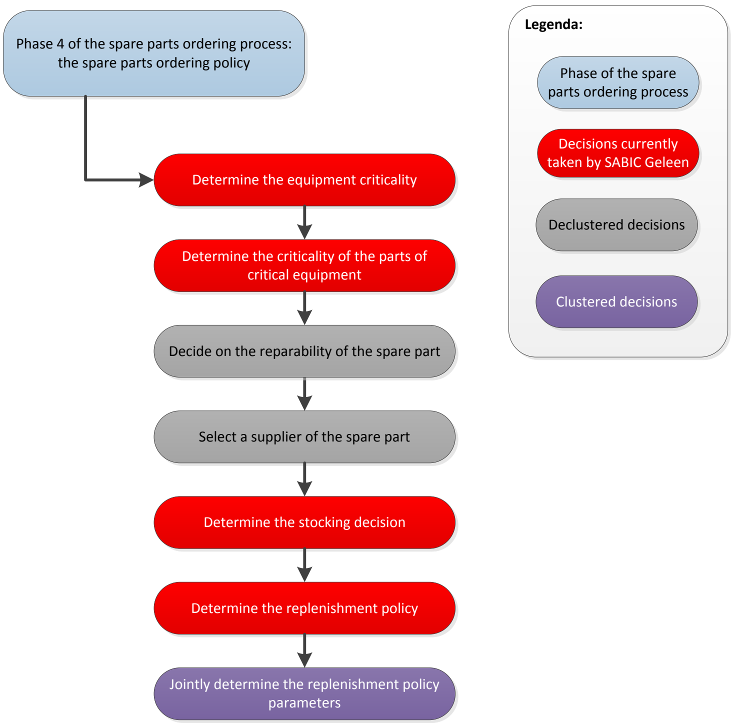

Figure 27: adjustments of the decisions and sequence of the spare parts ordering policy (copy of Figure 17)

b. The determination of the criticality of the equipment

Based on the comparison of literature with the current criticality determination tool of SABIC Geleen, we determined that the current tool meets all criteria as specified by literature. The determination of the boundary values and the risk acceptance level is company-specific and currently based on industry benchmarking data. We proposed to use the risk matrix that SABIC Geleen is going to use from January 2014 to determine the criticality of the equipment

c. The determination of the criticality of the associated spare parts

Currently SABIC Geleen uses the FMEA methodology, which is proposed by literature, to determine what components are critical for the functionality of the equipment. A Risk Priority Number is calculated, based on the scores of severity, occurrence (which are coupled to the criticality matrix), and detectability. Literature proposes to use same dimensions for each ranking scale. Currently this is not the case as SABIC Geleen measures severity and occurrence on a five-point scale, and detectability on a ten-point scale. We redesigned the detectability scale (see Table 45).

Table 45: proposed detectability scale of SABIC Geleen (Source: FMEA study SABIC Geleen, 2013) (copy of Table 19)

Detectability Score	Detectability
1	Detection is possible by elimination or alarm
2	Detection is possible by an operator during the inspection round
3	Detection is possible by periodical condition monitoring
4	Detection is possible by specific maintenance inspections or plant shutdown actions
5	Detection is only possible by extraordinary coincidence

d. The decision on the reparability of the spare part

Currently, SABIC Geleen decides on the reparability of the spare part based on two decisions; a non-economic decision where it is decided whether it is technically feasible to repair the component and an analysis based on cost models (i.e. economic criteria). The economic decision is currently purely based on the costs of repair versus the purchasing costs at SABIC Geleen, whereas literature proposes to also incorporate supply lead times of the component. The Level Of Repair Analysis model is used and solved using the greedy algorithm (see section 6411.1 for a detailed description of the LORA and the greedy algorithm). An Excel tool is designed to aid the employees of SABIC Geleen in the decision whether to repair or discard a component.

e. The decision at which supplier the spare part is ordered

Literature assumes that for choosing a supplier, multiple suppliers are available which guarantee the desired quality of the component. While this is not the case for SABIC Geleen, these decisions should be explicitly made. SABIC Geleen does classify vendors on twelve criteria to determine whether a supplier is qualified to supply components to SABIC Geleen. Compared with literature, lead time is not included. We proposed to include this variable in the vendor qualification questionnaire. An Analytical Hierarchy Process is proposed to calculate the weights of each factor and determine whether a supplier is qualified for delivery. An Excel tool is designed to aid the employees of SABIC Geleen with calculating the criteria weights.

Once a demand for a spare part occurs, SABIC Geleen demands tenders from the qualified vendors and the supplier which offers the component at the lowest price is allowed to deliver the part. We propose to incorporate the supply lead time in this decision as well. Again an Analytical Hierarchy Process is used to calculate a benefit-cost ratio. The supplier with the highest benefit-cost ratio should then be chosen to deliver the demanded component to SABIC Geleen. We developed an Excel tool to aid the employees with the selection of a supplier.

f. The decision on whether to stock the spare part or not

Literature proposes to include spare part criticality, price, demand value, and spare part specificity as variables to determine the decision on whether to stock a spare part or not. These variables have an effect on the stock levels, not on the decision whether or not to stock a spare part. We propose to base the stocking decision on the criticality of the equipment and the expected supply lead time using Table 46.

Table 46: matrix used to make a decision which spare parts to stock, based on the equipment criticality and the expected supply lead time (Source: Approved Best Practice 133, SABIC Europe Intranet, 2009) (copy of Table 33)

		Equipment criticality			
		1	2	3	4
Spare parts expected supply lead time	> 5 days				
	3 < days ≤ 5				
	1 < days ≤ 3				
	8 ≤ hours ≤ 24				
	< 8 hours				

g. The determination of the spare parts replenishment policy

Currently, SABIC Geleen uses the (R,s,S)-replenishment policy for all components which are stocked on site in Geleen. Because the review period for all but floor stock components is small compared to the delivery lead time, (s,S)-replenishment policies may be assumed. However, the use of a continuous base-stock replenishment policy is optimal for components with a high price and low demand volumes, e.g. spare parts. An important assumption of the continuous base-stock policy is that the demand of the component is stationary during its lifetime (e.g. no seasonal effects). The Manager Reliability & Integrity of the Site Improvement department feels that this is the case for the majority of spare parts of SABIC Geleen. We propose to use the continuous base-stock replenishment policy for all but the floor stock components, where the currently used (R,s,S)-replenishment policy is proposed.

h. The determination of the spare parts replenishment policy parameters

Because of the proposal to use the continuous base-stock policy for almost all components of SABIC Geleen, only one replenishment parameter, the maximum stock level S has to be defined. Currently, SABIC Geleen calculates the maximum stock level based on the Economic Order Quantity. Purely based on costs, stock levels are determined. Not including supply lead times could cause not meeting the target system availability. Using an item approach, which includes the supply lead time of the components, arrives at stock levels of components to meet the target system availability. For insurance spare parts, SABIC Geleen uses the stock pooling strategy, which is broadly discussed by literature. Therefore, no redesign is developed for this spare part category.

i. Design of the system approach for determining the replenishment policy parameters

Literature proposes to use a system approach, Multi-Echelon Technique for Recoverable Items Control (METRIC), in order to include the effects of system availability. Using the METRIC technique instead of the item approach achieves the same target system availability at lower costs (see Appendix I – Explanation of the Multi-Echelon Technique for Recoverable Item Control (METRIC) model for a detailed description of the METRIC technique). An Excel tool is developed to aid the employees of SABIC Geleen in the calculation of the replenishment policy parameters while achieving the target system availability at the lowest investment costs. Using the system approach for a case study, a cost saving of almost 40% was achieved.

18.1.4.2. Redesigns of the repair or discard process

Regarding the repair or discard process of SABIC Geleen, the following decisions are redesigned:

a. The disassembled defective repairable spare part is not directly sent to the repair shop

The Maintenance Field Planners do not always contact the Maintenance Engineers when technical support is necessary for performing a maintenance activity which causes the maintenance to be unnecessary delayed. We propose that the Maintenance Engineers of the Site Improvement department filter the notifications on the status Technical Support Necessary and contact the Maintenance Field Planner in case previously unknown notifications are discovered.

The Maintenance Engineers should describe in the Technical Mission Statement the exact actions which need to be taken regarding the defective repairable spare part (e.g. where the disassembled component should be located)

Finally, we propose to use the replenishment proposals of repairable spare parts as a reminder for the Maintenance Engineer to check with the Maintenance Field Planner whether the components are delivered to the repair shop for revision. The replenishment proposal should be sent to the Maintenance Engineer of the Running Business department because he has more knowledge on the current delivery progress of the maintenance activity.

b. The repairable spare parts are not tracked and traced

Currently, SABIC Geleen hired a dedicated job leader to track and trace all maintenance orders to external parties. We propose to also use a track and trace system on the repairable spare parts so that the Maintenance Engineers of the Site Improvement department are able to track the status of the component.

c. The Maintenance Field Planners do not check the availability of the spare parts and do not differentiate components on the different spare parts categories

Before the Maintenance Field Planners make the planning of the maintenance activities they should check with the Purchase Schedulers whether the needed spare parts are immediately available, and if not, what the expected supply lead time of the spare part is. Incorporating the availability of the spare part and the expected supply lead time leads to a more realistic maintenance planning.

d. The discard procedure is not followed or even forgotten by the Maintenance Engineers

In order to solve this problem, it is proposed to make it impossible for the Maintenance Engineers to issue a replenishment order for a repairable spare part before they issued the dispose command. It is proposed to keep using the replenishment proposal as a reminder for the Maintenance Engineer to issue the dispose command if necessary.

e. The increase in stock levels when a new spare part is already ordered before the repaired spare part will return to stock after a successful repair

The same solution is proposed as the solution to solve the problem of not following or forgetting the discard procedure (see point d. above).

f. The supply lead times and prices are not updated in the SAP information system

We propose to update the supplier information periodically using a feedback loop. Ideally, the suppliers should inform SABIC Geleen when the supply lead time or price of the component changes. This is however not always the case, and therefore resources are needed to determine for which spare parts with what frequency the supplier information should be updated to achieve at a cost efficient solution. Additional research is needed to determine for which spare parts and with what frequency the supply information should be updated.

18.2. RECOMMENDATIONS

This section provides the recommendations for SABIC Geleen regarding this research.

18.2.1. IMPLEMENT AND APPLY THE REDESIGNED DECISIONS AND SEQUENCE OF THE SPARE PARTS ORDERING POLICY

It is recommended to SABIC Geleen to change the decisions and the sequence of them, taken in the spare parts ordering policy, in order to achieve maximum system availability at lower costs. For each decision which needs to be taken in the spare parts ordering policy of SABIC Geleen, redesigns are developed (see chapter 9 until chapter 16 for detailed explanations of the redesigned solutions). When implementing the redesigns, maximally around [redacted] could have been saved in 2012.

18.2.2. IMPLEMENT AND APPLY THE REDESIGNED DECISIONS OF THE SPARE PARTS REPAIR OR DISCARD PROCESS

Currently, SABIC Geleen has problems with the repair process of defective repairable spare parts. In order to improve the repair process of SABIC Geleen, in chapter 17 the main problem areas or SABIC Geleen regarding the repair process are described, and redesigns are developed to achieve target system availabilities at lower costs. It is recommended to SABIC Geleen to implement the proposed solutions. When implementing the redesigns, maximally around [redacted] could have been saved in 2012.

18.2.3. DEVELOP REDESIGNS FOR THE SECOND AND THIRD PHASE OF THE SPARE PARTS ORDERING PROCESS

We developed redesigns for the spare parts ordering policy and repair process of SABIC Geleen because the negative economic effects were largest for these phases of the spare parts ordering process in 2012, i.e. approximately [redacted] could be saved when solving the problems of the spare parts ordering policy and approximately [redacted] could be saved when solving the problems of the repair process. The added economic value lost because of problems related to the process between the identification of a need for a spare part and the actual ability to order the part (phase two of the spare parts ordering process) and the actual ordering (phase three of the spare parts ordering process) was approximately also [redacted]. Note that SABIC Geleen could maximally save approximately [redacted] in 2012. The delayed maintenance work orders caused losses in multiple spare parts ordering process phases and therefore, the lost value is assigned to multiple phases of the spare parts ordering process. Because a significant amount of money could be saved when redesigns are developed for the second and third phase of the spare parts ordering process, we recommend SABIC Geleen to further research these areas and develop redesigns in order to solve (part of) the problems related to these phases.

18.2.4. RECORD MAINTENANCE AND ASSET UTILIZATION DATA IN ONE INFORMATION SYSTEM

Currently, SABIC Geleen uses two different information systems, the SAP information system for recording maintenance work orders, and the PROMISE information system for recording asset utilization data. Both information systems are specified separately from each other. This makes it difficult to compare data from both information systems, because no direct linkage between the information systems exists. In order to improve the comparison of maintenance data with asset utilization data, we recommend SABIC Geleen to combine both information sources into one information system, e.g. SAP. Research, e.g. a master thesis project, is needed to investigate what information system could be used, what solution should be designed, and how this should be implemented in the information system.

18.2.5. IMPROVE MAINTENANCE DATA REGISTRATION

As mentioned in Appendix E – Cleaning and filtering the zpm_stat_list the filtering and cleaning of the maintenance data of 2012 required four full time work weeks. SABIC Geleen uses a detailed information system where maintenance data is registered, the SAP information system. However, registered data is not always reliable or valid (e.g. missing values in approval dates, spare part delivery dates); it would be relevant for SABIC Geleen to verify the data before use so that more reliable conclusions can be made. Secondly, other sites of SABIC worldwide also use the SAP information system and have access in each other's data. However, the Maintenance and Reliability Engineers of the Site Improvement department of SABIC Geleen do not use consumption data of other sites to determine the likelihood of a failure (e.g. in the FMEA study). Sharing the data provides the Maintenance and Reliability Engineers with a more reliable estimation. Finally, the data in the SAP information system is incomplete; spare parts are taken from stock on wrong work orders, Bill Of Materials do not exist, etc. To more reliably estimate failure rates of components, in order to more reliably estimate the need for spare parts, accurate shared data would be of a large benefit. Concluding, it is recommended to improve the maintenance data registration with clear rules and guidelines and to verify all registered data before conclusions are made.

18.2.6. IMPROVE ASSET UTILIZATION DATA REGISTRATION

In section 2.2.2 it is mentioned that it is currently not recorded in the asset utilization if production is lost because the maintenance activity was delayed because of spare part unavailability. This makes it difficult to determine how severe the problem of spare part unavailability is for SABIC Geleen. Now we scanned the subject texts in order to determine whether the production loss was completely contributable to the unavailability of a spare part. If it was not the case, but the production loss corresponded with a maintenance order which was delayed because of spare part unavailability, it was estimated, purely based on the experience of the Manager Reliability & Integrity of the Site Improvement Polymers department that 10% of the total production loss is caused by the unavailability of the spare part. In order to arrive at a more underpinned and reliable production loss contributable to spare part unavailability, we recommend to determine in the asset utilization data the exact amount of lost production because of spare part unavailability. Finally, SABIC Geleen currently uses asset utilization margins which are not up to date (e.g. sometimes the current asset utilization margin is 50% of the used long-term average asset utilization margin used for calculating the lost economic value). We recommend SABIC Geleen to update the asset utilization margins in order to arrive at a more reliable estimation of lost economic value due to spare part unavailability.

18.2.7. INVESTIGATE THE PROBLEM OF BLACK STOCK

In section 2.1 the problem of black stock, i.e. the ordering and stock keeping of components outside the scope of the information system, for SABIC Geleen is mentioned by several employees. Because black stock is not registered in the information system, no data is collected and the severity of the problem cannot be quantified. However, because it is a frequently mentioned problem by multiple employees of several departments within SABIC Geleen, the general feeling exists that improvements in this area could be made. Research, e.g. a bachelor thesis project, is proposed to investigate the relevance of the problem. If the problem proves to be relevant, a Master student could develop redesigns to overcome the problem of black stock.

18.3. ACADEMIC RELEVANCE

This master thesis is a case study regarding the spare parts ordering process in the process industry. A framework is developed to describe the spare parts ordering process. The framework is based on a literature review of several spare parts ordering processes, which are combined and compared. Based on the knowledge and experience of the employees of SABIC Geleen, a usable redesigned framework is developed.

BIBLIOGRAPHY

Bacchetti, A., Plabani, F., Saccani, N., and Syntetos, A. (2011). Spare parts classification and inventory management: a case study. (Working paper, No. 408/12). Manchester: Salford Business School, 37.

Bakx, L. (2010). The Final Order Problem for Non-Repairable Items at Vanderlande Industries. Master thesis, Eindhoven: TU/e.

Basten, R., Van Der Heijden, M., and Schutten, J. (2011). Joint optimization of level of repair analysis and spare parts stocks. (BETA publication: Working papers, No. 346). Eindhoven: Technische Universiteit Eindhoven, 21.

Beekhuizen, R. (2011). Identification of Purchasing and Supply Strategies for Service Parts: A lifecycle perspective. Master thesis, Eindhoven: TU/e.

Botter, R., and Fortuin, L. (2000). Stocking strategy for service parts – a case study. *International Journal of Operations & Production Management*, 20(6), 656 – 674.

Bruijn, M. De (2013). Redesign of the Maintenance Concept Development Framework for Heineken, with an application on the Packers of Production Line 7 at Heineken Zoeterwoude. Master thesis, Eindhoven : TU/e.

Carretero, J., Pérez, J., García – Carballeira, F., Calderón, A. Fernández, J., García, J., et al. (2003). Applying RCM in large scale systems: a case study with railway networks. *Reliability Engineering & System Safety*, 82(3), 257 – 273.

Driessen, M., Arts, J., Van Houtum, G.J., Rustenburg, W., and Huisman, B. (2010). Maintenance spare parts planning and control: A framework for control and agenda for future research. (BETA publication: Working papers, No. 325). Eindhoven: Technische Universiteit Eindhoven, 36.

Espíndola, D., Frazzon, E., Hellingrath, B., and Pereira, C. (2012). Integrating Intelligent Maintenance Systems and Spare Parts Supply Chains. *Information Control Problems in Manufacturing*, 14(1), 1017 – 1022.

Fortuin, L., and Martin, H. (1999). Control of service parts. *International Journal of Operations & Production Management*, 19(9), 950 – 971.

Ghodsypour, S., and O'Brien, C. (1998). A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming. *International Journal of Production Economics*, 56, 199 – 212.

Graves, S (1999). A Single-Item Inventory Model for a Nonstationary Demand Process. *Manufacturing & Service Operations Management*, 1(1), 50 – 61.

Groof, T. De (2010). Developing a framework for optimizing inspection intervals for a large installed asset base. Master thesis, Eindhoven: TU/e.

Haas, R., and Meixner, O. (2006). An Illustrated Guide to the Analytic Hierarchy Process. Retrieved May 28, 2013, from Institute of Marketing & Innovation, University of Natural Resources and Applied Life Sciences: Vienna. Website: http://www.boku.ac.at/mi/

Huiskonen, J. (2001). Maintenance spare parts logistics: Special characteristics and strategic choices. *International Journal of Production Economics*, 71, 125 – 133.

Internal presentation SABIC Europe: Site Geleen: fixed costs 2012. (2012). Internal documents. Last reviewed on May 17th 2013.

Intranet SABIC Europe: Approved Best Practices 014 – Improve Equipment Reliability. (2010). Internal documents SABIC. Last reviewed on February 7th 2013.

Intranet SABIC Europe: Approved Best Practice 133 – Determining of min-max parameters. (2009). Internal documents SABIC. Last reviewed on June 27th 2013.

Intranet SABIC Europe: Organization structure manuals. (2012). Internal documents SABIC. Reviewed on December 4th 2012.

Intranet SABIC Europe: Work Processes. (2010). Internal documents SABIC. Last reviewed on June 24th 2013.

Karsten, F., and Basten, R. (2012). Spare parts inventory pooling: how to share the benefits? (BETA publication:Working papers, No. 372). Eindhoven: Technische Universiteit Eindhoven, 51.

Kok, A. De, Fortuin, L., and Van Donselaar, K. (2007). Analysis of stock control models for one location with one product. *Handout stock control Logistics 1 course Eindhoven University of Technology,* 34.

Kranenburg, A. (2006). *Spare Parts Inventory Control under System Availability Constraints*, PhD dissertation, Technische Universiteit Eindhoven, Eindhoven, The Netherlands.

Lith, I. Van (2004). Geen Smarts zonder spare parts: Een verbeterproject gericht op de planning en besturing van reserveonderdelen voor het productieapparaat van Netherlands Car B.V. Master thesis, Eindhoven: TU/e.

Louit, D., Pascual, R., Banjevic, D., and Jardine, A. (2011). Optimization models for critical spare parts inventories – a reliability approach. *Journal of the Operational Research Society*, 62, 992 – 1004.

Manufacturing Excellence Work Processes, Meeting and Organization Structure; the coherency (2012). Internal booklet SABIC Geleen.

McDermott, R., Mikulak, R., and Beauregard, M. (2009). *The basics of FMEA.* New York: CRC Press.

Profile Site Geleen (2008). Last revised on March 13th, from http://sabic-limburg.nl/sabic-limburg/profiel-site-geleen

Rustenburg, W. (2000). The Single-Site, Single-Indenture Model. In Zijm, W., and Kok, A. De (Eds.), *A System Approach to Budget-Constrained Spare Parts Management* (35 – 48). Cip-data library Technische Universiteit Eindhoven.

Rustenburg, W., Van Houtum, G.J., and Zijm, W. (2001). Spare part management at complex technology-based organizations: an agenda for research. *International Journal of Production Economics*, 71 (1 – 3), 177 – 193.

Rustenburg, W., Van Houtum, G.J., and Zijm. (2003). Exact and approximate analysis of multi-echelon, multi-indenture spare parts systems with commonality. In Shanthikumar, J., Yao, D., and Zijm, W. (Eds.), *Stochastic Modelling and Optimization of Manufacturing Systems and Supply Chains*. Kluwer, Boston (MA), 143 – 176.

Saaty, T., and Alexander, J. (1981). Thinking With Models: Mathematical Models in the Physical, biological and Social Sciences, Chapter 8. London: Pergamon Press.

SABIC Enterprise Risk Management – SABIC Risk Management and Risk Matrix Guideline. (2013). Internal documents SABIC. Reviewed on June 11th 2013.

SABIC Geleen FMEA Study. (2013). Internal documents SABIC. Reviewed on June 4th 2013.

SABIC Geleen Monthly Report Plant. (2012). Internal documents SABIC. Reviewed on April 4th 2013.

SABIC Geleen Vendor Qualification Questionnaire. (2011). Internal documents SABIC. Reviewed on June 17th 2013.

SABIC Vision + Performance Report & Accounts (2011). Last revised on December 4th 2012, from http://www.sabic.com/corporate/en/binaries/SABIC_AR2011_ENGLISH_tcm4-8233.pdf

Sherbrooke, C. (1968). METRIC: A multi-echelon technique for recoverable item control. *Operations Research*, 16(1), 122 – 141.

Sherbrooke, C. (1992). *Optimal inventory modeling of systems*. New York: Wiley.

Sherbrooke, C. (2004). *Optimal inventory modeling of systems. Multi-echelon techniques.* 2nd ed. Kluwer, Dordrecht (The Netherlands).

Smidt, M., and Dekker, R. (1997). On the (S – 1, S) Stock model for renewal demand processs: Poisson's Poison. *Probability in the Engineering and Informational Sciences*, 11, 375 – 386.

Stengl, B., and Ematinger, R. (2001). *SAP R/3 Plant Maintenance making it work for your business*. 1st ed. Essex: Addison-Wesley.

Syntetos, A., Boylan, J., and Croston, J. (2005). On the categorization of demand patterns. *Journal of Operational Research Society*, 56(5), 495 – 503.

Tai, A., and Ching, W-K. (2006). A Two-echelon Model for Inventory and Returns. In Haasis, H-D., Köpfer, H., and Schönberger, J. (Eds.), *Operations Research Proceedings 2005* (131 – 136). Berlin – Heidelberg: Springer.

Thonemann, U., and Bradley, J. (2002). The effect of product variety on supply-chain performance. *European Journal of Operational Research*, 143(1), 548 – 569.

Velagić, A. (2012). Spare parts management improvement at KLM Equipment Services. Master thesis, Eindhoven: TU/e.

Figures and tables

Below, a list of all Figures and a list of all Tables provided in this master thesis is presented.

Figures

TABLES

APPENDIX A – LIST OF ABBREVIATIONS

The table below provides an overview of all used abbreviations in this master thesis.

Abbreviation	Definition
ABPR	Approved By Production
ADI	Average Inter-Demand Interval
AHP	Analytical Hierarchy Process
BOM	Bill Of Material
CMI	Centrally Managed Inventory
CTP	Capacity To Produce
CV^2	Coefficient Of Variation
EOQ	Economic Order Quantity
FMEA	Failure Mode and Effect Analysis
HDPE	High Density Poly Ethylene
KPI	Key Performance Indicator
LB	Losses due to business
LDPE	Low Density Poly Ethylene
LE	External losses
LM	Losses due to Maintenance
LORA	Level Of Repair Analysis
LP	Losses due to Production
METRIC	Multi-Echelon Technique for Recoverable Item Control
MRP	Material Resources Planning
PP	Poly Propylene
RB	Running Business department
RCM	Reliability Centered Maintenance
RPN	Risk Priority Number
SABIC	Saudi Basic Industries Corporation
SI	Site Improvement department
SIPol	Site Improvement Polymers department
SS	Site Services department
TDRP	Technical Service Repairable Account
TMS	Technical Mission Statement
TSNE	Technical Support Necessary
WFMA	Waiting For Material

APPENDIX B – LIST OF DEFINITIONS

The table below provides an overview of all definitions and their explanations used in this thesis.

Definition	Explanation
Analytical Hierarchy Process	A structured technique for organizing and analyzing complex decisions (in this thesis for selecting a supplier for a component)
As good as new repair	Repair of a component after failure into a condition or state which is comparable with the condition or state of a brand new component (Collins English Dictionary, 2003)
Asset Utilization	The ratio of actual output compared with the maximum theoretically feasible output
Asset utilization margin	The price for which the produced product is sold in the market
Availability	The probability that a system or component is operating at a specified time (Barlow & Proschan, 1975)
Benchmarking data	The results of an investigation to determine how competitors and/or best-in-class companies achieve their level of performance (Business Dictionary, 2013)
Benefit	An advantage or profit gained from regeneration (The Free Dictionary, 2009)
Black stock	Stock which is ordered by maintenance employees not using the developed ordering information system, and is therefore not registered
Breakdown	The act or process of failing to function or continue (Collins Thesaurus of The English Language, 2003)
Business loss	The loss of volume during a day as a result of limitations in market demand, defined in production units (Intranet SABIC Europe Work Process 09 Asset Utilization)
Component	A part or element of a (technical) system (The Free Dictionary, 2009)
Consumable spare part	Part which is scrapped after replacement (Driessen et al., 2010)
Continuous base-stock replenishment policy	Inventory levels are checked continuously (i.e. always if demand occurred, the inventory level is checked). The aim of the policy is to keep the inventory constant at a predetermined stock level, i.e. the base-stock level
Corrective maintenance	Maintenance carried out after a failure and it means all actions resulting from failure (Wang, 2002)
Cost efficient	Economical in terms of the goods or services received for the money spent (Collins English Dictionary, 2003)
Criticality	The quality, state, or degree of being of the highest importance (The Free Dictionary, 2009)
Criticality matrix (Risk matrix)	Tool used for determining the criticality of the system
Delay time	A two-stage failure process of a component, that is, from new to the initial and identifiable point of a hidden defect, then from this point to an eventual failure caused by the defect if not attended to (Wang, 2012)
Delivery lead time	The time between which an order for a component is placed and the time it is received (The Free Dictionary, 2009)
Discard process	The steps and procedures to be taken when a defective component is thrown away (The Free Dictionary, 2009)
Downtime	The period of time when a plant or (technical system) is not in operation, especially as the result of a malfunction. It includes all nonproductive time (Collins English Dictionary, 2003)
Economic Order Quantity model	Tool used for determining the order-up-to level by comparing ordering costs and inventory holding costs
Equipment	See system

External loss	The loss of volume per product during a day as a result of external calamities (e.g. power loss, lightning, raw materials) defined in production units (Intranet SABIC Europe Work Process 09 Asset Utilization)
Failure Mode and Effect Analysis	A technique aimed at systematically assessing all the potential failures of a (technical) system with its potential impact on human, environment or financials, and what actions are suitable for decreasing the potential impact
Fill rate	The probability of not running out of spare parts stock when a failure occurs (Cavalieri et al., 2008)
Impact	Measurement of a result on a company or social group (in this thesis the result of delayed maintenance work orders)
Improvement	The process of achieving a condition superior to an earlier condition (Collins Thesaurus of the English Language, 2003)
Insurance spare part	Spare parts that are very reliable (i.e. have a very low rate of failure), are highly critical to the availability of the system and not readily available in case of failure (Driessen et al., 2010)
Integrity	State of a system where it is performing its intended functions without being degraded or impaired by changes or disruptions in its internal or external environments (Business Dictionary, 2013)
Item approach	Technique for determining stock levels of components, incorporating the supply lead time, where each component should minimally meet the target fill rate
Level Of Repair Analysis	An analysis conducted to determine whether an item should be repaired or discarded after failure
Long-term	Relating to or extending over a relatively long time, a year or longer (Collins Thesaurus of the English Language, 2003)
Maintenance	All actions appropriate for retaining an item/part/component/equipment/ (technical) system in, or restoring it to a given condition, which ultimately reduces production loss and downtime as well as the environmental and the associated safety hazards (Dhillon, 2002)
Maintenance activity	Set of actions performed on a component or (technical) system aiming to keep or return the state of the component or (technical) system to an acceptable level where it is able to perform its function with the designed integrity
Maintenance code	Codification used to distinct different maintenance activities (e.g. corrective or preventive maintenance)
Maintenance loss	The loss of volume per product during a day as a result of unexpected maintenance issues defined in production units (Intranet SABIC Europe Work Process 09 Asset Utilization)
Maintenance planning	A planning of the maintenance activities regarding what activities should be done, by whom, within an estimated time interval, at what (technical) system
Maintenance work order	A request for a maintenance activity and all needed information (e.g. the ordered spare parts, the planned starting and finish date)
Malfunction	Fail to function or function improperly (Collins English Dictionary, 2003)
Medium-term	Relating to or extending over a moderate long time, a month or quarter of a year (Collins Thesaurus of the English Language, 2003)
Minimal repair policy	Repair of a (technical) system, subsystem, or equipment which is just enough to get the system operational again (RGA Reference Glossary, 2010)
Multi-Echelon Technique for Recoverable Item Control	Technique used for determining stock levels, including the lead time of the component, and the effects on the system availability and investment costs, aiming to meet the target system availability at minimum investment costs
Notification	A formal announcement (in this thesis that a preventive or corrective maintenance activity is needed for a component or (technical) system)
Obsolete stock	Inventory items which are out of use or out of practice (Business Dictionary, 2013)
Parameter	A numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation (The Free Dictionary, 2009)

Performance	Total amount of high quality goods produced in a specified period of time
Petrochemical	Any chemical substance obtained or derived from petroleum or natural gas (Collins English Dictionary, 2003)
(Chemical) Plant	A building or group of buildings, consisting of equipment/(technical) systems, necessary for a (chemical) manufacturing operation for processing (chemical) products
Preventive maintenance	Maintenance is carried out before failure in order to retain equipment in specified condition by providing systematic inspections, detection, and prevention of incipient failure (Wang, 2002)
Problem	A perceived gap between the existing state and a desired state, or a deviation from a norm, standard, or status quo (Business Dictionary, 2013)
Production loss	Losses due to shortcomings in production and technology (Intranet SABIC Europe Work Process 09 Asset Utilization)
Reliability	The ability of a person or system to always perform and maintain its functions
Repair lead time	The time between which the defective component is sent to a repair organization for repair activities until it is available for use
Repair process	The steps and procedures to be taken when a defective component is repaired and stocked after repair for future use
Repairable spare part	Part that is repaired rather than procured after failure, i.e. part that is technically and economically repairable. After repair the part becomes ready-for-use again (Driessen et al., 2010)
Replenishment policy	A formal policy that outlines the schedule and procedure of how often the inventory status should be determined (i.e. the review period), when a replenishment order should be placed, and how large the replenishment order should be (Silver, Pyke, & Peterson, 1998)
Replenishment proposal	Proposal of the SAP information system to order a component because the inventory level dropped below the reorder point
Risk Priority Number	A technique, used in the FMEA study, for measuring and analyzing the risk of component failure, measured in severity, occurrence and detectability
Safety	The state of being certain that adverse effects will not be caused by some agent under defined conditions (Collins Thesaurus of the English Language, 2003)
Short-term	Relating to or extending over a limited period, a day or less (Collins Thesaurus of the English Language, 2003)
Small stop	A moment of stopping production in a short time period (maximally one calendar week) in order to do preventive or corrective maintenance on the equipment or technical system
Spare part	A duplicate part to replace a lost or damaged part of a machine, system, or equipment (The Free Dictionary, 2009)
Spare part category	The categorization of spare parts in classes according to the criticality level, and the expected supply lead time of the spare part (AVL List, 2010)
Spare parts ordering policy	Rules and decisions regarding the criticality of the equipment, the criticality of associated components, the reparability of the components, the choice of a supplier, the decision to stock the spare part, the stocking location decision, the determination of the replenishment policy and the parameters
Spare parts ordering process	The process of knowing that one needs a spare part to perform the maintenance activity to the actual assembly of the new part and the removal of the old part and all steps and decisions in between
Spare part specificity	The extent to which a component is tailored for and used by a customer (Driessen et al., 2010)
Stock pooling strategy	Stocking of a spare part in one location where multiple companies/sites are able to use it when their own component breaks down. Commonly used strategy for stocking insurance spare parts
Supply lead time	The time from the moment a demand for a spare part occurs to the moment it is received by the demanded party

System approach	Technique for determining stock levels of components, incorporating the supply lead time and effects on the system availability and investment budget, aiming to meet the target system availability at minimum investment costs
System availability	The percentage of time when a system will be able to produce the demanded products with the desired speed and quality
Technical Mission Statement	Technical support provided by the Maintenance Engineers what and how maintenance actions should be performed
Technical system	A combination or assembly of components that forms a system or equipment, designed for performing its technical functions as a single unit (e.g. a gearbox)
Turnaround	Scheduled events wherein an entire process unit of an industrial plant is take off stream for an extended period for renewal or preventive maintenance activities, where the shutdown is for a longer period of time (i.e. around three calendar weeks)
Utilization rate	The weighted average of the ratios between the actual output of a system to the maximum that could be produced per unit of time, with existing plant and equipment (Johanson, 1968).

Appendix C – Subset of ZPM_STAT_LIST data including a definition list and a timeline

Table 47: Subset of the data of 2012 as retrieved from the SAP system of SABIC Geleen

Date	Notifctn	MntPlant	Coding	Date NIPR	Req. start	Basic fin.	Order	PlGrp Ordr	Date WOOP	Date TOS	TOS Del	Date PLND	Date PERM	Date RTBS	Date WFMA	WFMA Del	Date Start	Date ABPR	Prio Ordr
2-1-2012	10186117	FP01	60M	3-1-2012	2-1-2012	9-1-2012	5193737	323	3-1-2012				22-2-2012	3-1-2012	3-1-2012	31-1-2012	3-1-2012	1-2-2012	1
18-1-2012	10187857	FP01	22M	20-1-2012	25-1-2012	27-2-2012	5195492	520	23-1-2012			25-1-2012	26-1-2012	27-1-2012	21-3-2012	27-3-2012	7-2-2012	28-2-2012	3
25-1-2012	10188771	FP01	60M	26-1-2012	1-2-2012	6-4-2012	5195701	520	26-1-2012			7-2-2012	7-2-2012	8-2-2012	3-4-2012	11-4-2012	7-2-2012	11-4-2012	2
10-2-2012	10190564	FP01	60M	10-2-2012	10-2-2012	10-2-2012	5197228	323	10-2-2012				22-2-2012	10-2-2012	10-2-2012	13-2-2012	15-2-2012	17-2-2012	0
23-5-2012	10199372	FP02	22E	24-5-2012	23-5-2012	1-6-2012	5205372	323	24-5-2012				13-11-2012	24-5-2012	13-7-2012	13-7-2012	30-5-2012	13-7-2012	1
23-12-2012	10217062	FP03	60M	27-12-2012	4-1-2013	11-1-2013	5222578	546	4-1-2013	28-12-2012	3-1-2013	3-1-2013		3-1-2013	11-1-2013	28-1-2013	4-1-2013	28-1-2013	1
5-3-2012	10192720	FP03	23M	6-3-2012	5-3-2012	12-3-2012	5199254	322	5-3-2012			5-3-2012	13-3-2012	5-3-2012	6-3-2012	13-3-2012	5-3-2012	13-3-2012	1
13-3-2012	10193338	FP03	60E	13-3-2012	13-3-2012	20-3-2012	5199848	322	13-3-2012			13-3-2012	6-9-2012	13-3-2012	18-6-2012	26-6-2012	13-3-2012	26-6-2012	1
1-2-2012	10189420	FP03	60I	30-3-2012	30-3-2012	6-4-2012	5201173	322	30-3-2012			30-3-2012	22-8-2012	30-3-2012	3-4-2012	23-4-2012	3-4-2012	23-4-2012	1
16-4-2012	10196204	FP03	40	16-4-2012	16-4-2012	23-4-2012	5202568	322	16-4-2012			16-4-2012	16-4-2012	16-4-2012	16-4-2012	27-4-2012	16-4-2012	27-4-2012	1
9-8-2012	10205528	FP03	60A	10-8-2012	20-8-2012	10-9-2012	5211582	722	13-8-2012			16-8-2012	16-8-2012	20-8-2012	22-8-2012	21-9-2012	22-8-2012	21-9-2012	2
21-12-2012	10216996	FP03	23M		26-12-2012	26-12-2012	5217445	532	28-10-2012			29-10-2012	29-10-2012	2-11-2012	21-12-2012	28-12-2012	21-12-2012	28-12-2012	P
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Note 1: In the original zpm_stat_list, a small description of the discovered problem (i.e. the short text of the notification) was depicted between column two and three. This column is removed because the content does not give information about what spare part was unavailable which caused the work order to be late.

Note 2: Between column three and four (for the notification) and after column 20 (for the work order) originally there were columns which depicted the code of the local technical service plant. However from 2007, SABIC Geleen decided to use one central technical service. Because SABIC Geleen does not use the local technical service plant coding anymore, the columns were removed from the original zpm_stat_list.

Note 3: Between column four and five there was originally a column which indicated the priority of the notification. However, because this should be per definition the same priority as the one depicted in the order in column twenty (Prio Ordr), this content does not give new information and is therefore deleted from the dataset.

Note 4: The planner group of the notification, which was originally between column five and six because the planner group of the notification should per definition be the same as the planner group of the order (column nine). Therefore this content does not give new information and is therefore deleted from the dataset.

Note 5: Between column six and seven, originally the required end date was indicated. This date was based on the priority of the notification. It appeared that, on average in 1.4% of the work orders the required end had a value whereas there was no value filled in in the basic finish date column. For these orders we chose to cut the value of the required end date and paste it in the basic finish date cell. Because the required end date should be per definition the same as the basic finish date of the order (and the basic finish date is almost never changed) we chose to remove the column of the required end date because the information does not add additional value.

Note 6: Between column seven and eight, originally the order types were depicted (i.e. one could conclude from these order types whether the order concerned a corrective or preventive maintenance activity or a technical or technological change). This information is however already contributed in column four (the coding of the maintenance activity) and therefore the column was removed from the zpm_stat_list.

Note 7: Between column nine and ten originally the order plan indicator was depicted. This indicated whether the scheduling was done with the Primavera scheduling tool or not. This content does not reveal useful information of the causes why a work order was late and therefore the column was deleted from the zpm_stat_list.

Note 8: Originally column eighteen (Date Start) was called Date WIP which indicated the moment at which the work order was in the schedule and could be started. However, because this does not give us information on the exact start date of the maintenance activities the date is adjusted by the actual start date (e.g. the moment of preparing the work order).

Note 9: After column 19 there were additionally three columns which indicated a finish date of the maintenance activities (i.e. Date user technical complete, system technical complete and the completion date). The approval date by production indicates the earliest date for which the maintenance activity is finished and the system is able to perform with full integrity from there one. Post-maintenance activities such as scaffolding or installation of the insulation are not finished but they do not affect the integrity of the system. When the approval date was not filled in whereas the completion date was (on average 11%), these values were cut and paste in the empty approval date cell and thereafter the columns with the completion dates were deleted from the zpm_stat_list because they did not contain new information.

Table 48: Definition list of the columns of the zpm_stat_list data

# of the column	Name of the column	Definition of the column	Options and clarifications
1.	Date	Date at which the notification is created	n/a
2.	Notifictn	Number of the notification	This number could be filled in into the SAP system (iw23: display notification) to reveal more information (e.g. Long description of the problem)
3.	MntPlant	Code of the plant	• FP01: High Density Poly Ethylene plants (LD3 and LD4) • FP02: UH (regards a plant owned by DSM but maintenance is done by SABIC Geleen because of economies of scale and realizing full time equivalent jobs of the maintenance specialist • FP03: Low Density Poly Ethylene (S15, S16, and S17) • FP04: Site Logistics Poly Olefins (regards the conveyer belts for transportation of the plastic pellets and the machines for filling the big bags • FP05: Polypropylene plants (PPF3 and PPF6) • FP06: Naphtha cracker 3 (NAK3) • FP07: Naphtha cracker 4 (NAK4) • FP08: Logistics (regards the transportation of liquids and gasses in and between the different plants owned by SABIC Geleen at the Chemelot site, as well as the storage tanks
4.	Coding	Code of the maintenance activity	• 21: an inspection • 22: a repair to the system which was perceived during inspection • 23: periodical maintenance activity (except inspections) • 24: planned non-maintenance related activity (e.g. cleaning the reactor on a planned basis) • 30: technical improvement • 40: non-maintenance related activities (i.e. Management of Change) • 60: breakdown maintenance activity • 67: unplanned non-maintenance related activity (e.g. cleaning the reactor on an unplanned basis) Note that categories 21, 22, 23, 30 and 60 make a distinction between maintenance activities related to automation (A), electrical (E), instrumentation (I), and mechanical (M) maintenance activities
5.	Date NIPR	Date at which the notification is handled in the gatekeeping process	See for more information on the gatekeeping process section 5.2
6.	Req. start	Desired start date of the maintenance activities	The date is dependent on the chosen priority. Maintenance activities may be started earlier or later than the desired date
7.	Basic fin.	Desired finish date of the maintenance activities	The date is dependent on the chosen priority. Maintenance activities may be finished earlier than the desired date, but they need to be finished before the desired date (hard deadline)
8.	Order	Number of the work order	This number could be filled in into the SAP system (iw33: display order) to reveal more information
9.	PlGrp Ordr	Code of the planner group of the work order	The code of the planner group indicates the different parties who are authorized to perform the maintenance activities: • 200 series: preventive yearly work orders which should be performed by internal maintenance personnel • 300 series: maintenance activities regarding priority 0 and 1 for the polymers plants (FP01 – FP05) • 400 series: maintenance activities regarding priority 0 and 1 for the Chemical & Intermediates plants (FP06 – FP08) • 500 series: maintenance activities regarding priority 2, 3, and p (preventive) for the polymers plants (FP01 – FP05) • 600 series: maintenance activities regarding priority 2, 3, and p (preventive) for the Chemical & Intermediates plants (FP06 – FP08) • 700: preventive yearly work orders which should be performed by an external maintenance party • 700 series (except 700): maintenance activities performed by external maintenance parties (except the yearly work orders)
10.	Date WOOP	Date at which the notification is transformed into a work order	n/a

# of the column	Name of the column	Definition of the column	Options and clarification
11.	Date TOS	Date for which a demand for a Technical Mission Statement occurred	If the maintenance activities are so complex that the maintenance employees cannot perform the maintenance activities without technical support, this is developed by the Maintenance Engineers
12.	Tos Del	Date for which the Technical Mission Statement is finished	n/a
13.	Date PLND	Date for which the work order is ready to be budgeted	The order receives a budget authorization before the activities are allowed to start. Note that for work orders with a high priority (i.e. priority 0 or 1) the budget authorization might be after the actual finish date because these orders need immediate attention to solve the breakdown or malfunction as quickly as possible (the main issues for orders with such a priority are not budget related)
14.	Date PERM	Date for which the work order is authorized	The order receives an authorization by the operation specialist or the execution responsible
15.	Date RTBS	Date for which the work order is ready to be scheduled	n/a
16.	Date WFMA	Date for which a demand for a material or service occurred	n/a
17.	WFMA Del	Date for which the material was delivered or the service was completed	This date indicates the moment when the material is physically available at the warehouse and could be picked up by a maintenance employee to use
18	Date Start	Date for which the maintenance activities were actually started	The date includes preparatory activities like scaffolding or removal of the insulation
19.	Date ABPR	Date for which the maintenance activities were actually finished	n/a
20.	Prio Ordr	Priority of the work order	• 0: corrective maintenance with the highest priority (the maintenance activities should be performed as soon as possible, even in night or weekend shifts) • 1: corrective maintenance where the activities should be performed within five work days • 2: corrective maintenance where the activities should be performed between five and twenty work days • 3: corrective maintenance where the activities should be performed before 180 calendar days (approximately 6 months) • p: preventive maintenance activity Note: SABIC Geleen assumes that per definition all corrective maintenance activities are able to be finished within six months

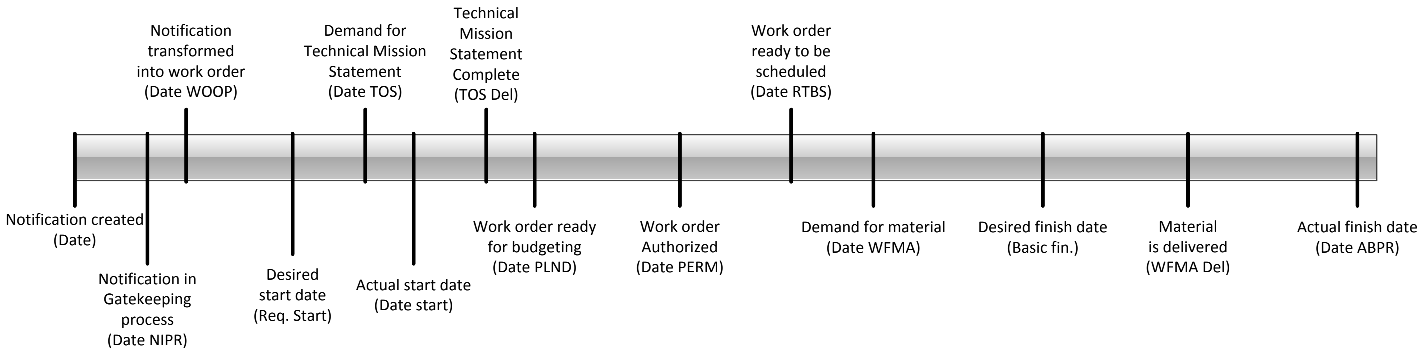

Figure 28: Chronological depiction of the notification and work orders and the statuses as depicted in the zpm_stat_list

APPENDIX D – SUBSET OF ASSET UTILIZATION DATA INCLUDING A DEFINITION LIST

Table 49: Subset of the data of the year 2012 as retrieved from the PROMISE asset utilization database of SABIC Geleen

Plant	StartTime	EndTime	Product	AllocatedAPL	Stoplength	Cause	SubCause	Remark
LD3	12-4-2012			135		Equipment Failure	Equipment Failure	Delivery time of the failed equipment was too long
UH	jun-12	jun-12		55.6				Destillation reduced from C5603 to C5604 because of a failed fuse
S15	2-1-2012 7:00	9-1-2012 7:00	Stamylan	44	0	Product Quality	Product Quality	
S15	3-1-2012 15:48	4-1-2012 23:22	STOP	32.55	180	People, Procedures & Training	PP&T Maintenance	Defect valves 15K102, wrongly assembled during stop
S15	1-6-2012 21:51	3-6-2012 1:53	STOP	108.5	600	People, Procedures & Training	PP&T Maintenance	Spare part unavailable, speedlimiter failed because of stop
...	...	...	...	...	...	...	...	...

Table 50: Definition list of the columns of the PROMISE asset utilization data

# of the column	Name of the column	Definition of the column	Options and clarifications
1.	Plant	Name of the plant	• FP01: LD3, LD4 • FP02: UH • FP03: S15, S16, S17 • FP04: 16X, 17X, 18X, 28X, 84X • FP05: PPF3, PPF6 • FP06: NAK3 • FP07: NAK4 • FP08: Log
2.	StartTime	Date at which the problem first occurred	Note that for a non-stop related breakdown or malfunction the first work day of the week at which the problem occurred is indicated
3.	EndTime	Date at which the problem is solved	Note that for a non-stop related breakdown or malfunction the first work day of the week after the StartTime is indicated. This date is only applicable for S15, S16, S17 (FP03) because of a more automated PROMISE system.
4.	Product	Distinction whether maintenance could be done during production or that the maintenance activities are stop related	• Production: the breakdown or malfunction could be solved while still producing • Stop: (part of) the system should be stopped in order to do the maintenance activities This information is only applicable for S15, S16, S17 (FP03) because of a more automated PROMISE system
5.	Allocated APL	Allocated production loss (in tons)	The amount of product lost because of the malfunction or breakdown
6.	Stoplength	Time that the system was stopped because of solving the breakdown or malfunction (in minutes)	Note that this is only applicable when the maintenance activity was stop related and only for S15, S16, S17 (FP03) because of a more automated PROMISE system
7.	Cause	Cause of the breakdown or malfunction	e.g. Equipment failure; lack of personnel; people, procedures & training (PP&T), etc.
8.	SubCause	More details on the cause of breakdown or malfunction	n/a
9.	Remark	Description of taken (maintenance) actions or findings	n/a

APPENDIX E – CLEANING AND FILTERING THE ZPM_STAT_LIST

It was mentioned by several Maintenance and Reliability Engineers of the Site Improvement Polymers department that one should take into account that the conclusions based on the zpm_stat_list are only as reliable as the underlying data. The engineers and the key instructor SAP mentioned that the data could be filled in wrongly by the responsible persons. The feeling of them is that this could be a significant amount of data, which gives us a reason for checking and cleaning the dataset. We then have the most reliable dataset as possible to base the analysis on. Furthermore, because we deal with a vast amount of work orders of 2012 for all eight types of factories ([redacted] work orders), we need to filter the dataset based on work orders which are delayed because of spare part unavailability. In order to select a subset of work orders which were delayed most because of spare part unavailability, we use the following selection criterion:

$$\begin{aligned} &percentage\ (\#\ of\ work\ orders\ of\ a\ category\ /\ total\ \#\ of\ work\ orders) \\ &\qquad * mean\ delay\ of\ the\ unavailability\ of\ a\ maintenance\ code\ (days) \end{aligned} \tag{E.1}$$

where the delay of the work orders is calculated as follows:

$$\begin{aligned} &Delay = Date\ ABPR - Basic\ finish\ date && if\ Date\ ABPR > Basic\ finish\ date \\ &Delay = 0 && if\ Date\ ABPR\ \leq Basic\ finish\ date \end{aligned} \tag{E.2}$$

The work orders which score highest on the criterion are selected for further analysis.

The following steps were undertaken to make the data as reliable as possible, which took about four full time work weeks (see Table 51 for the amount of work orders remaining after each cleaning and filtering step):

- Check if a notification resulted in a work order: if the problem or malfunction depicted in the zpm_stat_list did not have a corresponding order number, the notification was not transferred into a work order. The necessary information is not available and these data points are deleted from the dataset.
- Check if a work order appeared more than once in the zpm_stat_list: if these orders were retained, the effect of some orders would be incorrectly larger than work orders that appear once in the zpm_stat_list because of a larger frequency which results in an invalid analysis. In order to ascertain a valid analysis, of all work orders which appeared more than once, only the first data point is retained.
- Check the work orders which had no filled-in basic finish date: if an order had no basic finish date filled-in, whereas the required end date of the notification was filled-in, this value was adopted because per definition they should be the same. If the notification also had no filled-in finish date, SABIC Geleen does not require a finish date which means that the priority of the notification and the corresponding work order are very low. These work orders are not included in the analysis as it is not possible to determine the amount of delay of the work order. In order to filter only the work orders which have a very low priority, the basic finish date should be checked.
- Filter the data based on the removal of orders without a material demand: because we want to measure the impact of delay of work orders because of spare part unavailability, we should include only work orders with a demand for spare parts.
- Check the work orders which had no filled-in approval date: if a work order does not have a filled-in approval date, the order is assumed to be still active (i.e. maintenance activities are not finished). In order to correctly classify orders which are still active, we need to check whether the work order is still open. We do this by checking for these orders whether the order did have a completion date. If this was the case, this date is assumed to also be the approval date of the work order. The missing value of an approval date while the maintenance activities are already finish could be because the system did not log the approval date because the order was not saved in the SAP system after changing the status of the order. According to the key instructor SAP, after changing a status, intermediately the work

order should be saved to be able to log the change in the status. Checking the approval date was done by manually filling in the order number in the display order screen of the SAP system (iw33: display order), using the action log of the work order (tab extras, documents for order, action log). This method is however inconclusive. Therefore the approval date is double checked by looking at the actual end date (in the header tab) and by looking at the final inspection dates by production in the operations tab.

- Filter the data based on the removal of yearly work orders: a yearly work order is an order which demands for a maintenance job to be done on a yearly returning basis (e.g. visually inspect the gearbox on a weekly basis). The difficulty in analyzing these orders is that they are created and opened on January 1st and closed on December 31st of the same year (in this case 2012). However, there is no status in the zpm_stat_list which is able to indicate whether the activity (e.g. weekly inspection) has been performed on time.
- Check and validate the work orders on coding: in order to minimize the effects of using wrongly filled in data, all filtered orders were checked manually on mistakes or erroneous data points. First the code of the notification is checked manually for missing values (iw23: display notification). If the coding was not filled in, the corresponding order was checked for a code. We also validated the codes on an erroneous value, because it appeared that some inspections (which should receive a 21 code) had the wrong code (for example 23).
- Check and validate the delivery dates: the posting date of the material was checked in the SAP system (components tab: purchasing data, purchase requisition, purchase document, goods receipt). If the material is already delivered, the posting date from the goods receipt document is adopted in the zpm_stat_list.
- Check and validate the actual start date: orders with a missing start date were checked manually to see when the maintenance activities were started. This was checked in the header data tab (iw33: display order) in the actual starting date field or by looking in the operations tab for the work order preparation activity date if the actual starting date field was not filled-in.
- Check and validate the actual finish date: the filled-in approval date (from the action log or from the operations tab) may be incorrect. This is because these dates indicate the planned finish date instead of the actual finish date of the maintenance activities. The problem with the planned finish date is that it could be that the order was already approved by production according to the action log, but the (urgency) ordered materials were not yet delivered (as could be seen in the components tab). It is unlikely that one orders material to do maintenance activities and the approval date of the order is before the posting date of the material. If it was the case that the posting date was after the approval date whereas it appeared from the short or long text in the notification that the material was needed for doing the maintenance activity, the posting date of the material is chosen as the approval date of the work order. The logic behind this is that for a lot of work orders the maintenance activities are finished the same day as they are started. Furthermore, the postal date is the only date which is known for which the maintenance activities could be finished. We should note therefore that the assumed approval date is a lower bound of the actual finish date.

After we have determined the work orders which remain after all the cleaning and filtering steps, it is determined how much of these orders are too late (i.e. are not finished before or on the basic finish date) according to formula 2.3.

The work orders which were indicated as too late are further investigated by manually inserting them in the SAP system (iw33: display order). In the header tab, the scheduled start and finish date are depicted. We compared the actual finish date of the orders which were categorized as too late with the schedule finish date (see the amount of orders which also did not meet the schedule finish date in column 10 of Table 51). These work orders are the topic of further investigation.

Table 51: number of work orders remaining after cleaning and filtering the data. Note that the number of remaining work orders is cumulative (i.e. the number of orders remaining from the former step serves as a starting point for the current step)

Plant	Initial # of work orders	# of work orders remaining after removal work orders without order number	# of work orders remaining after removal work orders which appeared more than once in the zpm_stat_list (only the first data point is retained)	# of work orders remaining after filtering work orders without a required end date	# of work orders remaining after filtering work orders without a demand for material	# of work orders remaining after filtering work orders without an approval date	# of work orders remaining after filtering yearly work orders	# of work orders too late	# of work orders which also did not meet the scheduled finish date
FP01	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP02	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP03	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP04	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP05	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP06	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP07	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
FP08	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Appendix F – Explanation of the main steps of the Analytical Hierarchy Process when selecting a supplier

F 1. Determine the level of buyer-supplier integration

The level of buyer-supplier integration defines which criteria are important to define for selecting a supplier. Buyer-supplier integration strategies are defined on five levels (Ghodsypour & O'Brien, 1996):

- Level 1: at this level no integration between the buyer and the supplier is desired,
- Level 2: at this level logistical integration between the buyer and supplier exist, and the supplier has a direct role in the competitiveness of the buyer,
- Level 3: at this level operational integration is defined. For achieving this level of buyer-supplier integration, not only the output characteristics of the supplier should be considered, but also the way in which the services are provided (e.g. the flexibility of the production line or the quality of the produced products),
- Level 4: at this level the integration of the buyer's process and products with those of the supplier is desired, and
- Level 5: a business partnership is desired at this level of integration, which means that strategic directions of the suppliers become very important for the buying party.

F 2. Define the criteria for supplier selection

The determination of which selection criteria are important for selecting a supplier are directly related to the level of buyer-supplier integration, i.e. at a higher integration level, more strategic criteria are becoming more important to base the selection of a supplier on. For the five integration levels described in section F 1, the following variables could be included as a selection criterion for deciding which supplier is chosen for supplying the spare part. Note that the number of criteria is cumulative, i.e. the criteria of a former level also need to be taken into account. Determining what criteria should be included for deciding which supplier should be selected is specific for each company and dependent on the perceived importance of a criterion by management. Ghodsypour and O'Brien (1996) defined the following criteria as a baseline to determine the selection process on:

- Level 1: price and quality are the most important criteria for selecting a supplier,
- Level 2: importance is given to the suppliers' logistical performance. Besides price and quality, also delivery flexibility (e.g. urgently delivering spares) , minimum order sizes, supply lead times, and supply lead time reliability (i.e. what fraction of time the promised supply lead time is actually realized) (operational logistical elements) should be considered in the supplier selection process,
- Level 3: at this level, not only the logistical performance is considered, but also the way in which the performance is achieved (suppliers' process capabilities like set up time) should be considered in the assessment process,
- Level 4: design involvement, management ability, culture (supplier's human resources) should be taken into account in this level of integration, and
- Level 5: for this level of integration, also the fit between strategic decisions of the supplier and SABIC Geleen (like corporate integration strategy) need to be taken into account, besides the technological (level 1 to level 3) and human resources criteria (level 4) of the former levels.

F 3. Calculate the weights of the criteria

After it is determined what criteria are included in the supplier selection process, the criteria should be weighted based upon the relative importance of a criterion compared to other criteria, i.e. pairwise comparison. For quantitative criteria, the weights of the criteria are normalized, i.e. determined by calculating the relative importance compared with other criteria and the sum of all criteria weight factors add to one (so that the weight of each criteria is easy to understand). For qualitative criteria, Saaty and Alexander (1981) developed a scale from 1 to 9 which indicates the judgment of preference of one option compared to another option (see Table 52). Note that if one criterion, i, has a numerical rate assigned to it when compared with another criterion, j, then j has the reciprocal value when compared with criterion i. If all criteria are pairwise compared, also then the weights could be determined by normalization.

Table 52: Saaty's 1 - 9 scale for AHP preference (Source: Saaty & Alexander, 1981)

Verbal judgment of preference	Numerical rate
Equal importance	1
Weak importance of one over another	3
Essential or strong importance	5
Demonstrated importance	7
Absolute importance	9
Intermediate values between the two adjacent judgments	2,4,6,8

The weights of the criteria are then determined by calculating the eigenvalue. The eigenvalue is calculated by the following algorithm:

Step 1: Squaring the pairwise comparison matrix (i.e. multiply each row with each column of the matrix and add the scores),

Step 2: Calculate the row sums (adding the values of all cells in a row of the squared matrix) and normalize them, i.e. give the criteria a weight between zero and one, where the total of the weight factors adds to one,

Step 3: Repeat step 1 and step 2.

If: the difference between the eigenvalues in two consecutive iterations is bigger than a set threshold value return to *step 1*,

Else: stop.

The eigenvalues of the criteria are the weights of the criteria for selecting a supplier.

F 3.1. Example calculating the criteria weights

First, the pairwise comparison matrix has to be determined where each criterion is compared with all other criteria (see Table 53 for an example of a pairwise comparison matrix for the determination of the importance of each criterion for supplying furnace pipes to SABIC Geleen).

Table 53: example pairwise comparison matrix for supplying furnace pipes to SABIC Geleen

	Stability	Presence	Dependence	Quality	Capability	Insurance	Experience/ references	Credentials	Analysis	Cost/value	Safety, Health, and Environment	Lead time	Miscellaneous
Stability	1.00	1.00	2.00	0.50	1.00	2.00	2.00	2.00	2.00	0.50	1.00	0.50	2.00
Presence	1.00	1.00	2.00	0.50	1.00	2.00	2.00	2.00	2.00	0.50	1.00	0.50	2.00
Dependence	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Quality	2.00	2.00	4.00	1.00	2.00	4.00	4.00	4.00	4.00	1.00	2.00	1.00	4.00
Capability	1.00	1.00	2.00	0.50	1.00	2.00	2.00	2.00	2.00	0.50	1.00	0.50	2.00
Insurance	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Experience/ references	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Credentials	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Analysis	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00
Cost/value	2.00	2.00	4.00	1.00	2.00	4.00	4.00	4.00	4.00	1.00	2.00	1.00	4.00
Safety, Health, and Environment	1.00	1.00	2.00	0.50	1.00	2.00	2.00	2.00	2.00	0.50	1.00	0.50	2.00
Lead time	2.00	2.00	4.00	1.00	2.00	4.00	4.00	4.00	4.00	1.00	2.00	1.00	4.00
Miscellaneous	0.50	0.50	1.00	0.25	0.50	1.00	1.00	1.00	1.00	0.25	0.50	0.25	1.00

Then the first step of the algorithm described in section F3 should be performed. The matrix has to be squared and normalized in order to arrive at eigenvalues which depict the relative importance of each criterion, where each score is between zero and one, and where the sum of all eigenvalues adds to one. For the supply of furnace pipes the following criteria weights are found (see Table 54):

Table 54: example criterion weight factors for supplying furnace pipes to SABIC Geleen

Criterion	Criterion weight factor
Stability	0.0769
Presence	0.0769
Dependence	0.0384
Quality	0.1538
Capability	0.0769
Insurance	0.0384
Experience/references	0.0384
Credentials	0.0384
Analysis	0.0384
Cost/value	0.1538
Safety, Health, and Environment	0.0769
Lead time	0.1538
Miscellaneous	0.0384

The steps described above (squaring the matrix and normalize the scores) should be repeated as long as the difference between the new eigenvalue scores and the former eigenvalue scores is larger than a preset threshold value. For our example, the criterion weight factors after the second iteration are exactly the same as after the first iteration, so the found criterion weight factors (indicated in Table 54) are the final solution. For our example, we see that quality, cost/value, and lead time are the most important criteria to ultimately decide which supplier is allowed to deliver the furnace pipes to SABIC Geleen.

F 4. RATE THE ALTERNATIVE SUPPLIERS

After the weigh factor of each criterion is determined, SABIC Geleen could choose on which criteria potential suppliers are rated. For the example of the furnace pipes, SABIC Geleen should choose to rate potential suppliers on the delivered product quality, cost/value, and the promised lead time. However, because SABIC Geleen does not make concessions regarding product quality, this criterion is not included for rating potential suppliers. To determine the score of a potential supplier on the chosen criteria, for each criterion a pairwise comparison matrix should be determined. Using the algorithm described in section F 3 determines the score of a potential supplier on each criterion.

F 5. COMPUTE THE OVERALL SCORE OF EACH SUPPLIER AND SELECT THE SUPPLIER WITH THE HIGHEST OVERALL SCORE

The weight factors for the criteria, determined in section F 3, and the scores of potential suppliers on the criterion, determined in section F 4, determines the overall score of a supplier. The score of a potential supplier on a criterion should be multiplied with the criterion weight for that criterion to arrive at a weighted average score for each supplier.

However, only using scores and ignoring the costs might not provide you with the most efficient solution (e.g. the shortest lead time is achieved at very high costs, whereas a little longer lead time costs much less). Haas and Meixner (2006) propose to include costs after the benefits of the alternatives are evaluated. The costs should also be normalized (a relative number between zero and one, where the weights add up to one) in order to compare the costs with the benefits (in our example lead time). The benefit value should be divided by the cost value to come up with a benefit-cost ratio. The highest benefit-cost ratio indicates the best supplier because it provides the highest benefits compared to its costs and should therefore be selected as a supplier for the spare part.

APPENDIX G – EXPLANATION OF THE ITEM APPROACH AND GREEDY ALGORITHM

G 1. MODEL DESCRIPTION AND ASSUMPTIONS

For explaining the item approach, we consider a single component. If the components fail, the equipment is assumed to go down potentially resulting in long downtimes when spare parts are not immediately available. In order to prevent long downtimes due to long repair or delivery lead times, spare parts should be available when the component fails. The maximum stock level of component i is indicated by S_i, and the price of component i is denoted by c_i, expressed in Euros.

Failures of component i are assumed to occur according to a Poisson process with constant rate m_i (lifetimes of the components are negative exponentially distributed and failures can occur when the system is out of operation), which is valid to assume for components with a relatively high price and relatively low demand values, e.g. spare parts (Louit et al., 2011). Furthermore, when the number of technical systems is high, the total demand process for all components, which do not have negative exponentially distributed lifetimes, converges rapidly into a Poisson process, independently of the underlying time to failure distribution. Therefore, the use of a Poisson distribution in spare parts inventory modeling has found wide application (Louit et al., 2011).

If a ready-for-use component is available when a component fails, the defective component is replaced by a new spare part (in a negligible amount of time) and the defective spare part is sent to the repair shop. It is assumed in the item approach that all defective components can be repaired. The assumption that a failed item can always be repaired is not valid for SABIC Geleen (e.g. consumption material like rubber seals cannot be repaired after failure). If the assumption does not hold, one is allowed to relax this assumption by assuming that a new part is procured in case repair is not possible for a failed part.

Another assumption of the item approach is that the repair lead times for a component are independent, i.e. the capacity of the repair shop is assumed to be infinite. This assumption holds for SABIC Geleen because multiple maintenance parties (internally or externally) have the knowledge and resources to repair the spare part. One should note that the repair lead times are seen as delivery lead times in the item approach.

If component i is repaired, it is placed back in the stock on hand (OH_i). The repair and distribution structure of the item approach implies a one-for-one replenishment policy (also known as continuous base-stock policy) ($S_i - 1, S_i$), which is a reasonable assumption for relatively expensive components. If there is not sufficient stock on hand to meet the demand for the component, the request for the ready-for-use spare part is backordered (BO_i). The objective of the item approach is to determine the base-stock level S_i of component i, such that the target fill rate is met, where the target fill rate is defined as the probability of not running out of spare parts stock when a failure occurs (Cavalieri et al., 2008).

Concluding, the following assumptions are determined in the item approach:

1. Failures of the component occurs according to an independent Poisson process with a constant rate, which holds for spare parts
2. All defective components can be repaired or if not, a new component is procured,
3. The repair shop has ample capacity, i.e. is considered to be an infinite server, which holds for SABIC Geleen because multiple maintenance parties have resources and knowledge to repair the component, and
4. A one-for-one replenishment policy is applied for the component, which is a justified assumption for relatively expensive components.

G 2. DETERMINATION OF THE SYSTEM AVAILABILITY

Initially, we have S_i spare parts of component i in stock. The number of items in repair is indicated as the number 'due in' of component i and is denoted by DI_i, also referred to as pipeline stock. The following stock balance equation holds:

$$S_i = OH_i + DI_i - BO_i \tag{G.1}$$

Because the assumptions that failures of components occur according to a Poisson process and the ample capacity of the repair shop the theorem of Palm holds.

Using Palm's theorem, we can derive the distributions of the amount of components due in. From this distribution the backorder probability for a component can be defined:

$$PBO_i(S_i) = P(BO_i > 0) = P(DI_i > S_i)$$

$$= \sum_{x=S_i+1}^{\infty} P(DI_i = x) = 1 - \sum_{x=0}^{S_i} P(DI_i = x) \tag{G.2}$$

where $P(DI_i = x)$ indicates the probability that the amount of component i in the repair shop is equal to x.

Because of Palm's theorem, the probability of $x$components 'due in' is described as:

$$P(DI_i = x) = \frac{(m_i ET_i)^x}{x!} e^{-m_i ET_i} \tag{G.3}$$

which leads to the derivation of the fill rate of component i by summing the probability of a due in for each x until the base-stock level minus one :

$$\beta_i(S_i) = \sum_{x=0}^{S_i-1} P(DI_i = x) \tag{G.4}$$

G 3. ALLOCATION PROCEDURE

The objective of the allocation procedure is to determine the base stock level S_i of component i such that the actual fill rate at least meets the target fill rate (β_0) which is formulated as:

$$\beta_i(S_i) \geq \beta_0 \tag{G.5}$$

$$S_i \in \mathbb{N}_0 \tag{G.6}$$

where $\mathbb{N}_0 = \{0,1,2, \dots\}$.

The procedure is carried out until the fill rate of the component meets or exceeds the target fill rate. The formal procedure is described in algorithm G1.

Algorithm G1.: Allocation process for the single item single indenture model

Step 1: $Set\ S_i = 0$

$$Compute\ P(DI_i = x) := (m_i ET_i)^x/(x!))\exp\{-m_i ET_i\}, for\ x \in \{0,1,2, \dots\}$$

$$Compute\ \beta_i(S_i) := \sum_{x=0}^{S_i-1} P(DI_i = x)$$

$Compute\ \hat{C} := c_i S_i$

Step 2: $If\ \beta_i(S_i) < \beta_0$

$then$

$S_i := S_i + 1$

$$Compute\ \beta_i(S_i) := \sum_{x=0}^{S_i-1} P(DI_i = x)$$

$Compute\ \hat{C} := c_i S_i$

$else\ stop$

APPENDIX H – EXPLANATION OF THE CURRENT DETERMINATION OF THE REORDER POINT

SABIC Geleen currently uses the following procedure for calculating the reorder point (Approved Best Practice 133, SABIC Europe Intranet, 2009):

- Remove the peak consumption from the historic consumption, i.e. if a consumption for a particular month is more than two times the average consumption per month over the complete consumption history, the consumption value is removed,
- The consumption of a component is defined over a moving window of time, equal to the delivery lead time of the component during the component consumption history, e.g. if the delivery lead time of a component is equal to two months, the consumption is calculated by summing two months of demand over a rolling horizon equal to the consumption history of the component, and finally
- The consumption with the highest value during the consumption history of the component is determined to be the reorder point of the component

H 1. EXAMPLE OF THE CURRENT DETERMINATION OF THE REORDER POINT

In order to explain the determination of the reorder point, we apply the procedure of Appendix H to an example. We first need to remove the peak consumption value from the demand data. See Table 55 for the demand values of the consumption history. We examine a component, e.g. a seal, which is introduced in January 2011 and has a lead time of three months.

Table 55: demand values during the consumption history of a seal of SABIC Geleen

Year/Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2011	0	0	0	0	1	0	0	5	0	0	3	0
2012	0	1	1	0	0	0	0	0	0	2	0	1

Step 1: determine the average consumption during the consumption history.

$$Average\ consumption = \frac{sum\ consumption\ values\ over\ the\ consumption\ history}{total\ number\ of\ months\ in\ the\ consumption\ history}$$

$$= \frac{0 + 0 + \cdots + 0 + 1}{24}$$

$$= \frac{14}{24} \approx 1$$

Step 2: remove the peak consumption from the historic consumption.

If the consumption is more than 2, the consumption value is removed from the dataset. This means that the consumption of August 2011, November 2011, and October 2012 are deleted from the dataset.

Step 3: determine the consumption during the lead time over a rolling horizon during the consumption history

For three months, i.e. the lead time of the seal, the consumption is summed. This is done for a rolling horizon during the consumption history (i.e. first the demand values of January, February, and March 2011 are summed, then February, March, and April 2011 are summed, until October, November, and December 2012 are summed). See Table 56 for the summed consumption values during the consumption history

Table 56: summed consumption values of the seal of SABIC Geleen over a rolling horizon during the consumption history

Months of the rolling horizon	Summed consumption values
Jan., Feb., and Mar. 2011	0
Feb., Mar., and Apr., 2011	0
Mar., Apr., and May 2011	1
Apr., May, and June 2011	1
May, June, and July 2011	1
June, July, and Aug. 2011	0
July, Aug., and Sept. 2011	0
Aug., Sept., and Oct. 2011	0
Sept., Oct., and Nov. 2011	0
Oct., Nov., and Dec. 2011	0
Nov., Dec. 2011, and Jan. 2012	0
Dec. 2011, and Jan., and Feb. 2012	1
Jan., Feb., and Mar. 2012	2
Feb., Mar., and Apr., 2012	2
Mar., Apr., and May 2012	1
Apr., May, and June 2012	0
May, June, and July 2012	0
June, July, and Aug. 2012	0
July, Aug., and Sept. 2012	0
Aug., Sept., and Oct. 2012	2
Sept., Oct., and Nov. 2012	2
Oct., Nov., and Dec. 2012	3

Step 4: Determine the reorder point.

The maximum summed consumption value over a rolling horizon during the consumption history indicates the reorder point of the component. For our example, the maximum summed consumption over a rolling horizon is three, so the reorder point for the seal of SABIC Geleen should be determined to be three.

APPENDIX I – EXPLANATION OF THE MULTI-ECHELON TECHNIQUE FOR RECOVERABLE ITEM CONTROL (METRIC) MODEL

I 1. MODEL DESCRIPTION AND ASSUMPTIONS

For explaining the METRIC model, we consider an asset, consisting of I components, numbered from $1, \dots, I$. If one of these components fails, the complete equipment will go down and long downtimes may result. In order to prevent the long downtimes due to long repair or delivery lead times, spare parts should be available when a component fails. The number of spare parts for component i is indicated by S_i, and the price of component i is denoted by c_i, expressed in Euros.

For each component i, failures are assumed to occur according to a Poisson process with constant rate m_i (lifetimes of the components are negative exponentially distributed and failures can occur when the system is out of operation). If failures cannot occur when the system is down, it is still reasonable to assume this if the period in which the system is down is short and occurs only rarely which will be the case for sufficient values of the base-stock level. Furthermore, when the number of technical systems is high, the total demand process for all components converges rapidly into a Poisson process, independently of the underlying time to failure distribution. Therefore, the use of a Poisson distribution in spare parts inventory modeling has found wide application (Louit, Pascual, Banjevic & Jardine, 2011).

If a ready-for-use component is available when a component fails, the defective component is replaced, according to a First Come First Serve (FCFS) policy by a new spare part (in a negligible amount of time) and the defective spare part is sent to the repair shop. It is assumed in the METRIC-models that all defective components can be repaired and that the repair lead times T_i for component i are independent and identically distributed random variables. If the component is repaired, it is placed back in the stock on hand (OH_i). The repair and distribution structure of the METRIC model implies a one-for-one replenishment policy (also known as continuous base-stock policy) ($S_i - 1, S_i$). If there is not sufficient stock on hand to meet the demand for a spare part, the request for the ready-for-use spare part is backordered (BO_i). A limited budget C might be given in the METRIC model to invest in the spare parts. The objective of the model is to determine the base-stock levels $S_1, S_2, \dots, S_I$, such that the system availability ($A(\underline{S})$) is maximized, where the availability is defined as the expected percentage of time that the system is not down due to a lack of spare parts.

The following assumptions are determined in the METRIC-model:

1. Failures for different components occur according to independent Poisson processes with a constant rate,
2. All defective components can be repaired,
3. The repair shop has ample capacity, i.e. is considered to be an infinite server,
4. For each component, the repair lead times are independent and identically distributed random variables,
5. A one-for-one replenishment policy is applied for all components, and
6. The number of failures during each period is independent of the number of backorders (which is justified because an asset will almost never be completely down when a backorder occurs, e.g. because the maintenance employees are able (by some improvisation) to keep the system operating at a minimum level of performance and hence, failures of other components may still occur).

I 2. Determination of the system availability

Initially, we have S_i spare parts of component i. The number of items i in repair is indicated as the number 'due in' of component i and is denoted by DI_i, also referred to as pipeline stock. The following stock balance equation holds:

$$S_i = OH_i + DI_i - BO_i \tag{I.1}$$

Because the assumptions that failures of components occur according to a Poisson process and the ample capacity of the repair shop the queuing theory of Palm holds.

Using Palm's theorem, we can derive the distributions of the amount of components due in. From this distribution the backorder probability for component i could be defined:

$$PBO_i(S_i) = P(BO_i > 0) = P(DI_i > S_i)$$

$$= \sum_{x=S_i+1}^{\infty} P(DI_i = x) = 1 - \sum_{x=0}^{S_i} P(DI_i = x) \tag{I.2}$$

where $P(DI_i = x)$ indicates the probability that the amount of component i in the repair shop is equal to x.

Because of Palm's theorem, the backorder probability could be rewritten as:

$$PBO_i(S_i) = 1 - \frac{\sum_{x=0}^{S_i}(m_i ET_i)^x}{x!} e^{-m_i ET_i} \tag{I.3}$$

which leads to the derivation of the system availability by multiplying the individual product availabilities:

$$A(\underline{S}) = \prod_{i=1}^{I}\left(1 - PBO_i(S_i)\right) \tag{I.4}$$

where $\underline{S} = (S_1, S_2, \dots, S_I)$.

I 3. Allocation procedure

The objective of the allocation procedure is to determine the base stock levels $\underline{S} = (S_1, S_2, \dots, S_I)$ such that it minimizes the costs, under the constraint that the availability of the system should at least meet the target availability (A_0) which is formulated as the following linear integer programming problem:

$$\min \sum_{i=1}^{I} c_i S_i \tag{I.5}$$

subject to:

$$A(\underline{S}) \geq A_0 \tag{I.6}$$

$$S_i \in \mathbb{N}_0 \; for\; all\; i = 1, \dots, I$$

where $\mathbb{N}_0 = \{0,1,2, \dots\}$.

Rustenburg (2000) shows that if each component i is decreasing and convex as a function of S_i, a greedy approach can be applied to solve the problem. He determines that the component is decreasing and convex from:

$$S_i \geq \max\{\lceil m_i ET_i - 2\rceil, 0\} \; for\; all\; i = 1, \dots, I \tag{I.7}$$

This problem may be solved by using a greedy heuristic. First, the base-stock levels are set that they satisfy formula I.7, which determines the corresponding investment $\hat{C} = \sum_{i=1}^{I} c_i S_i$. For each associated component from the asset, the reduction in backorder probability per monetary value is calculated when the base-stock level for that component is increased by one, which is indicated by Δ_i:

$$\Delta_i = \big(PBO_i(S_i) - PBO_i(S_i + 1)\big)/c_i$$

The component with the highest Δ_i is selected for storage (i.e. a knapsack problem). The total costs will rise with c_i and the procedure is carried out until the availability of the system meets or exceeds the target availability. The formal procedure is described in algorithm I1.

Algorithm I1.: Allocation process for the METRIC model

Step 1: Set $S_i \coloneqq \max\{\lceil m_i ET_i - 2\rceil, 0\}\ for\ all\ i = 1, \dots, I$

$Compute\ PBO_i(S_i) \coloneqq 1 - \sum_{x=0}^{S_i} P(DI_i = x), where$

$P(DI_i = x) \coloneqq (m_i ET_i)^x/(x!))\exp\{-m_i ET_i\}, for\ x \in \{0,1,2, \dots\}$

$$Compute\ A(\underline{S}) \coloneqq \sum_{x=0}^{S_i} P(DI_i = x)$$

$$Compute\ \hat{C} \coloneqq \sum_{i=1}^{I} c_i S_i$$

Step 2: $\Delta_i \coloneqq \big(PBO_i(S_i) - PBO_i(S_i + 1)\big)/c_i\ for\ all\ i = 1, \dots, I$

$k = argmax\ \Delta_i\ for\ all\ i = 1, \dots, I$

Step 3: $If\ A(\underline{S}) < A_0$

$then$

$S_k \coloneqq S_k + 1$

$Compute\ A(\underline{S}) := \sum_{x=0}^{S_i} P(DI_i = x)$

$$Compute\ \hat{C} \coloneqq \sum_{i=1}^{I} c_i S_i$$

$else\ stop$