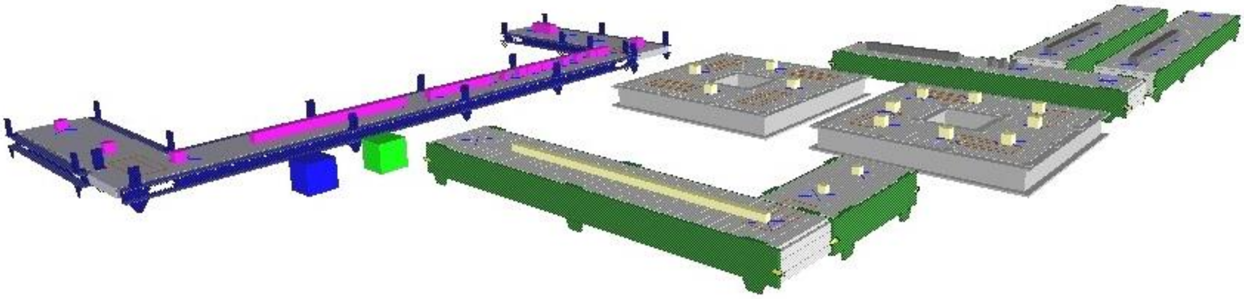

Quantifying effects of maintenance

Investigation on how to quantify effects of maintenance using discrete-event simulation

Master's thesis in Production Engineering

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Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2014

Quantifying the effects of maintenance

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Quantifying the effects of maintenance –
Investigation on how to quantify the effects of maintenance using a discrete-event simulation approach
Master of Science Thesis [Production Engineering, MPPEN]

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ABSTRACT

The use of simulation to analyze and plan maintenance activities is still limited in comparison with planning production activities. The aim of the thesis is to identify relevant Key Performance Indicators (KPIs) through interviews and to quantify these using discrete event simulation (DES). The approach is exemplified in a manufacturing case study, where the time for preventive maintenance (PM) and the need for corrective maintenance (CM) were analyzed at different time periods. Results of the manufacturing case study shows the complexity of PM and of mapping its effects. The result also shows the importance of understanding a system to find and eliminate root causes. In addition, two future scenarios were simulated. Future scenario 1 simulate the effect of increased operator involvement during corrective repairs. The result showed a potential increase in technical availability and lower maintenance costs. Future scenario 2 simulates the effect of increasing the reliability of the production system. The result showed that performing right and more PM have the potential of increasing technical availability and economical profit. In conclusion, this thesis shows that simulation has the potential to be a strategic decision support tool regarding maintenance in a production system.

Keywords: Maintenance, maintenance planning, maintenance decision support, discrete event simulation, key performance indicators

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Last but not least we would like to thank Johan Bengtsson from GTC for introducing us to this thesis and for spreading his energy and enthusiasm for improving maintenance activities.

Gothenburg, June 2014

Nadine Karlsson and Camilla Lundgren

Abbreviations

CM – Immediate corrective maintenance

CM by technician – Immediate corrective maintenance by technician during planned production

DES – Discrete-event simulation

Fault time – Unplanned downtime due to failure. Downtime logged by the software Axxos®

MTBF – Mean time between failures

MTTR – Mean time to restoration / Mean time to repair

MWT – Mean waiting time

MDT – Mean down time

OEE – Overall Equipment Effectiveness

PdM – Predictive maintenance

PM – Preventive maintenance

ROA – Return on assets

ROE – Return on equity

Total PM – Scheduled PM and service requests

TPM – Total productive maintenance

Scheduled PM – PM performed by operators and technicians on periodic and predetermined times during unplanned production

Service requests – PM performed by technician on unplanned production time

VDM – Value driven maintenance

Q - Quarter

CONTENTS

1. INTRODUCTION

Machine breakdowns resulting in system loss is one of the main reasons why Swedish manufacturing industry only utilizes 55% of existing production resources. Hence, there is a great potential for increasing both profit and competitiveness by improving the efficiency of maintenance activities. However, the ability to quantify the effects of various decisions regarding maintenance activities and maintenance strategies are limited since few methods and tools are currently available. The purpose of this thesis is to support management in making maintenace decisions by visualizing how PM may affect the production performance and cost. The thesis was performed in cooperation with an industrial partner and a technical college, e.g. Wellspect HealthCare and Gothenburg Technical College (GTC). Furthermore, the authors cooperated with participants in the research project; Framtidsoperatören (the Operator of the future) to gather information.

1.1. BACKGROUND

Decisions made in industry have become increasingly more complicated with more inputs to consider, e.g. production flow, personnel, and costs. To motivate changes, managers need a state-of-the-art tool to support decisions related to planning, operations, and design (Rohrer, 2002). There are currently several strategy approaches to maintenance, e.g., corrective maintenance (CM), preventive maintenance (PM), and predictive maintenance (PdM). The optimal solution to avoid stops in production due to unpredictable failures is to continuously know the condition of a machine and take service and repair action only when needed. By using discrete event simulation (DES) to simulating a system, its performance can be evaluated in face of uncertainty, i.e. predicting failures based on previous behavior of the system (Hederson and Nelson, 2006). Working with PM techniques requires support from upper management, since decisions to allow maintenance activities may require rescheduling of the production (Wireman, 2010). The DES model will therefore be used as a visual tool to facilitate maintenance decisions at Wellspect HealthCare.

Wellspect HealthCare is a leading global provider of innovative urological and surgical products and services (Wellspect HealthCare, 2014). The main office is located in Mölndal, Sweden, and focuses on the production of low friction catheters. The company is interested in using a tool that demonstrates how various maintenance decisions may affect the company’s profit. A contact person at GTC introduced the idea of the thesis and played a major part in the start-up of the project.

The purpose of the research project Framtidsoperatören is to develop new, sustainable, and competitive concepts for future industrial operators. The research project is focused on providing the future operator with proper tools to meet the social, economic, and sustainable challenges of the future. This thesis collaborated with Framtidsoperatören to identify newly developed tool to assist operators in production and/or maintenance related activities.

1.2. Purpose

Currently, few methods and tools are available to evaluate decisions regarding maintenance activities. The company wishes to assess the economic effect of employed maintenance activities to support maintenance related decisions. The purpose of this thesis is to garther an understanding of how PM affects the production performance and cost to facilitate these decisions, using simulation.

1.3. Goal

The goal is to identify relevant KPIs measuring maintenance activities in production and quantifying them using simulation. The simulation model will be connected to a user interface to support future experimentations. The scope of the thesis is demonstrated in Figure 1. A DuPont model will be included in the simulation model to visualize the financial effect of maintenance decisions.

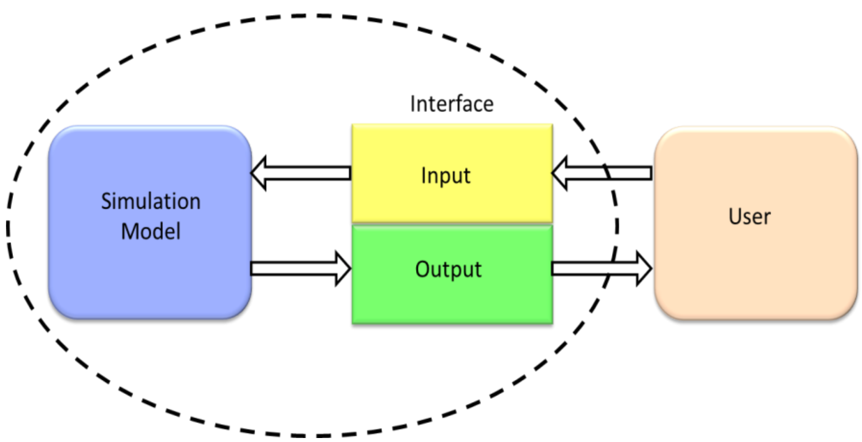

Figure 1: The thesis will focus on creating a simulation mod el and a user interface.

1.4. Research Questions

The following research questions were formulated to specify the objectives of the thesis, to provide a focus are for the aim of the thesis.

- Which KPIs should be used to quantify the effects of maintenance in the model?
- How has PM related activities and CM affected production performance, cost, and profit?

The first research question was stated to identify appropriate KPIs, which facilitate the assessment of performed maintenance activities.

The second question was stated to evaluate how PM may affect the need of CM in terms of production performance, costs, and profit, using DES. Moreover, the question includes an evaluation of using DES as a decision tool for maintenance activities.

1.5. Delimitations

The simulation model includes a single production line, assembling and packing a final product. The demand on the specific product group is growing. Hence, the financial calculations were based on relation between maintenance and profit on that specific line. The range of exchanged spare parts was limited using ABC analysis (Selective inventory control), i.e. using a selection of the most expensive spare parts based on their total annual cost. The selection is presented in the methodology chapter, subchapter 2.8. Furthermore, the thesis does not include experimentations or optimization of maintenance strategies, scheduling etc. Finally, the simulation model is developed to test the effect of various maintenance activities and does not include risk analysis or safety analysis of performed maintenance tasks.

2. METHODOLOGY

This chapter describes the methodologies used to fulfill the purpose and goals of the thesis. The chapter includes literature review, data collection, cognitive walkthrough, use-case description, simulation, selection of spare parts, and a description of how a DuPont model is used for profit evaluation.

2.1. LITERATURE REVIEW

The thesis includes a literature review from previous studies within the area of simulation and maintenance. The review aims to investigate present state regarding simulation of maintenance activities and to cover various maintenance strategies. Likewise, research on how to design a user interface to achieve a high usability was conducted. Besides gaining knowledge within the field of study, the authors have used the knowledge to make appropriate assumptions. Searching for relevant literature was conducted using Chalmers library databases and Google Scholar. The following databases were primarily used:

- ProQuest
- Scopus
- Science Direct
- Google Scholar

The key words used in the literature search are presented in the list below. The words were used individually or combined:

- Maintenance
- Maintenance strategies
- Simulation
- KPI
- DuPont
- Return on assets
- ABC-classification
- 80-20 rule

2.2. USE-CASE DESCRIPTION

The simulated production system consists of a line composed of three sub lines, divided into 47 sections. Line 2 consists partly of a parallel flow while the two others are single flows. The sub lines are together handling three types of materials, assembled at two merging points. The products are mainly handled in batches of six. The sections are synchronized, thus there are no buffers in-between the sections, meaning that if one section stops, the entire line stops. The line is supposed to run continuously except for an 8 hours stop each week, scheduled for PM. In addition, the line stops if the production target is achieved. Three operators are responsible for operating the line, managing setup, material filling, quality control and repair of less complicated failures. Six operators are responsible for packing the final product at the end of the line. If a failure occurs, either an operator or a technician is responsible for repairing the failure, depending on the severity of the problem. A conceptual model can be seen in Figure 2. For further description of maintenance related activities at the line, see *Empirical data* chapter 4.

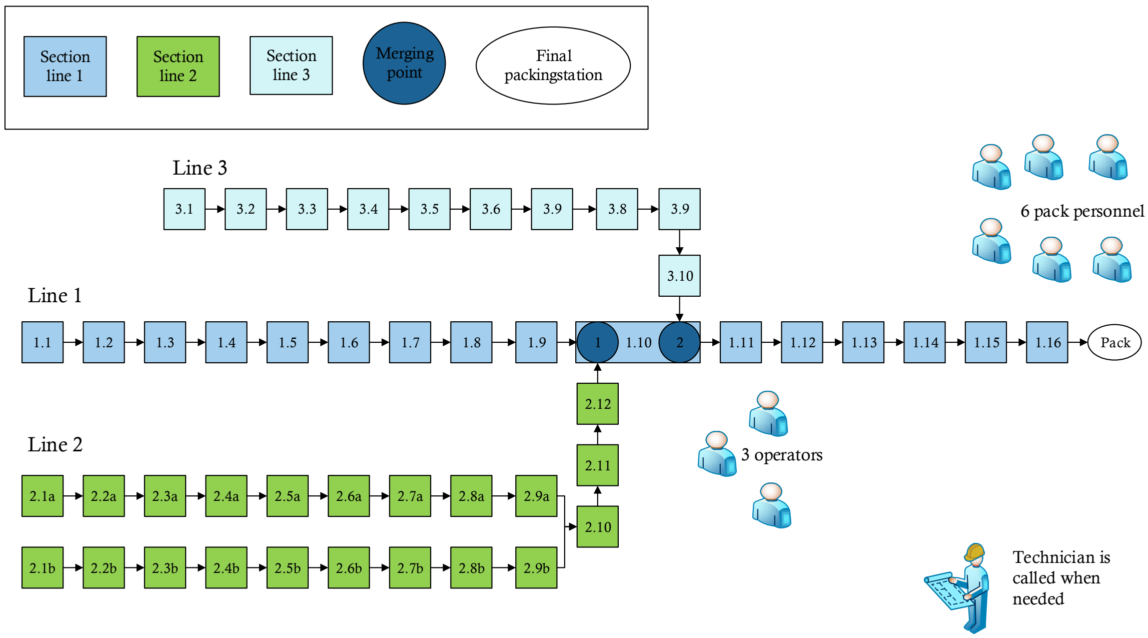

Figure 2: Conceptual model of the production line.

2.3. DATA COLLECTION

Data can be divided into two different types; quantitative data and qualitative data. Quantitative data is measurable, objective, and statistically correct. Qualitative data refers to subjective data, generally collected by observing what people do and say (Anderson, 2006). To obtain these results, both qualitative and quantitative data was collected; quantitative data to build the simulation model and qualitative data to gather knowledge, make appropriate assumptions where data was missing, and to determine appropriate KPIs.

2.3.1. QUANTITATIVE DATA

To quantify the effects of maintenance, a simulation model was used to gather quantitative data of production performance, cost, and profit. The simulation model was based on quantitative data from Axxos®, the industrial control system (Axxos, 2014), and Aretics®, the control system for maintenance (Aretics, 2014). To build up the model, documents regarding production, PM schedule, spare parts replacements, work time for CM by technician, work time for PM, and work time for service requests were studied. Furthermore, financial data for the DuPont model and data to calculate cost of different maintenance activities were collected with assistance from the financial operations controller at the company.

2.3.2. QUALITATIVE DATA

To create an understanding of the current state of production maintenance at the company, the authors performed both observations and interviews. Observations were conducted to get a better understanding of the process and the collected data. Interviews were held with operators, technicians, engineers, and managers to gather additional information regarding the production and its related activities, to get an understanding of previous change initiatives, and to understand how these have affected the data. All interviews were held face-to-face to get a deeper interaction with the interviewees. According to Opdenakker (2006), face-to-face interviews are preferred when the social cues from the interviewee is of importance. It enables the interviewer and the interviewee to directly react on intonation, body language, and to what the other person says. The majority of interviews were semi-structured, thus based on predetermined questions with additional supplementary questions. Semi-structured interviews enable interesting discussions without going off-topic (DiCicco-Bloom and Crabtree, 2006). The predetermined questions can be seen in Appendix A. Besides the understanding of how maintenance is and has been performed at the company; interviews were held to determine relevant KPIs, and to identify possible areas for improvements. Furthermore, relatively unstructured interviews were performed, where the interviewees freely could speak about maintenance procedures without being led by questions. According to DiCicco-Bloom and Crabtree (2006), no interview can be completely unstructured; it is more or less a guided conversation.

2.4. *COGNITIVE WALKTHROUGH*

Cognitive walkthrough was used as evaluation method to improve the user interface created in MS Excel®. It is a methodology to assess the usability of a system and to identify causes for usability problems (Polson et al, 1992). By using cognitive walkthrough, features of the user interface can systematically be evaluated, preferably in an early stage of the design (Lewis et al, 1990).

The method can be divided into two phases; preparation and evaluation. The preparation includes specifying possible tasks that are of interest to evaluate. For each task, the following should be defined; an initial state of the user interface, sequence of actions to successfully perform the task, and the user´s initial goal. The aim of the evaluation step is to analyze the interaction between the user and the interface. For each action by the user, the following prerequisites has to be determined; goals the user should have to lead up to the specific action, how the state of the interface will induce the user to make correct actions and set up correct goals, and how the response from the user interface, after an action has been performed, can change the user´s goal (Polson et al, 1992).

The cognitive walkthrough was performed with future users as test persons. During the walkthrough, the authors observed the users behavior and identified possible usability problems. After the walkthrough, the authors and the user discussed issues regarding the usability, and also the content of the user interface. Further, simulation as a tool for decisions regarding maintenance issues was discussed, to evaluate if the simulation model and user interface could be used in their maintenance planning. The questions asked can be seen in Appendix B.

2.5. *Framtidsoperatören - Workshop*

In the beginning of the project, the authors attended a workshop for participant involved in the project Framtidsoperatören. The authors attended the workshop to get a general understanding of the project Framtidsoperatören and to identify relevant tools and activities that aim to assist operators and increase internal communication, thus determine how increased operator involvement may reduce production downtime. Tools and activities considered relevant to the company and applicable on the specific production line were further evaluated.

2.6. *Maintenance Fair*

The authors participated as presenters and exhibitors at an annual maintenance fair; Underhållsmässan in Gothenburg. The thesis was present to get an overall idea of the interest of simulation and visualization in Swedish industry and to discuss the idea of the thesis to discover additional viewpoints and interesting KPIs. Mainly, the fair enabled the authors to interact with people specialized in maintenance to gather relevant information on state-of-the art maintenance products within the field.

2.7. *Simulation*

A simulation model makes it possible to test and analyze changes in a system during a compressed period of time. In this thesis, DES was used to model the production and to quantify the effects of maintenance; by simulating how PM related activities affects production performance, cost, and profit. Based on this information, the simulation model should serve as a tool to assist in maintenance decisions. According to Banks et al (2010), simulation is an appropriate tool to visualizing the system and to sell solutions to customers and employees. In this case, the maintenance manager is interested in visualizing the effects of maintenance to demonstrate its importance to the employees and the business management.

2.7.1. Model Building

The model was build using Banks methodology. Banks methodology is a method used in simulations projects and includes project planning, creation of conceptual model, coding base model (model of the current state), and verification and validation of the model (Banks et al, 2010). The sequence of Banks methodology can be seen in Figure 3.

Building of the simulation model was done in Automod®, based on observations of the system and guided tours along the line with the operators and the line manager. In addition, interviews and process mapping were performed. Quantitative data of stop times in production was collected from computerized data sources used at the company. Stop times are logged online by the system

Axxos®, where the operators are responsible for manually documenting which section caused a failure longer than one minute. Quantitative data of PM tasks and CM tasks were collected from a maintenance system in which the company manually plans and documents performed maintenance work, Aretics®.

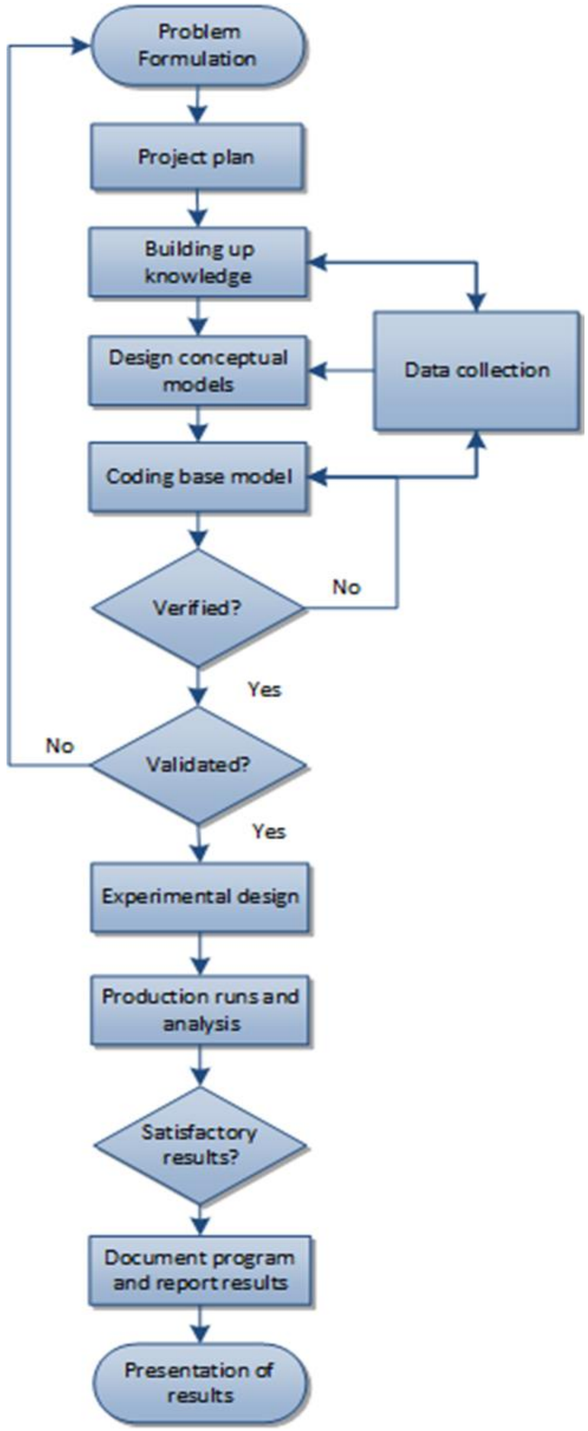

Figure 3: The steps in Bank´s methodology (Banks et al, 2010).

2.7.2. Abstraction Level

It is important to be aware of problems in the model to estimate its accuracy. The authors have made assumptions and simplifications to fill out gaps where data were missing and to handle the complexity of reality. Moreover, a model builder has to be aware of the cost effective limit, where further improvements will not produce major changes in the output. The model is just a theoretical representation of reality and it can therefore never produce a perfect replicate. The main assumptions and delimitation are:

- MTBF was calculated and used with an exponential distribution in the model. Exponential distribution is suitable for events that occur continuously and independently at a constant average rate. The distribution is commonly used in practical reliability analysis (Finkelstein, 2008).
- MTTR (stop time) was calculated and used with a gamma distribution, shape 2.
- Stop time includes both waiting time and repair time.
- Technicians work time is not directly affecting the production in the model. Stop times due to CM by technicians was included in the calculation of MTTR.
- The distribution of work time followed a triangular distribution, where minimum, most common and maximum times were based on work registered for each section in Aretics®.
- All costs assumption was made in cooperation with the financial department at the company.
- Cost of various maintenance activities includes cost of personnel and cost of spare parts.
- Cost of PM was calculated as hourly cost of operators and technicians. Total scheduled PM is assumed to be 50/50 between operators and technicians.
- Cost of service requests was calculated as hourly cost of technicians.
- Cost of fault time was calculated as hourly cost of operators and packaging personnel. If CM by technician is required, cost for technician was added to the cost of fault time.
- The simulation model was considered a selection of spare part based on an annual cost classification.
- Changes in ROA were mainly dependent on products produced (income) and fault time (cost of personnel).
- Setup, material filling, short stops, lacking raw material, and stops due to not planned production were based on Q4 2013.
- The time difference between stop time and CM for technicians was assumed to be repair time by operators.
- Both fixed and variable costs of a product was a variable cost in the simulation model, since the financial departments has been calculated the costs per product.
- Income per product was generalized, using a purchase price from *"Värmlands Landsting"* (2013).

- The profit from the produced products is instant.
- Non-coded stops were categorized as shared stops for the whole line. Shared stops are those stops that cannot be distributed to a specific section or line.

2.7.3. Experimental Plan

As mentioned in the introduction of this chapter, appropriate KPIs relating to maintenance planning and evaluation was first identified from interviews. Cognitive walkthrough was then performed to evaluate the KPIs and to assess how the simulation model and its user interface could be used for maintenance planning. DES was used to compare real cases and quantify the differences using identified KPIs. The cases were based on quarter 3 (Q3) in 2013, quarter 4 (Q4) in 2013, and quarter 1 (Q1) in 2014. The experiments were simulated using quantitative MTBF data and MTTR data for each section and quarter, using equation 1 and 2. The real cases were simulated using DES to equate the planned production time and external faults between the quarters.

$$MTBF = \frac{production\ time}{number\ of\ failures} \qquad (1)$$

$$MTTR = \frac{downtime\ due\ to\ failure}{number\ of\ failures} \qquad (2)$$

Q4 in 2013 was used as a base model to verify the construction of the model. Q4 was considered normal production, since data in Q3 contained non-coded stops and the production in Q1 was heavily affected by external factors, e.g. material shortage. The base model was connected to a user interface using MS Excel®. The design of the user interface was evaluated using cognitive walkthrough. Thereafter, the data of the different quarters were inserted, simulated, and compared to identify the effect of various amount of total PM and man-hours spent on CM. Total PM consists of scheduled PM and service requests. Moreover, two future scenarios were simulated. Each simulation was run for 91 days (a quarter), used a warm-up period of 168 hours and 5 replications, with a confidence interval of 90%.

Real case

The reason for simulating the three latest quarters was the lack of structure in earlier quarters, due to ongoing efficiency improvements of maintenance tasks and inconsistent data structure in both Axxos® and Aretics®. Therefore, Q1 and Q2 2013 were studied but not in detail. The identified non-coded stops in Q3 were assumed to be common failures for the whole line, which is why the individual fault time for each section was not considered reliable and therefore not used in the section level analysis.

Time spent on scheduled PM and service request was studied for each quarter and section using data from Aretics®. Missing timesheets entries in reported service requests were given times based on similar jobs performed on the specific section. The service requests and the scheduled PM were not included in the model and was instead calculated in MS Excel®, as these jobs are performed during nonscheduled production hours and has therefore no direct effect on production. In addition, specific spare parts were evaluated and selected in the calculation of the total cost, see subchapter 2.8.

FUTURE SCENARIO 1

At the workshop with Framtidsoperatören, the authors were presented with various tools designed to assist operators of the future. The tools can for example provide the operator with work instructions or a list of common errors to facilitate error detection. Moreover, repair instructions could be used to enable operators to prepare and in other ways assist the technician before his or her arrival.

To demonstrate how simulation could be used to evaluate possible effect of using tools to provide operators with instructions to start the repair, the authors have created a future scenario with reduced MTTR for each section. The time reduction was assumed by the authors to be 5%. The assumption was based on minimum waiting time, number of CM by technician, and total fault time of the line in Q4 2013. The used equation can be seen in Equation 3, where total waiting time is calculated by multiplying minimum waiting time with number of CM by technician. The minimum waiting time was obtained from unstructured interviews with a maintenance technician and operators. The authors chose to use the minimum waiting time since the waiting time varies between 5 to 30 minutes. It is of importance to highlight that the time reduction factor is not based on any research, since it has not yet been tested.

$$Time\ reduction\ factor = \frac{Total\ waiting\ time}{Total\ fault\ time} \qquad (3)$$

Time for scheduled PM, service requests, and spare parts were assumed to be the same when comparing the two future scenarios, meaning that changes in cost of personnel during CM were of interest.

FUTURE SCENARIO 2

If the company identifies root causes, it is possible to make a realistic evaluation of what to expect. The authors have therefore made a simulation based on the lowest total fault time in Q4 and Q1 and used the quarter’s corresponding PM, thus simulating a system with a realistically higher reliability. Data regarding MTBF, MTTR, total PM, and CM by technicians were taken from the best quarter and used for the experiment. Spare part replacement in future scenario 2 was assumed to be the same as in the base model, since the authors cannot determine how spare part exchanges is affected. Therefore, the cost analysis is limited to only include variations in cost of personnel.

2.7.4. Verification and Validation Techniques

There are different ways to verify and validate a simulation model. Verifying the simulation model is primary to ensure an error free code (Sargent, 2010). Computerized model verification was used to ensure that the conceptual model and the simulation model were consistent. Another primary technique was to go through the code step by step to see if it is programmed correctly.

To validate the model, hence to ensure that the model corresponds to the real system, the following techniques were used (Sargent, 2010):

- *Animation*: Observing the operational behavior and movements of parts graphically.
- *Event Validity*: Using the comparison of the occurrences of events in the model compared to the occurrence of events in the real system.
- *Face Validity*: Using individuals who know the real system to determine if the results from the model are reasonable.
- *Historical Data Validation*: Using historical data to compare if the model behaves as the real system.
- *Internal Validity*: To run several replications to determine the variability in the model. If the model has a large variability, there might be a reason to question the model's result.

2.8. ABC Classification and 80-20 rule

ABC classification was used to identify the most critical spare parts used in the production line. The classification was conducted based on annual usage and annual costs during 2013. The 80-20 rule was then applied to confirm the classification by identifying the relation in the list of spare parts. Interviews were also conducted to verify that the classification was in accordance with the approach of the company.

Inventory is often grouped into classes to manage them more efficiently. ABC classification is a well-known method for classifying inventory into different groups. Grouping allows management to set common control policies for each group and to monitor them accordingly (Chakravarty, 1981). A common ABC approach is to classify items by volume or value, as it is often found that a small number of items account for a large share of the volume or cost. The classification is based on the Pareto principal, which states that roughly 80% of problems comes from 20% of the causes. The rule is also known as the 80-20 rule and is claimed to appear in several aspects of business operations. Therefore, many businesses can easily improve their profitability by focusing on the 20 % most effecting areas (Edwards, 2011).

2.9. DuPont

A DuPont model was used to break down return of equity (ROE) or return on assets (ROA) into elements. These elements allow an analyst to determine and understand the source of superior or inferior return by comparing the values between similar industries, production sites etc. A complete description of the DuPont model is described in the theory chapter, subchapter 3.7.

In this thesis, the DuPont model was used as a visual tool to increase the understanding between different maintenance activities and ROA. The model was simplified to only include variables relevant to the single line studied in this thesis. The simplification of the model was defined in accordance with a financial operations controller in the financial department. Some of the values in the model was approximated based on classified restrictions. The contribution margin depends on products produced and the income is dependent on cost of fault time and CM, since the financial department have divided the company's total cost between each product and based the annual budget on these values. ROA is thereafter calculated as net income divided by total assets. The adopted DuPont can be seen in Figure 4.

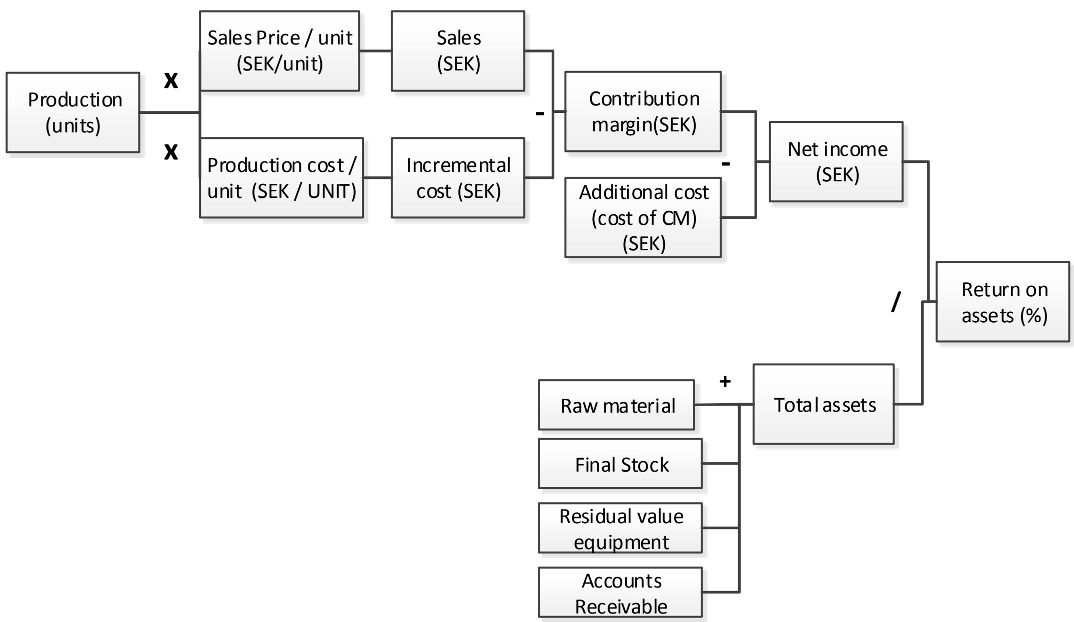

Figure 4: The figure describes the DuPont model used in this thesis.

2.10. *REFLECT IN ACTION*

During the project, the authors have been reflecting in action to evaluate the progress of the thesis. Reflection was crucial to ensure that the project was moving in the right direction; both with respect to the customer's expectations and the authors' goals. By dedicating time for reflection, the information gathered during the project were properly evaluated and used optimally. The authors have also reflected on the project from a sustainable perspective; including economic, environmental, and social aspects. The economic aspect was strongly considered, as the project quantifies the effect of maintenance using an economical KPI. The social aspect was further considered in the development of the user interface to ensure the usability and in deciding upon appropriate tools to assist the operators. Reflection was an important method both during the project and even more so, in the analyzing process of the results and in discovering interesting discussion points, presented in chapter 4 and 5.

3. Literature review

This chapter describes the theory used for choosing the methodologies, which will serve as a base of knowledge within relevant areas related to the project. The chapter includes previous studies regarding simulation and maintenance, theory on simulation and production maintenance, production maintenance in general, KPIs, methods on how to create an appropriate user interface, statistical distribution, and further theory on how to interpret a DuPont model.

3.1. Previous studies on Simulation and maintenance

Haarman and Delahey (2004) states maintenance managers often find it difficult to convincingly express the benefits of maintenance. Stochastic simulation can be used to evaluate system performance in the face of uncertainty and predict failures based on the previous behaviour of the system (Hederson and Nelson 2006). However, this requires historical data on the behaviour of the system, or/and high level of knowledge of the system. There are several examples of studies where simulation was used to analyze and improve maintenance activities.

Kaiser (2007) compares the influence of different maintenance strategies on common manufacturing models by using Arena simulation software. The author focused on comparing time-based PM strategy with PdM strategies. The PdM strategies uses Gebraeel et al. (2005) degradation model to predict failure of individual components. The project included three studies on maintenance policies. The first study simulated PdM maintenance using a developed policy based on Gebraeel's et al. (2005) sensory-updated degradation model (an equation of equipment degradation depending on time and products produced). This model was compared to a degradation-based PdM policy developed by Lu and Meeker (1993) and a reliability-based PM policy. Simulating the effect of various strategies on an individual workstation was the basic principle behind the results. The second study evaluated the impact of reality-based PM and sensory-updating PdM on a production line with several workstations. The third study compared reliability-based spare part replacement policy developed by Armstrong and Atkins (1996) with the sensory-updated model used in the earlier studies. The studies showed that the failure predictability of a system was improved by using sensory-updated degradation models, which resulted in an overall lower maintenance cost.

Suliman and Jawad (2012) present a mathematical model to optimize PM age, time T, and lot size for single unit production system. The PM age is described as the time between PM activities. The system being modeled was assumed to have a constant and continuous demand. PM activities occurred with a periodic time T and made the system as good-as-new. After a random production time, the system falls into an out-of-control-state where non-confirming items are being produced. During the out-of-control-states, the system may fail at any time. Failure will result in longer repair time and increase the repair cost. In the model, five costs were taken into consideration; setup cost, maintenance cost including preventive and reactive costs, inventory holding cost, non-conforming items cost, and shortage cost. Two scenarios were tested in the model, one where maximum level of inventory was reached when the system shifted to out-of-control-state, and one when maximum inventory level was not reached. The results of the study showed that scenario 2 had a lower optimum PM age for minimum total cost compared to scenario 1 where the maintenance age was greater for a minimum total cost. A sensitivity analysis was done to determine which cost parameters affected the model performance. The analysis showed that maintenance age is sensitive to PM costs and inventory holding costs. Further, it was less sensitive to shortage costs and nearly not influenced by corrective maintenance (CM) costs. It was also tested how introduction of periodic inspections affected the cost. The result showed that it increased the total cost without any effects of the PM age.

Gopalakrishnan et al. (2013) discuss an approach to use DES to coordinate maintenance strategies into production planning. The example was conducted in an automotive case study, with the aim to investigate how maintenance strategies affect the production performance and robustness of production plans. The simulation model shows a possibility to increase productivity by 5% by introducing priority-based planning of maintenance activities. The simulation model was further used to investigate how increasing operator responsibility has the potential to increase productivity. The model showed that operators with knowledge of all the machines in a production area increase the productivity by approximately 11%, since any of the operators are able to repair a failure.

Another example of how DES has been used to improve maintenance operations is Ali et al. (2008) simulation and optimization of a system to identify critical stations to design maintenance scheduling. Furthermore, the stations impact on the overall system performance was evaluated and an optimal scenario could be identified. A similar study was conducted by Altuger and Chassapis (2009), who used Arena-based simulation to evaluate different techniques to perform preventive maintenance scheduling on a bread packaging line. The aim was to promote simulation as a tool in the decision-making process of selecting a correct PM scheduling technique. The paper provided an overall map on how to incorporate simulation in decisions. In a study by Sharda and Bury (2008), DES was used to determine and understand how the overall production performance was affected by different component failures. Simulation was used to evaluate the components that contributed to the largest production losses, and to further analyzed how for example; new equipment installation affected the production performance. The study shows the potential of using simulation to examine production capabilities in case of changed policies regarding component failures.

3.2. PRODUCTION MAINTENANCE AND MAINTENANCE MANAGEMENT

Maintenance is a generic name for activities performed in purpose of improving actions and prevention actions to repair, or reduce breakdowns of a production system. However, the definition of maintenance can vary between companies. In this report, maintenance will be referred as defined by the European standard (SS EN 13306, 2001):

"*A combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function".*

Maintenance contributes to a sustainable development of society through the analysis of its environmental, safety, and economical effects. Maintenance is currently critical for organizations to maintain competitiveness (Holmberg et al., 2010). The purpose of having a maintenance plan is to minimize the combined cost of running the business and maintaining the production. A manager has a range of maintenance strategies available to reach that aim, mainly run-to failure/CM, time-based maintenance/scheduled PM, design out, and condition-based maintenance. The following chapter will review the range of these strategies and their limitations. It also includes maintenance concept to describe various ways of working with maintenance. It will serve as a base of knowledge on how to work with maintenance in an organization.

According to Gupta (2009), maintenance management is defines as *"a combination of different skills, including knowledge and experience, necessary to identify maintenance needs and to specify remedies."*

Another definition from European standard (SS EN 13306, 2001) is: *"all activities of the management that determine the maintenance objectives, strategies, and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, improvement of methods in the organization including economical aspects."*

Maintenance management has the role of setting up aims and objectives to make decisions and to provide means for the maintenance organization to achieve the objectives. The main objective for maintenance management is in general (Gupta, 2009):

- To maximize the availability and reliability of the whole plant and its equipment, and to attain maximum possible returns on investments.
- Minimizing wear, tear and deterioration to prolong the time for an item to be useful.
- To ensure that all equipment required for emergency use will function.
- To ensure safety of personnel using the equipment.

According to American National Standard (2000), the maintenance management should ensure equipment and tools availability for manufacturing. It includes responding to reactive problems (failures) or scheduling for periodic PM (different maintenance strategies are further described in subchapters below). However, to find the optimum ratio between CM/PM, especially regarding replacement rate of spare parts, requires proper analysis. Furthermore, an analysis has to consider that a new machine tends to have a high probability to fail during the first weeks of operation due to installation problems. The probability of failure does then decrease to a lower level until a point in time where the probability increases again, due to equipment worn out. This probability curve, called the Bathtub curve, and is seen in Figure 5 (Mobley, 2004).

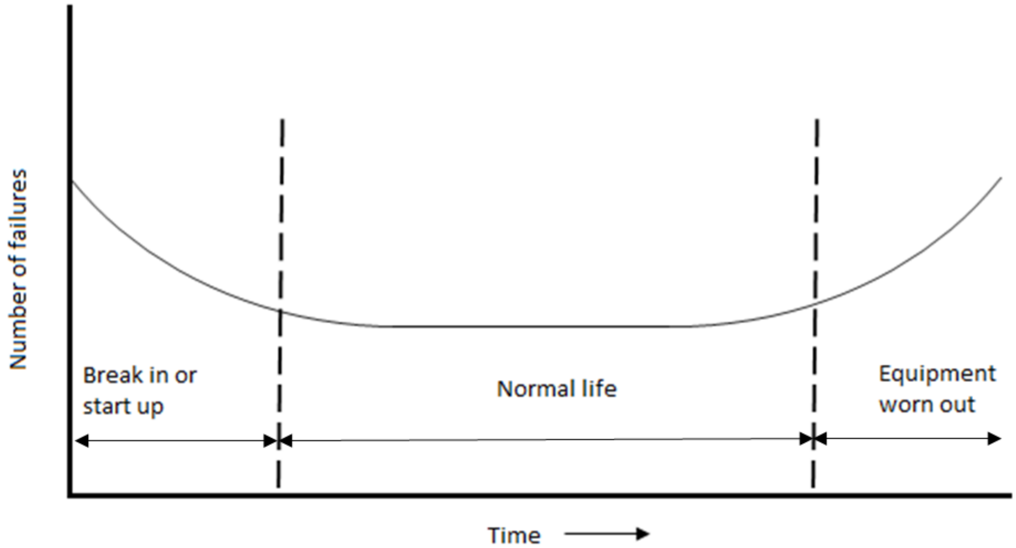

Figure 5: Batchtub curve, showing the number of failures of equipment during its lifetime (Mobleu, 2004).

A side from the obvious difficulties, there are important reasons why maintaining equipment is of interest. From a line manager's point of view, improved maintenance activities can lead to increased utilization of equipment, which contributes to reducing a production line's total down time. In addition, performing the right maintenance prevents the waste of tools and spare parts, reducing the total production cost (Gupta, 2009). From the maintenance management point of view, different strategies have to be evaluated to determine which strategy is more applicable depending on the specific situations. According to the European Standard (SS EN 13306, 2001), maintenance strategy is defined as *"management method used in order to achieve the maintenance objectives".* The following subchapters describe common maintenance strategies and in which settings they should preferably be used.

3.2.1. Corrective Maintenance / Run-to-Failure

Corrective maintenance (CM) is a reactive maintenance technique, requiring maintenance as a result of failure. European Standard (SS EN 13306, 2001) refers corrective maintenance as *"maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function".*

It is usually unexpected and has an impact of the production, thus no units can be produced. There are three causes why corrective maintenance is needed; human error, component failure, and no consideration to the recommendations of PM stated by the tool/machine supplier. A machine today consists of many mechanical and electrical components, and it is close to inevitable that one of them will fail. The tool/machine supplier is often aware which components are most likely to fail, and often provides the user with a list of recommended spare parts. The supplier also provides the user with recommended PM procedures to keep up the machine´s performance. If these PM tasks are not considered, more CM will be required (Lynch, 1996).

In a plant where CM strategy is used, money is not spent on maintenance until a machine or an equipment fail. However, it is an expensive technique with costs like; high spare part inventory costs, high overtime labor costs, low production availability, and high downtime (Mobley, 2004).

CM is appropriated if time to repair and cost of a stop is less significant, thus the consequence of the failure is small. The strategy requires little planning, as maintenance work is not scheduled until an incident occurs. The major disadvantages are that the failures may occur at an inconvenient time or that a failure may be missed, creating more damage than was originally planned. Also, the strategy lacks historical, present, and future data and may require a large standby crew and a large inventory to prepare for a variety of failures. If the repair team is occupied, additional failure leads to firefighting (Holmberg et al., 2010).

3.2.2. Preventive Maintenance

Unlike CM, PM requires more planning. It is a proactive maintenance strategy, and is referred to as *"maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or degradation of the function of an item"*(SS EN 13306, 2001).

What identifies PM is its time-based approach. PM tasks are based on time, and are performed with a set time interval (Mobley, 2004). The tasks are usually scheduled between production orders to avoid disturbances (Lynch, 1996). The main goal of PM is to reduce the probability and consequence of equipment failure (Holmberg et al., 2010). There are several preventive techniques and the subchapters below states some that are considered relevant to this project, either based on previous usage of the strategy, or because its considered relevant for future usage.

Time-based Maintenance

Planned maintenance focuses on preventing failure by using scheduled maintenance. The strategy assumes that each component has a predictable lifetime, and is replaced based on run time or elapsed calendar time. The method replaces a component at a fixed time, or after a failure, depending on which scenario occurs first. The fixed time is determined by components characteristics, or on assumptions concerning the current demand, equipment characteristics, current maintenance situation, or on the extent of required maintenance procedure. The strategy is should be used in processes that cause repetitive degradation on the specific components. The advantages are the scheduled order of spare parts and the more effective use of time. However, failure may still occur and, if maintenance is performed when it is not needed, labor and spare parts are used unnecessarily (Mobley, 2004). This will in turn increase the risk of additional failures occurring as a consequence of the strip down (Holmberg et al., 2010). Furthermore, the plant's specific operation modes and variables have an impact on the components operational life, resulting in various failure rates depending on the operational conditions.

Opportunity Maintenance

If a factory is constantly running or physically moving, maintenance has to be planned around a window of opportunity. Planning is therefore needed to define what can be done when the operation is still running and what requires shutdown. Both time-based maintenance and opportunity maintenance may use statistical distribution to determine the interval of maintenance procedures (Holmberg et al., 2010).

3.2.3. Predictive Maintenance

Like PM, PdM is a proactive maintenance technique. However, there are some differences. PdM techniques are developed and designed to determine the condition of equipment in order to estimate when maintenance should be performed. This technique is described in the following two subchapters; condition-based PdM and statistical based PdM (Holmberg et al., 2010).

Condition-based Maintenance

Condition-based maintenance is a PdM technique, including activities to detect signs of failure by identifying changes in the physical condition of the equipment. This means that equipment is replaced when the monitor level exceeds the normal and the usage is maximized (Holmberg et al., 2010). Common techniques to predict when maintenance tasks are required are to use vibration monitoring, process parameter monitoring, thermography, tribology, and visual inspection. However, PdM is more like a philosophy to optimize a plants total operation, not only to monitor conditions (Mobley, 2004).

Overall, the major difference between PdM and PM is that PdM is based on actual conditions. The main advantages with PdM compared to PM are that component life is increased, worker and environmental safety is improved, and energy and cost savings are increased. Still, the cost efficiency needs to be considered, as some diagnostic equipment is expensive and staff may need additional training (Holmberg et al., 2010).

Statistical-based Predictive Maintenance

Opposed to condition-based PdM, statistical based PdM depends on statistical data from documentation of stoppages and failures. These are then used to predict future stoppages and failures (Holmberg et al., 2010).

3.2.1. Maintenance Inventory - Spare Parts

Having material and spare parts available when needed requires planning and control. Inventory of spare parts and personnel working with purchasing has therefore great impact on maintenance productivity (Wireman, 2010). Inventory is resources with an economic value that have the purpose to fulfill present and future needs of an organization (Gupta, 2009). These items often account for a one-third to one-half of the production budget (Dhillon, 2002). Therefore a well-managed inventory system is of importance in maintenance and in reducing operation costs caused by equipment downtime or productivity loss.

ABC CLASSIFICATION APPROACH

A maintenance inventory control system should provide information on material and parts required for planned maintenance and have these readily available. Items required for unplanned maintenance should on the other hand be controlled in the most cost effective way possible (Niebel, 1994). By categorizing items using an ABC classification approach, items can be classified based on annual dollar usage, unit cost, and material scarcity.

ABC classification approach is based on the Pareto principle, stating that a small percentage of items determine the achieved result under any condition (Dhillon, 2002). After the classification of items, control policies are established for each category. Classification of A items have a high priority and require frequent control of demand forecast, usage data, and close follow ups. Since these items are of high priority, management has to continuously review lead times and evaluate possible improvements. Next classification level has medium-priority and is classified as B items. These require regular attention and sufficient recording. C items are low-priority and do only require simple controls sufficient enough to meet the operation demand (Dhillon, 2002). Overall, the aim is to use control efforts to minimize high-cost inventory (Arnold, 1996).

When evaluating the annual cost, the holding cost is of importance to determine the cost of holding an inventory item over time. Holding costs include housing costs, labor costs of extra handling, investment costs, material handling costs, and miscellaneous costs. In addition to holding costs, ordering costs and setup costs have to be evaluated. Before determining costs, it is important to note that the annual inventory cost is close to 40 percent of the total value of inventory (Heizer and Render, 1996).

3.2.2. OPERATOR MAINTENANCE

Operator maintenance is maintenance performed by operators. It can be both preventive activities and corrective activities, depending on competence needed to restore a failure. Common examples of typical preventive operator maintenance are lubrication and inspections. Operator maintenance is a good way to increase the involvement and knowledge level of the operators. It has also a profound effect on continuous improvements by harnessing the symbiotic relationship between maintenance technicians and operators (Piper and Sumukadas, 1994). Idhammar (2014) states 75% of all failures can be avoided, or detected at an early stage, if effective operator maintenance is implemented.

3.3. MAINTENANCE CONCEPTS WITH FUNDAMENTAL IDEAS

This subchapter will explain concepts within maintenance and how these are related to larger production philosophies.

3.3.1. VALUE DRIVEN MAINTENANCE

Value driven maintenance, is a methodology for maintenance management to improve maintenance work by focusing on value drivers in maintenance. The idea of value driven maintenance is to connect maintenance with economy, with the aim to value maintenance with respect to profit. According to Haarman and Delahay (2004), maintenance does contribute with value for an organization, and that lacking maintenance is costly in terms of equipment that cannot meet availability requirements. However, maintenance management do often find it difficult to convincingly express the benefits in economic terms. Therefore, value driven maintenance has been developed as a methodology to easier show how maintenance contributes to an organizations overall business performance.

According to Haarman and Delahay (2004) there are four value drivers in maintenance; asset utilisation, resource allocation, cost control, and Safety, Health and Environment. The drivers can be obtained from Figure 6. The aim with improving asset utilization is to increase the availability to be able to produce more products, or produce the same amount within a shorter period of time. However, improvements of the availability must be paid back by the increased amount of product produced, or time saved. The resource allocation refers to the use of resources; technicians, spare parts, knowledge, and contractors. Smart use of resources will result in cost savings in areas of inventory, logistics, and unnecessary or usable spare parts. The cost control driver aims to optimize maintenance staff and work to reduce the maintenance costs. The fourth driver, Safety, Health and Environment, SHE, is a factor which importance has been increased in recent years. Lacking safety and health in an organization will be costly due to accidents and sick leaves. SHE-factors add value to an organization in terms of decreased absenteeism of personnel and increased technical availability. It may be easy in theory to deliver *"maximum availability at minimum costs"* (Haarman and Delahay, 2004) while in reality it comes down to prioritizing; decreasing the costs or increasing the uptime.

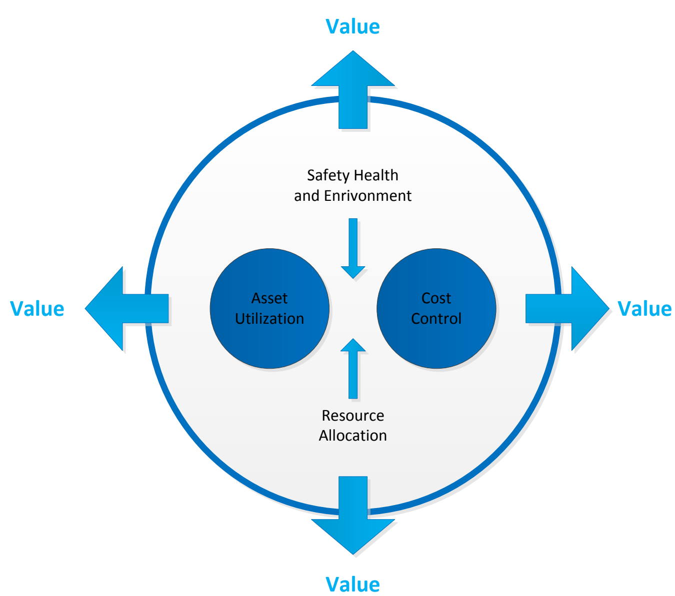

Figure 6: Description of what brings value in a maintenance perspective (Haarman and Delahay, 2004).

3.3.2. Reliability Centered Maintenance

Reliability-centered maintenance (RCM) is a maintenance planning process and philosophy where PM activities are determined with reliability of the system or equipment in centre. A general accepted definition of reliability is, according to Hinchcliffe and Smith (2004):

"*Reliability is the probability that a device will satisfactorily perform a specified function for a specified period of time under given operating conditions*."

Moubray (1997) states that a RCM analysis should consist of the following seven questions:

- What are the asset's functions and expected performance in its present operating condition?
- In what possible ways can the asset fail to fulfil its functions?
- What are the causes of each failure?
- What are the consequences of each failure?
- What makes each failure relevant?
- How can one predict or prevent each failure?
- What action should be taken if a proactive task cannot be determined?

It is impossible to determine PM activities that prevent, mitigate, or detect failure occurrences without knowledge of the system and its failure modes. RCM includes a failure mode and effects analysis (FMEA). FMEA is an analysis that is used to determine the probability, consequence, and causes of failures. A well-executed FMEA will result in useful information about the system or equipment failure mode, which can be used when planning PM activities (Hinchcliffe and Smith 2004).

RCM may sound similar to other maintenance planning processes today, but there are four features that identify and characterize RCM (Hinchcliffe and Smith 2004):

- Preserve systems function – The first and most important feature of RCM. By determine the systems function it is possible to determine the expected output. The primary task is to preserve the expected output. In RCM, the analyst should know which equipment relate to which function so that maintenance is performed based on the function, and not assuming that each item of equipment is equally important.
- Identify failure modes that can disrupt functions – To eliminate the function losses are the next objective to consider. Functional failures could not always be determined as "have it" or "do not have it". There are some in-between-states, which is important to examine.
- Prioritize the function to preserve the function, meaning deciding in what order or priority the functions should be assigned in order to allocate budget and resources.
- Perform appropriate and effective PM, meaning creating a systematically plan to preserve the function to determined necessary PM activities based on the failure mode, which component, and what priority.

3.3.3. LEAN MAINTENANCE

Lean maintenance originates from Lean philosophy, focuses on removing waste and improving equipment performance by applying lean strategies on maintenance processes. The concept combines the philosophy of lean with the planning and scheduling methods of Total productive maintenance (TPM) planning and strategies from Reliability Centered Maintenance (RCM) (Levitt, 2008). Many of the tools used in Lean maintenance are also used in Lean manufacturing: 5S, Just-in-time, eliminating waste, Kaizen, etc.

The concept of Lean maintenance emphasizes the importance of adapting the maintenance depending on the machine. An organization must learn to recognize when it is time to perform maintenance to avoid wasting resources by performing wrong work, wasting spare parts, and having stops in production. Idhammar (2013) identifies the biggest losses, hence the biggest improvement opportunities in maintenance according to the following list:

- Manufacturing reliability
    - Loss in quality, stop times, and in speed.
- Partnership between operations, maintenance, and engineering
    - Operator based maintenance, reliability related design
- Eliminating root causes
    - Choose correct problem, correct it, educate and teach
- Storage
    - Reduce storage value and preserve service level to maintenance
- Integrating and applying knowledge and skill
    - Multi skills training
    - Implementing flexible work systems
- Over manufacturing
- Over maintenance
    - Perform too much and wrong preventive maintenance
    - Perform preventive maintenance before it is needed
    - Do corrective maintenance with higher priority than needed
- Use of new technology.
    - Better maintainability
    - Smart tools and methods

3.3. *ECONOMICS OF MAINTENANCE*

Maintenance has a large financial post in industry today. Though, it may also have a key role in contributing to a company's competiveness if executed efficiently (Salonen, 2011)[1]. The total cost of maintenance is currently contributing to 6.2 % of the industry's turnover. This being said,

[1] Original reference, (Ahlmann, 2002) has not been available for review

one-third of the cost relating to maintenance is unnecessarily spent on bad planning, overtime, and other expenses as a result the lack of PM, etc. (Salonen, 2011)[2].

The general idea of CM is that it is justifiable when the impact of failure is rather small, as it could affect the downtime in dependable systems. The strategy may alternatively be considered when replacements are organized in terms of personal and spare parts (Lind & Muyingo, 2012).

A preventive strategy is rational if the consequences of a fault are high compared to having PM that in advance reduces the risk of a breakdown (Lind & Muyingo, 2012). PM can also be adapted to the user and the situation by planning based on produced products, monitored condition, age, or specific circumstances. However, Tsang (2002) has noted that replacement schedules are usually based on supplier's recommendations, which are often overestimated in terms of the need for replacements. In addition, the lack of knowledge of their customer's specific case and customer-adapted solution hampers the estimation. When making decisions regarding maintenance, it is therefore important to make estimations based on the specific situation.

3.4. KPI

According to International Standard (2011) KPIs are defined as quantifiable and strategic measurements to reflect an organizations performance. It is each organization´s responsibility to find appropriate KPIs to measure and monitor critical indicators or key processes to be able to assess the performance (Smith and Hawkins, 2004). KPIs are therefore unique for every organization and can differ between departments within the same organization. KPIs should be set in relation to management goals, meaning that KPIs need to be monitored in order to reach the goals of the organization or department. Wireman (2005) states that KPIs should be developed by first defining top KPIs, then determine KPIs at corporate level, and finally determine indicators for each subsequent level or department. The structure is designed to avoid confliction between KPIs indicators at different level in the company.

3.4.1. KPIs For Maintenance According to Literature

Smith and Hawkins (2004) describe KPIs as either leading or lagging indicators. A leading indicator measure performance before a problem occurs while a lagging indicator indicate that a problem has occurred.

[2] Original reference, (Wireman, 1990) has not been available for review

As mentioned above, KPIs should be defined in order to measure and confirm if a goal has been reached. According to Smith and Hawkins (2004), there are some rules for setting up good metrics/indicators. The main focus should be on activities for maximum benefits and value creation; an indicator should not conflict with other indicators and, should be positive. Common KPIs for maintenance can be seen in Figure 7.

Reliability/Maintainability
- ➢ MTBF (mean time between failures) by total operation and by area and then by equipment.
- ➢ MTTR (mean time to repair) maintainability of individual equipment.
- ➢ MTBR (mean time between repairs) equals MTBF minus MTTR.
- ➢ OEE (overall equipment effectiveness) Availability × Efficiency (slow speed) × Quality (all as a percentage).

Preventive Maintenance (includes predictive maintenance)
- ➢ PPM labor hrs. divided by Emergency labor hrs.
- ➢ PPM WOs (work orders) #s divided by CM (corrective maintenance, planned/scheduled work) WOs as a result of PM inspections.

Planning and Scheduling
- ➢ Planned/Schedule Compliance—(all maintenance labor hours for all work must be covered and not by "blanket work orders"). This a percentage of all labor hours actually completed to schedule divided by the total maintenance labor hours.
- ➢ Planned work—a % of total labor hours planned divided by total labor hours scheduled.

Materials Management
- ➢ Stores Service Level (% of stock outs)—Times a person comes to check out a part and receives a stock part divided by the number of times a person comes to the storeroom to check out a stocked part and the part is not available.
- ➢ Inventory Accuracy as a percentage.

Skills Training (NOTE: A manager must notify maintenance craft personnel about the measurement of success of skills training.)
- ➢ MTBF.
- ➢ Parts Usage—this is based on a specific area of training such as bearings.

Maintenance Supervision
- ➢ Maintenance Control—a % of unplanned labor hours divided by total labor hours.
- ➢ Crew efficiency—a % of the actual hours completed on scheduled work divided by the estimated time.
- ➢ Work Order (WO) Discipline—the % of labor accounted for on WOs.

Work Process Productivity
- ➢ Maintenance costs divided by net asset value.
- ➢ Total cost per unit produced.
- ➢ Overtime hours as % of total labor hours.

Figure 7: Maintenance related KPIs described by Smith and Hawkins (2004).

KPIs for maintenance performance recommended by International Standards (2011) are mean operating time between failure (MTBF), mean time to failure (MTTF), mean time to repair (MTTR), and CM ratio. The latter is the ratio between CM and the total time spent on maintenance, both corrective and preventive. A lower CM ratio means a better system reliability. A ratio of PM to CM describes the scheduling effectiveness and its influence on CM. A lower ratio suggest ineffective PM activities and a higher ratio, an over maintained system.

According to Mobley (2004), one of the best indicators for maintenance effectiveness is the number of production interrupts caused by maintenance problems. To be competitive, less than 1% of the total production hours should be related to maintenance problems.

Manpower utilization and overtime cost are other indicators mentioned by Mobley (2004). In an environment with many unplanned maintenance activities, overtime cost will be higher. Overtime due to maintenance activities should be less than 10% of total labor budget. It is not possible to eliminate unplanned maintenance, and therefore not either overtime costs. But these abnormal costs should not be a big part of total labor costs. Manpower utilization is the percentage of maintenance labor available that are spent on actual repairs and maintenance prevention tasks. Manpower utilization above 90% indicates a well-managed maintenance organization, where labor hours are utilized to achieve improved reliability. For reactive maintenance, where labors are waiting for something to break, the number of manpower utilization is usually lower than 50%.

Wireman (2005) describes an indicator, maintenance costs per unit produced, as total cost of maintenance activities divided by products produced. However, there may be other causes than maintenance and therefore, this indicator should not be used separately as a performance indicator. However, it could be useful for identifying a broad trend. A more accurate indicator for financial measurement is total maintenance costs as a percentage of total manufacturing costs.

Technical availability is an availability indicator, excluding other stops not related to maintenance. Examples of stops that are not taken into consideration are setup, material filling, and lacking raw material. Technical availability is described in Equation 4 (Haarman and Delahay, 2004).

$$Technical\ availability\ = \frac{Available\ time - downtime\ due\ to\ failure}{Available\ time} \quad (4)$$

Haarman and Delahay (2004) have stated 10 useful KPIs for value driven maintenance. These are:

- Cost of maintenance divided by assets yield value
- Availability
- SHE-factor
- Cost of preventive maintenance divided by total cost of maintenance
- Service requests managed before deadline
- Productivity of technician
- Value of spare parts in inventory divided by assets yield value
- Cost of outsourced maintenance divided by total cost of maintenance
- Training cost divided by total maintenance costs of whole organization
- Credibility of documentation

3.5. USER INTERFACE

The term user-system interface includes all aspects of system design that affect system use (Smith, 1982). Developing an effective user interface is critical to attain a highly effective system performance. User can adapt to poor design by increasing the effort, but added deficiencies will eventually lead to system failure, user complaints, and poor performance. Another identifier of poor interface design is underuse or the abandoning of an optimal system. The development of the system design is then considered to have been a waste of time, effort, and money (Smith and Mosier, 1986). If the interface, on the other hand, is given more thought and consideration, data entry may be improved. Keister and Gallway (1983) show how simple improvements to a user interface can result in a highly improved system performance. Their improvements included consistency in wording and procedures, online user guidance, re-entry rather that overtyping input changes, error messages, formatting and selection of displayed data.

Foote-Lennox (1996) proposes several ergonomic guidelines that should be considered when designing a user interface to computerized systems. Prompt all inputs, which means that if the system desired operator action, it must tell the operator exactly what procedures are required. Hence, the system should inform if it want something and what it wants. Once the user has completed entering a required input, the input should be acknowledged rapidly. A confirmation should inform the user on the success or failure of an action.

Another important area to consider is the display and construction of choices made by the user. Allowing a user to make a selection from several choices is usually easier than trying to formulate an action in a language that the computer understands. Key choices may for example be lightened up or in another way marked to reduce the complexity of the system. Additionally, the cognitive load should be considered by not making the user consider more than 7 ± 2 options simultaneously. It also includes not giving the user an option that is not currently possible, and therefore wrong (Foote-Lennox, 1996).

Adapting the interface to the rules of human culture will further make the user more comfortable in using the interface. Using familiar description and human convention will create higher acceptance as the user will perceive a sentence written in full text as more polite than if it were written using abbreviations. The interface designer should also consider using multilingual formulation and audio and/or visual symbols to reach a wider audience and reduce the workload of a user.

The designer must also consider how easy it is to make changes if the user makes mistakes, which is relevant if the user desires to reverse the effect of an action. The user is then able to experiment with a system more freely. If an error occurs, the interface should provide the user with enough information about the error and on how to correct it. Helpful tips could be added but should be regulated to not confuse the user. The user should also be able to determine when help is needed. By allowing the user to browse through the information, the desired information is easily found (Foote-Lennox, 1996).

Having a consistency between interfaces, for example between input and output, reduces the learning period. For example, different interfaces can be used for beginners and experts if the amount of information is too extensive (Foote-Lennox, 1996).

3.6. SIMULATION

In DES the state variables in the model are changing at discrete points in time (Banks et al, 2010). Simulation provides a high degree of confidence to ensure that a system will perform (Stanley, 2001). There are several advantages and disadvantages of simulation. In a perspective of cost, experimentation on a real system can be costly. Simulation enables experimentation on the system without interrupting the operations. It does also enable faster experiments, since a simulation model can run faster than real time. Experiments can be done with controlled conditions, and therefore, a direct comparison between different scenarios can be made. On the other hand, there is a risk that simulation results are seen as more precise than they actually are. Other disadvantages are expensive simulation software and time consuming model building, which requires further expertise. Furthermore, a model also requires a large amount of data (Robinson, 2004).

Automod® is a DES software. Automod® consists of one or more systems, subsystems, and additional movement systems. The movement system provides the user with possible material movement systems, including path movers, conveyors, robots, tanks and pipes, etc. Input parameters, such as velocity and acceleration, are used in the model to create corresponding model logic. The key strength of the program is that it provides a high flexibility in designing complex systems, unlimited size of models, statistical analysis features, graphic environment, and the ability to import graphic models from CAD tools. The animation environment enables the user to examine the process flow visually. The user can also examine the process by gathering statistics. Overall, these features provide the user with a tool that facilitates the verification and validation of the program, as well as communicating the process and possible changes to an external audience (Stanley, 2001).

In the process system in Automod®, products are called loads and move between different location, called processes, and compete for the system's resources, such as operators, queues, and equipment (Stanley, 2001). A load's inter-arrival rate, in and between processes, can either be read from an external file or be dependent on statistical distribution.

3.6.1. Statistical Distribution

In all production processes, and also in the daily life, there are some uncontrollable variations. It could, for example, be the processing time for a machine, the time it takes to do maintenance or the depth of a drilled hole. Statistical distribution is used as a way to understand the variation and to model randomness. The random variables and their statistics and probability are measured and analyzed to find an appropriate distribution (Forbes 2011). In simulation, statistical distribution has a central role in describing variation. For unpredictable variability, the distribution has to be specified according to the collected data and generate a sample before an event can be executed (Robison, 2004).

3.7. DuPont

The DuPont model, also called the Strategic profit model, can be used to identify weaknesses and strengths of a company's performance. It is also used to identify threats and internal factors of performance growth (Soliman, 2008). The analysis method explains ROA and ROE using two respectively three factors. ROE is calculated using profit margin, asset turnover and an equity multiplier to calculate the financial leverage. ROA relates profitability to the value of the assets while ROE is focused on determining how well a company uses shareholder investment (Stapleton, et al., 2002).

3.7.1. Return on Assets

ROA is used as an indicator of how profitable a company is relative to its total assets, the invested capital. ROA is displayed as percentage, calculated by dividing the annual earnings by the total assets. The ratio measures how effectively a company has been in converting invested capital into earnings during a given period (Black, 2010). A company's operations are funded by equity and debt, which in the end influences the ROA ratio. A high ROA ratio indicates that a company is earning more on less investment. Though, there is still a need to balance it against sustainability factors, risk factors, and reinvestments in business development, as these are considered to be long-term earnings. In addition, the ratio is highly dependent on the particular industry and therefore should only be compared to previous ROA ratios of a company or ratios in similar industries. Overall, a climbing ROA indicates a climbing stock price, as investors recognize that the management is skilled in allocating resources.

To increase the value of the ROA ratio, companies have focused more on lowering direct costs (Hansen, 2002), reducing stoppages, and having less spare parts in stock. Hansen (2002) in particular, stresses the direct link between OEE and ROA and how important it is to educate the workforce to understand OEE and how their work may affect it. Another important factor is the collaboration between the production department, engineering department, and maintenance department. Especially as uncertainty levels are high and require adaptation in order create sustainable success of a company.

3.7.2. DuPont Model

The first step in using the DuPont Model is to calculate the ROA using Equation 9. The values for net income and total assets are taken from the company's balance sheet. The ROA value is then compared to companies in the same industry. The DuPont Model is used to break down ROA to evaluate the contribution of each block. The contribution can then be compared to determine how the different blocks contribute to lowering ROA. The relations between the different blocks are further described below and can be seen in Figure 8.

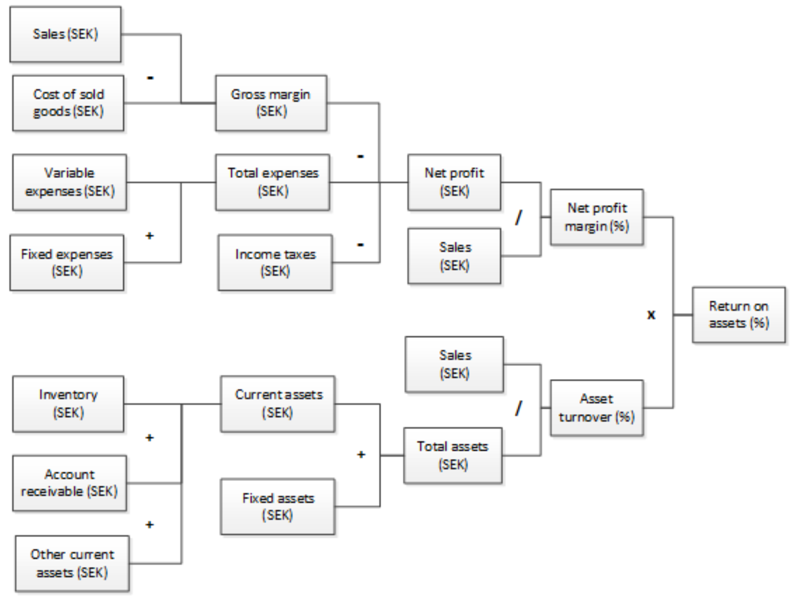

Figure 8: A description of a DuPont Model used to calculate the return on assets.

$$ROA = \frac{Net\ Income}{Sales} \times \frac{Sales}{Total\ assets} = \frac{Net\ income}{Total\ assets} \qquad (9)$$

NET PROFIT MARGIN

The net profit margin is determined by dividing net profit with sales. Net profit is the profit after accounting for all costs. It is calculated by subtracting the total expenses and income taxes from the gross margin. The gross margin is calculated by subtracting sales from cost of sold goods. Cost of goods sold are the direct costs attributed to the production of the goods sold by the company. These costs include material and the direct labour costs used to produce the goods. These costs do not include indirect costs.

Total expenses, also called business expenses, are categorized into fixed expenses and variable expenses. Fixed costs are costs that do not fluctuate dependent on goods or service produced for a given period of time and for given volume levels (Fixed costs, 2006). Fixed costs include rent, depreciation, lease payment for equipment, insurance, advertising, management salaries etc. Variable costs are directly or proportionately affected by changes in volume or activity levels (Variable costs, 2006). These costs include raw material, hourly production wages, inventory, shipping costs, packaging supplies etc.

ASSET TURNOVER

Assets are economic resources that are or can be converted into money (Sullivan and Shefferin, 2003). The asset turnover is calculated by dividing sales with total assets. The total assets are divided into current and fixed assets. The current assets are divided into three categories: inventory, account receivable and other current assets. Inventory refers to materials and goods that a business holds for sale or repair. The account receivable is money for services or goods that has not yet been paid for, and is still owned by the customers. Other current assets are liquid assets such as prepaid expenses, marketable securities, money, and equivalents. The fixed assets, also known as tangible assets, are assets and property that cannot be easily converted into cash. Fixed assets include property, plant, and equipment.

To fully understand how a specific production line related to the ROA, all values have to be evaluated based on the specific line. There are several methods a company uses to determine the contribution of a section or a department in a production plant, such as Activity-based costing. Activity-based costing further helps a business evaluate specific product and services (Engle, 2013).

4. RESULTS

This chapter presents the results and analysis of the formulated research questions. The chapter is divided into three subchapters; empirical data, addressing the choice of KPIs, and a presentation of the case study. Furthermore, the case study chapter is divided into results of the real case, future scenario 1, and future scenario 2. Due to secrecy, the majority of the quantitative results will be presented as a ratio, to only compare the quarters. The ratio is calculated based on the results from the base model, Q4.

4.1. EMPIRICAL DATA

This chapter summarizes the collected empirical data. The first part of the chapter presents the results from the conducted interviews, both semi-structured and unstructured. The second part summarizes the observations conducted. Thereafter, the empirical data regarding economy and results from the cognitive walkthrough are presented. Finally, Framtidsoperatören and their work are presented.

4.1.1. INTERVIEWS

The semi-structured interviews were held with three employees that are involved or have been involved in maintenance decisions at the company. The first interview was held with the maintenance manager, the second with an operation and maintenance engineer, and the third with the line manager responsible for the specific line. The maintenance manager is responsible for 25 shift-maintenance technicians, divided into five shifts. The manager is involved in all decisions relating to maintenance strategy, planning, and scheduling. The operation and maintenance engineer is involved in making maintenance activities more efficient and standardizing the maintenance procedures. The engineer has also a supporting function and participates in board meetings to provide managers with inputs regarding maintenance questions and decisions. The line manager is not directly involved in maintenance planning but is responsible for the operators at the line and for improving how they log failures and report errors. The line manager is also responsible for maintenance performed by the operators. Unstructured interviews have been performed with people with different responsibility within the organization. The interviews enabled discussions and resulted in information regarding the daily maintenance work, which had not been expressed during the semi-structured interviews.

The results of the interviews have been summarized in three subchapters. These describe how the company is working with maintenance today, the interviewees' view on KPIs relating to maintenance, and results from the cognitive walkthrough.

MAINTENANCE AT WELLSPECT HEALTHCARE TODAY

Maintenance at Wellspect HealthCare is continuously changing in order to reduce failures and to improve maintenance efficiency. The company has recently started implementing a rotating PM schedule on specific production lines. On the line in focus, scheduled PM is still performed on a weekly basis but with various maintenance tasks each week. This is a consequence of using agency staff, which requires fixed working hours. Each maintenance task is performed according to pre-scheduled maintenance points. The interval between specific points varies from weekly performed maintenance to maintenance performed once a year. The scheduled PM does not take the amount of production into consideration, and is only based on elapsed time. Scheduled PM points are performed both by operators and technicians. In addition, service requests are added and performed depending on the urgency of the job. Mostly, they are scheduled during unplanned production. The service requests are added when discovered, either during a scheduled PM or during planned production. All service requests are documented and reported in Aretics® and production stops are registered and monitored by the industrial system Axxos®. For each line, an operation and maintenance technician is responsible to schedule service requests during unplanned production.

If a failure occurs, the work procedure includes a 10 minutes troubleshooting performed by operators. If the problem is solved within that time, the operators log the cause of failure in Axxos®, where the fault time is saved. Stops shorter than one minute are documented automatically as short stops by Axxos®. If the operator is unable to solve the problem within 10 minutes, a technician is called. A technician arrives within 5 to 30 minutes depending on the current priority on the specific line and on the current workload of the technician. While waiting for the technician to arrive, the operator is supposed to prepare “as much as possible”. Failures repaired by technicians are documented as CM in Aretics®. If the technician has not located the source of failure within 30 minutes, a daytime operation technician is called. If the problem is not solved within 60 minutes, a service engineer is called. The team manager of the service engineers is called if the total fault time exceeds 190 minutes.

The technician who is responsible for a specific maintenance task is responsible to report the cause of a stop, action, work time, fault time, and used spare parts in Aretics®. Reporting is done manually, immediately or “when time is available”, depending on the current workload. Therefore, the dates of the actual maintenance job may differ from the date being documented. In the data, the authors observed lacking documentation in work time and/or downtime. Also, the coding of stop causes in Axxos® contained several non-coded stops in early quarters. The company is currently working on improving the reliability in the documentation of stops by placing a higher demand on correct documentation by operators and technicians. The authors have observed a reduced amount of non-coded stops in more recent quarters.

Regarding scheduled PM, the pre-scheduled maintenance points include a pre-determined working time, which only require a final reporting of the work being completed. Furthermore, there are no tools currently available at the company to facilitate troubleshooting. An operator did not find additional tools necessary, since the operators fast learns the most common problems on the line in focus.

The maintenance manager is the main initiator of improving the long-term maintenance strategy. Lean and value driven maintenance are key philosophies that have inspire ideas and improvement goals. The company currently uses MS excel, analytical methods (lean boards etc.), lean pyramid, and condition-based monitoring to evaluate maintenance. The condition-based monitoring is limited and includes temperature and similar measurements on liquids. Hence, there is no vibration monitoring or similar wear monitoring on any of the mechanical parts of the lines within the factory. Cost effect analysis is seldom used as a decision tool regarding maintenance and maintenance improvements. Even if the cost of spare parts is considered, the cost of fault time has not been evaluated or considered before decisions are made. Instead, the focus has been on increasing the technical availability in the factory and using common sense to reduce unnecessary PM points. Scheduled PM and inspection points have been removed depending on if it has a direct effect on the product or not. Points that are not directly affecting the final product have been removed or performed less frequent. Different methods have therefore been implemented to make the maintenance more efficient. Examples of improvements are: kitting before maintenance, collaboration between the production department and the production support department when planning the weekly maintenance, balancing lines, and reducing the fault time for maintenance on the line with highest priority. Overall, the production uptime and technical availability has a higher priority than evaluating the cost of maintenance and are therefore important factors in the production support department's long term cost reduction strategy.

Everyday maintenance decisions are dependent on predetermined classifications. These classifications are based on the current prioritization order. On a shop floor level, the number of complaints by an operator also affects the prioritization. Typically, the loudest operator gets a higher priority. In addition, the company does not have previous experience of simulation.

KPIs

KPI relating to maintenance has recently been implemented. During the later part of 2013, the department added the evaluation of technical availability, the ratio of scheduled PM/CM by technician/service request, scrap due to machine failure, MTBF, and MTTR. Technical availability has been in focus since it shows production support department's impact on production. Technical availability, MTBF and MTTR are extracted from Axxos®. Ratio of scheduled PM/CM by technician/service requests is compiled based on data from Aretics®. Both the maintenance manager and the maintenance engineer gave current KPIs a score of four on the adequate scale from one to ten. The motivation behind the low score was that data was currently not evaluated in an efficient way. KPIs are only evaluated on the whole production and not yet on line level, let alone on a section level. The maintenance engineer did also question the reliability of the data since the technicians currently lack standards on how to document in Aretics®.

As mentioned in previous subchapter, the company is working with continuous improvement. The KPIs are evaluated and correspond to the KPIs measured on all companies within Wellspect

Operations. The goals of the organization can also be shown in the personal goals of each technician. These are determined and evaluated together with the maintenance manager.

OVERALL PROBLEMS AND IMPROVEMENT AREAS

The production support department has been through radical changes during the recent year and has mainly focused on making scheduled PM more structured and time efficient. The improvements were focused on allocating reasonable times for each scheduled PM and on making each task more time efficient. Next phase for the company is to improve the prioritization of PM and to identify and start analyzing the factory on a line level. Another focus area is to reduce fault time and to find reoccurring errors. There is also a need to increase communication between departments and between responsibility areas to facilitate cooperation and change initiatives. Documentation is also in focus and the process of deciding on a standard is in progress. Both the maintenance manager and the maintenance engineer highlighted the problem of lacking standardized work, especially regarding documentation. Furthermore, it is desired to define the relation between PM and failure, and to identify which failures should be reactive and which require continuous inspection and maintenance. Lastly, the maintenance manager argues for improving classification of spare parts by investigating which should be in-house and how the use of nearby suppliers can reduce inventory.

ECONOMICS

To find an appropriate economical approach of the production line in focus and its associated products, the authors had help from a financial operations controller in the financial department. Due to confidentiality, no real numbers is allowed in this report. The financial department has neither been allowed to inform the authors about selling prices of the products. Therefore, the authors have assumed a price for each product, based on the purchased price from a customer in Sweden.

Wellspect HealthCare calculates cost per product, including costs of personnel, material, pre-production, spare parts, facilities, etc. The authors have therefore, after discussion with the financial operations controller, let the cost of production depend on products produce. When the line stops due to unplanned causes, the cost consists of waiting personnel and an additional cost if a technician is called. Since there is no need to produce as much as possible, it is not possible to argue for the loss of products produced.

4.1.2. COGNITIVE WALKTHROUGH

During the cognitive walkthrough, the test person’s first reaction to the user interface was the extensive content of information and high level of detail. The interface contains information that the test persons could not directly relate to, and which required some reflection. However, after reading instructions in the interface, the test persons understood the concept and were able to mark certain details that were later improved. One proposal was to hide sheets with extensive inputs and outputs. Furthermore, a suggestion was to make two types of external documents; the first with a low level of detail and the second with a high level of detail. The sheets with high level of detail included extensive instruction. The idea was to increase usability of the simulation model by creating a user interface independent on how familiar the user is with the line in focus. In addition, it was desired to separate instructions with pictures. Lastly, more diagrams and graphs were desired to simplify the output. Overall, there were positive attitudes toward simulation as a decision tool regarding maintenance planning.

4.1.3. OBSERVATIONS

Observations were held at the company to reach an understanding on how the production support department works with maintenance, what difficulties exist, and to identify current needs. During the thesis, several changes have been observed. The production support department has implemented lean boards, which show the technical availability, goals, and suggested improvement steps. The boards are standing in the coffee room and can easily be discussed during a break. New communication line and opportunities to discover and reflect on the effect of maintenance work have therefore been observed. These observations correspond to the interviewees' statement that the department is continuously improving their current way of working.

4.1.4. FRAMTIDSOPERATÖREN

The authors were introduced to the project Framtidsoperatören through a workshop arranged at GTC. Participants were representatives from GTC, industrial partners, and developers of Framtidsoperatören. The workshop included a presentation of tools aiming to assist operators in their daily work. Furthermore, brainstorming and discussions were held in order to give feedback on the tools that had been presented, some of which could be relevant to this thesis. Framtidsoperatören suggested digital work instructions, preferably accessed by a smart phone. Information in a digital format enables the user to easy select between different levels of detail in the instructions. The participant also discussed tools to reduce the time for troubleshooting including a list with common errors. When the error is found, the user receives work instructions, which enables the operator to start the repair while waiting for a technician. Involving and assisting the operators through tools may reduce fault time. When this report was written, Wellspect HealthCare was participating in a pilot study regarding the use of tools developed by Framtidsoperatören.

4.2. KPIS TO USE

KPIs used to quantify effects of maintenance were determined based on interview, cognitive walkthroughs, and theory. From interviews, the authors identified relevant KPIs used at the company today; MTBF, MTTR, and technical availability. MTBF describes how often failures occurs, MTTR is the mean time for each stop, and technical availability is the availability of the line excluding setup, material filling, and lacking raw material. These KPIs are used at the company to measure how the work performed by the production support department impacts the production on a factory level. Thus, the company is familiar with these measurements and understands how to interpret them. This was the main reason why the authors assessed MTBF, MTTR, and technical availability as relevant, and why these were further used to analyze the impact of maintenance, not only on a line level but also on a section level. Furthermore, the KPIs are easily extracted from the industrial system, and should be used to update the model and identify new critical maintenance areas.

Theory specifies various KPIs that can be used to simplify the comparison between the different sections and to find a breakeven point to determine when PM still is economically sustainable. The ratio of PM to CM is currently measured on a factory level and can further be measured on a section level to determine the effectiveness of PM activities. In addition, CM ratio can be used to determine the reliability of the sections.

Results from the cognitive walkthrough showed an interest in measuring the cost of various maintenance activities (e.g. PM and CM) in relation to the total maintenance cost. Therefore, a relevant cost KPI was determined; ROA, which gives an indication of how profitable a productions line, is in relation to its assets. CM cost ratio was selected from the list of KPIs presented by International Standards (2011).

4.3. Case Study

Results from the case study will be presented in terms of KPIs stated above. The case study was divided into a comparison between three quarters and two future scenarios. The subchapter of the real case will present the results on a line level and on a section level. Results from future scenario 1 and future scenario 2 will only be presented as a result on the whole line.

4.3.1. Real Case

This subchapter presents the results of the comparison between the three quarters. First, results of the whole line will be presented in terms of performance and time, cost, and return on assets. Next, the sections are analyzed to understand the holistic result from the line analysis. The results and analysis on a section level compare Q4 and Q1. Q3 was not used due to the lack of logged failure causes.

Performance

The performance was measured using technical availability, MTBF, and MTTR. Furthermore, the total fault time was divided into failures which can be fixed by an operator and failures which require a technician. Figure 9 shows an increase in MTBF and technichal availability between Q3 and Q4, meaning failures occurred less frequent. From Q4 to Q1, both technical availability and MTBF decreased. In regards to MTTR, it decreased through all quarters, meaning that mean downtime for a stop has continuously become shoorter. Figure 9 also shows that the standard deviation on all KPIs have reduced, indicating increased reliability, which is essential in order to understand and perform correct maintenance procedures. The values of Figure 9 can be seen in Table 1.

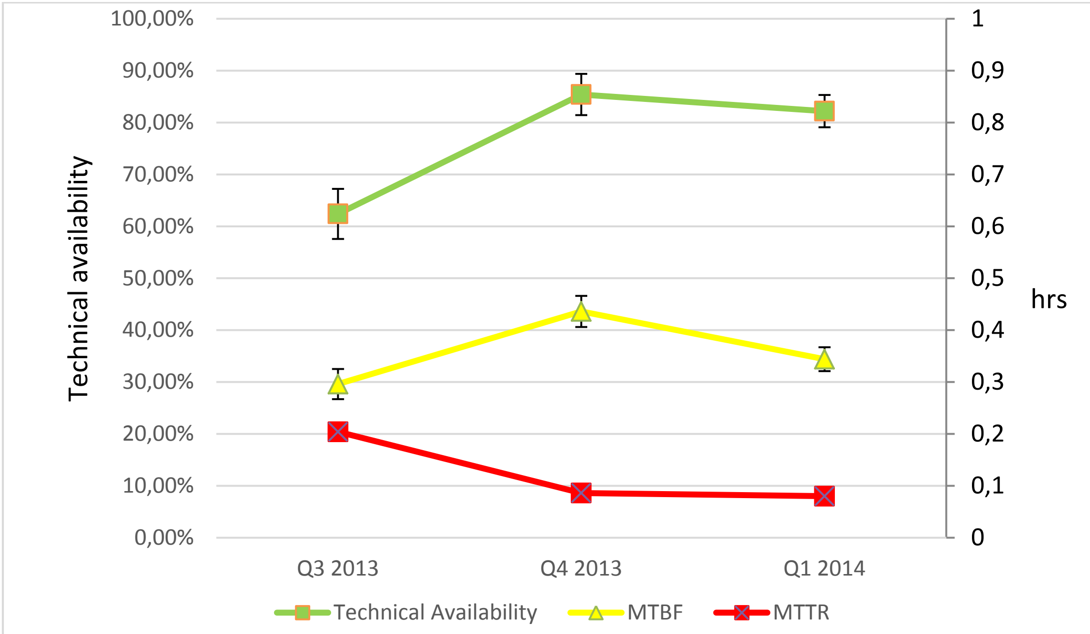

Figure 9: Results of technical availability, MTBF and MTTR

Table 1: Table of values presented in Figure 9.

	Q3 2013	Q4 2013	Q1 2014
Technical Availability	62.4%	85.4%	82.2%
Standard deviation	4.8%	3.9%	3.1%
MTBF (hrs)	0.296	0.436	0.344
Standard deviation (hrs)	0.029	0.03	0.023
MTTR (hrs)	0.204	0.086	0.08
Standard deviation (hrs)	0.015	0.014	0.012

Technical availability measure the proportion of the planned production time in which it was possible to produce. Therefore, technical availability has a direct impact on products produced. Products produced increased by 24% between Q3 and Q4, and decreased slightly by 4% between Q4 and Q1. The results can be seen in Figure 10 and Table 2.

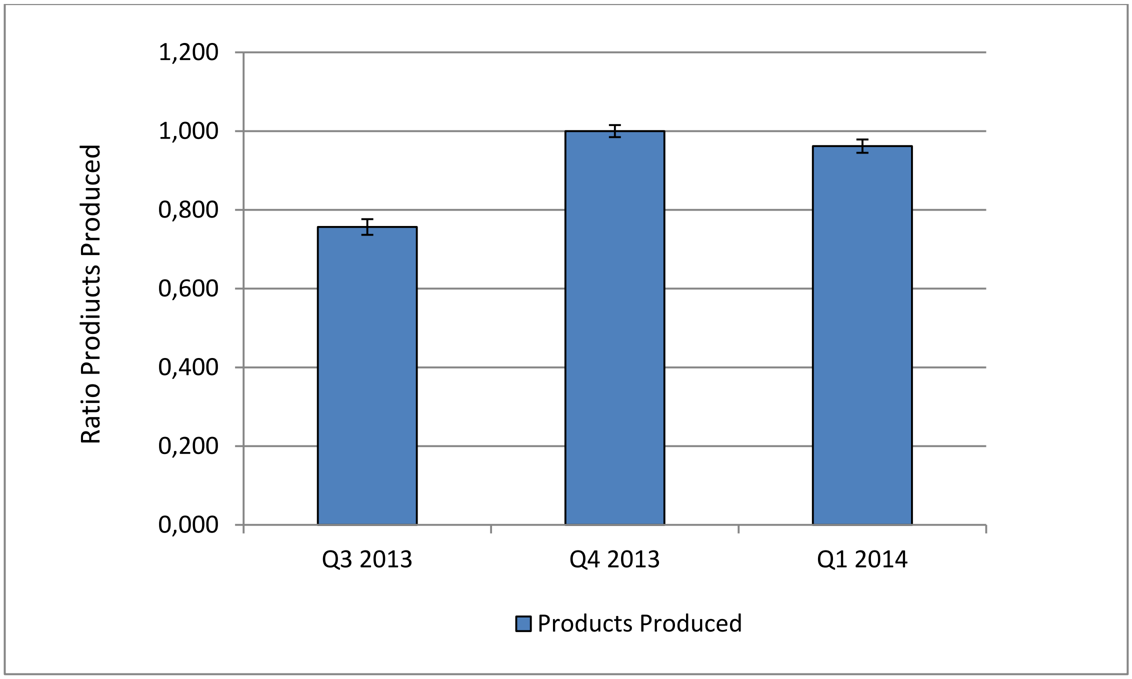

Figure 10: Products produced for the different quarters, relative Q4 2013.

Table 2: Table of values presented in Figure 10.

	Q3 2013	**Q4 2013**	**Q1 2014**
Products Produced	0. 76	1. 00	0. 96
Standard deviation	0. 020	0. 015	0. 017

Figure 11 and Table 3 show the results of total fault time and total PM time (man-hrs) in Q3, Q4, and Q1. The fault time reduced greatly between Q3 and Q4, and increased slightly in Q1. The result is consistent with information received during the interview, where the need to focus on finding chronic faults and reducing total fault time was discussed as a next improvement step.

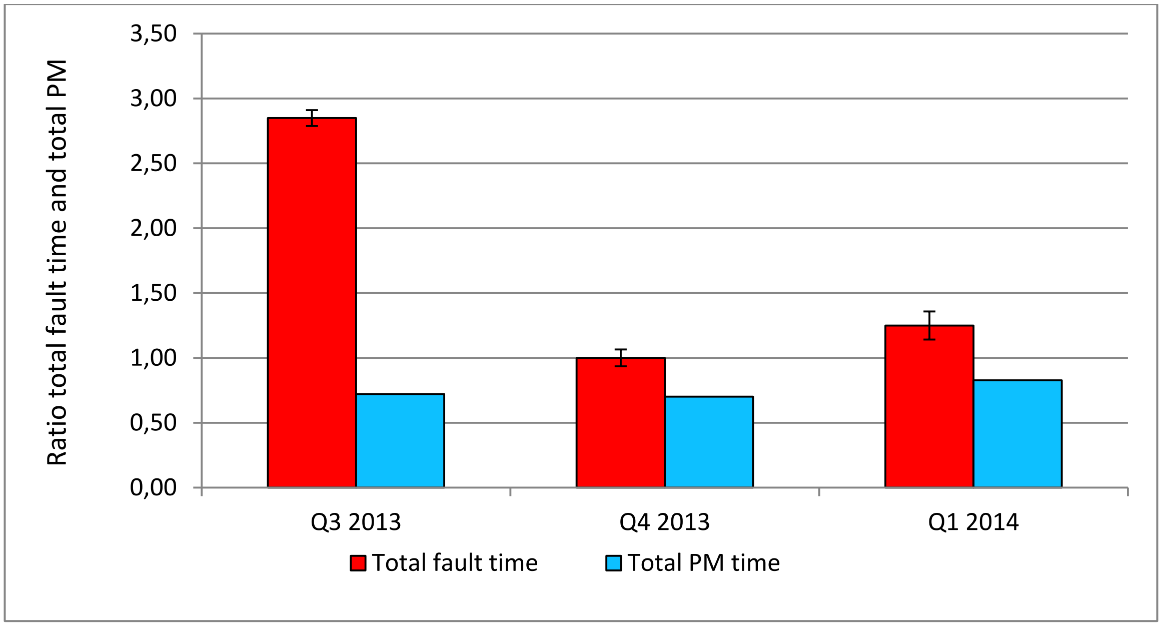

Figure 11: Diagram of time spent on different maintenance strategies relative total fault time Q4 2013.

Table 3: Table of values presented in Figure 11.

	Q3 2013	Q4 2013	Q1 2014
Total fault time	2.85	1.00	1.25
Standard deviation	0.01	0.07	0.11
Total PM time	0.72	0.70	0.83

In this case, it is important to include the number of performed PM since it has increased radically in Q1 compared to the other two quarters. The result suggests that the dedicated time for each PM task was reduced in Q1, since the dedicated resources have roughly remained the same. This result is consistent with information received during interviews, in which the interviewees' described an increase number of maintenance points and the revision of allocated time for each maintenance task. This can be seen in Figure 12 and Table 4.

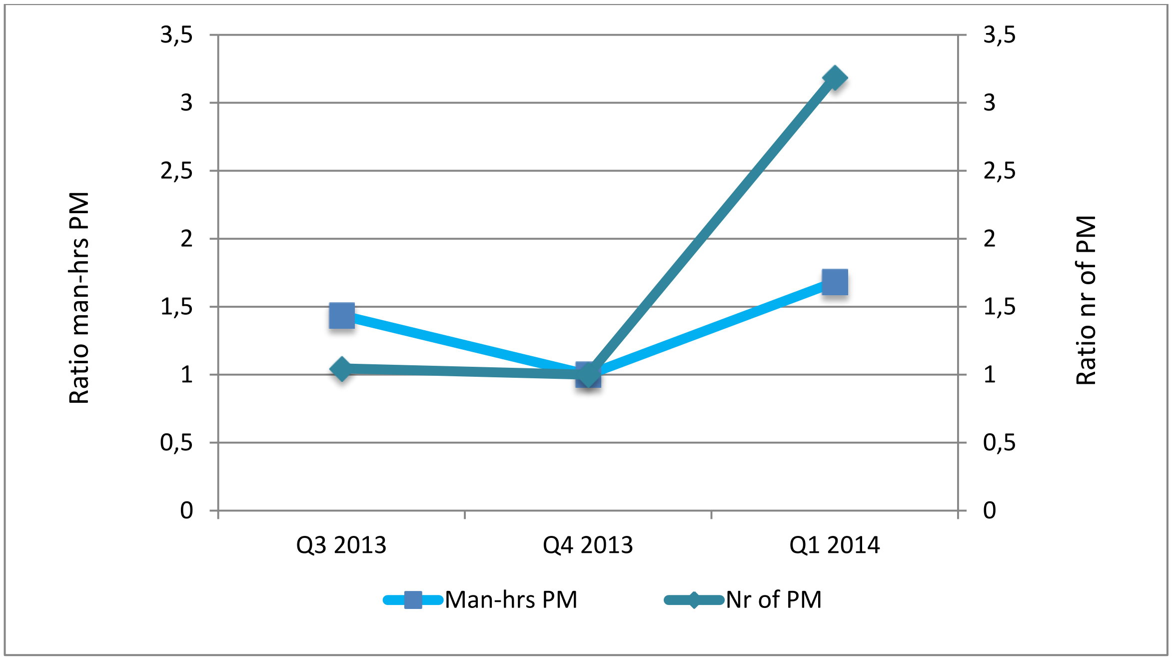

Figure 12: Graphs of number of scheduled PM and man-hrs spent on scheduled PM.

Table 4: Table of values presented in Figure 12.

	Q3 2013	Q4 2013	Q1 2014
Man-hrs PM	1.44	1	1.68
Nr of PM	1.05	1	3.19

Figure 13 and Table 5 gives an overall indication of how total fault time, CM by technician, scheduled PM, and service request has varied between quarters and how these might relate to each other. A further investigation shows that CM by technician, and its corresponding standard deviation, has roughly been halved between Q3 and Q1, indicating a reduced and more stable CM by technicians. Total fault time has increased between Q4 and Q1, meanwhile CM by technician has reduced in the same time period, which suggests that operators have managed to correct more failures in the last quarter compared to previous quarter.

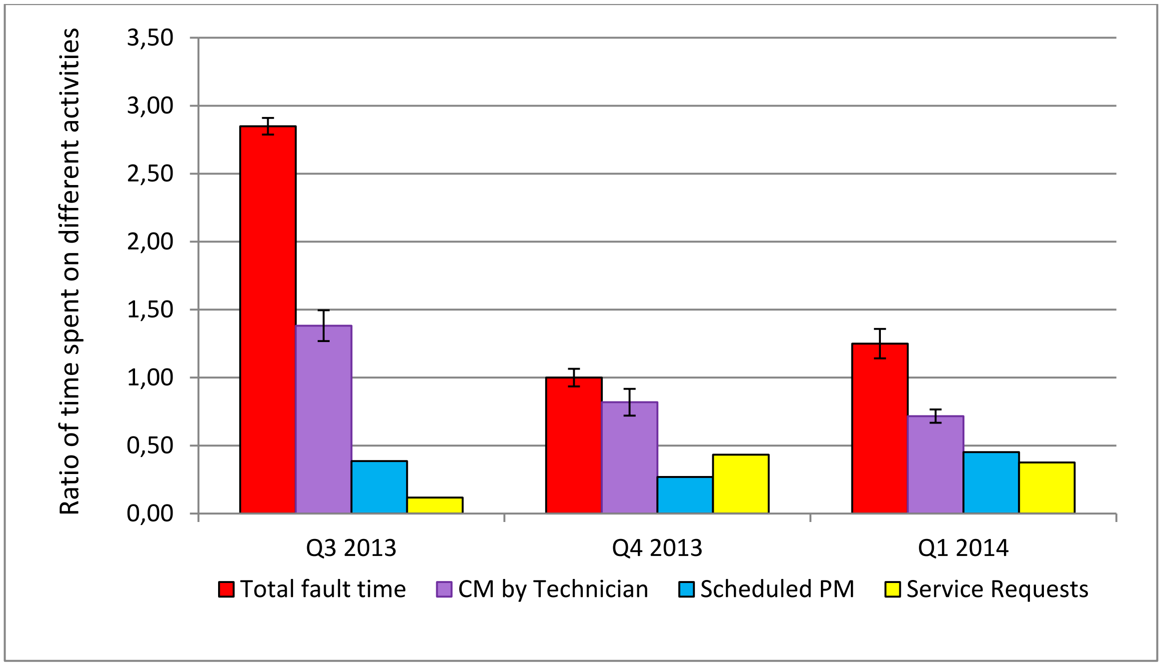

Figure 13: diagram of time spent on different maintenance tasks, relative total fault time Q4 2013.

Table 5: Table of values presented in Figure 13.

	Q3 2013	Q4 2013	Q1 2014
Total fault time	2.85	1.00	1.25
Standard deviation	0.06	0.06	0.11
CM by Technician	1.38	0.82	0.72
Standard deviation	0.11	0.10	0.05
Scheduled PM	0.39	0.27	0.45
Service requests	0.12	0.43	0.38

Figure 13 and Table 6 describes how total fault time was reduced. Figure 14 and Table 6 describes the deviation of different maintenance tasks; CM by operator, CM by technician, service requests, and scheduled PM. It does also show that less time spend on maintenance reduced from Q3 and Q4, and slightly increased to Q1.

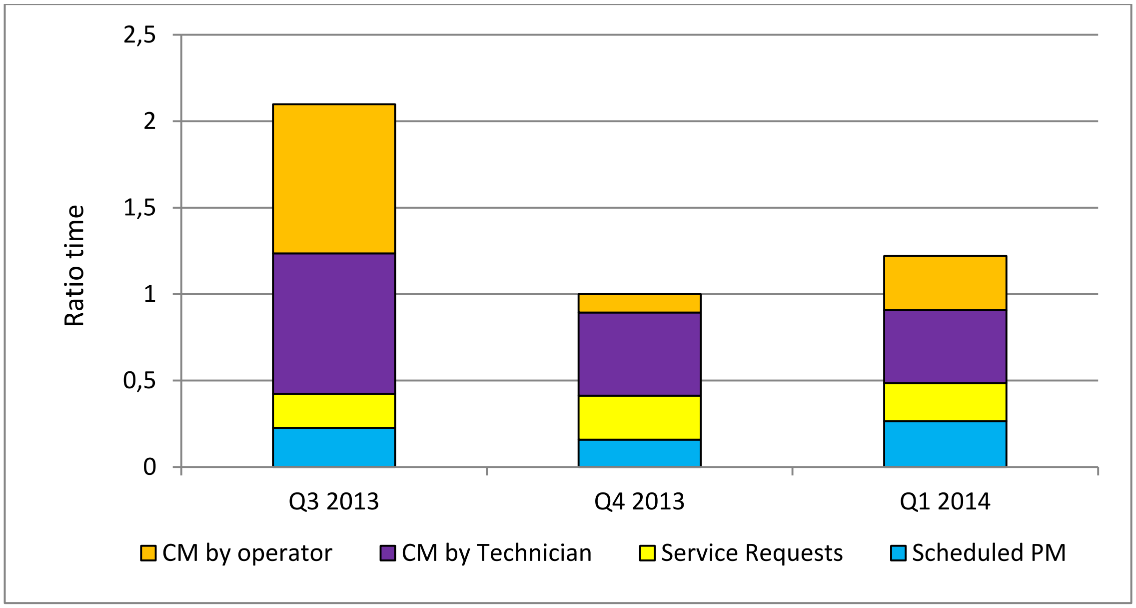

Figure 14: Diagram of amount of time spent on different maintenance tasks relative total maintenance time of Q4.

Table 6: Table of values presented in Figure 14.

	Q3 2013	Q4 2013	Q1 2014
CM by Operator	0.86	0.11	0.31
CM by Technician	0.88	0.48	0.42
Service request	0.20	0.25	0.22
Scheduled PM	0.23	0.16	0.27

A comparison between the repair time for operators and for technicians show that technicians were working a major part of total fault time in Q4, while operators tend to fix more stops in Q3 and Q1, see Figure 15 and Table 7. The increased amount of CM by technicians in Q4 could be explained by the increased spare part replacements, observed by the authors, compared to Q3 and Q1.

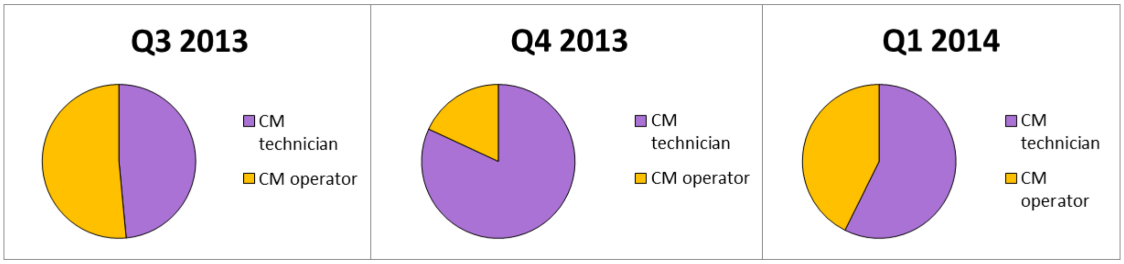

Figure 15: Diagrams of distribution of workload (time) during fault time between operators and technicians.

Table 7: Table of values presented in Figure 15.

	Q3 2013	Q4 2014	Q1 2014
CM Technician	49%	82%	57%
CM Operator	51%	18%	43%

COST

The cost of different maintenance activities (e.g. PM and CM) was compared between the three quarters. Figure 16 and Table 8 shows how total cost of maintenance has varied between Q3 and Q1. The largest difference is the 63 relative percentages reduced total cost in Q4 compared to Q3. In Q1, total cost increased slightly by 4 relative percentages compared to Q4. Overall, the results show a higher cost of PM in Q4 compared to both Q3 and Q1.

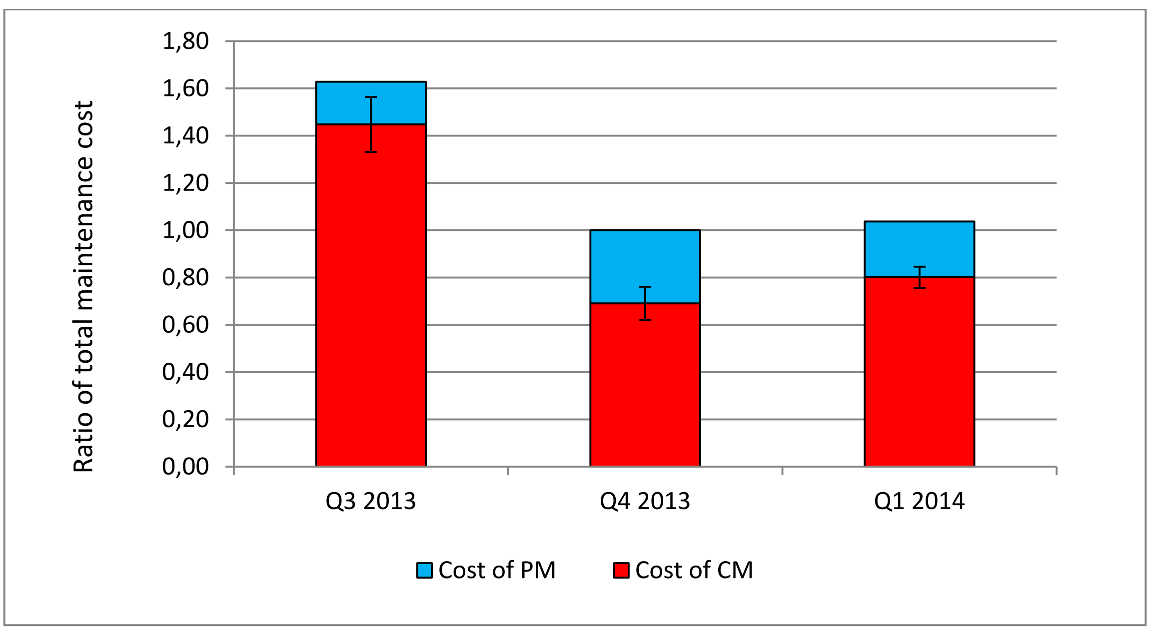

Figure 16: Diagram of Total maintenance cost relative total maintenance cost Q4 2013.

Table 8: Table of values presented in Figure 16.

	Q3 2013	Q4 2013	Q1 2014
Cost CM	1.45	0.69	0.80
Standard deviation	0.12	0.07	0.04
Cost PM	0.18	0.31	0.24
Total maintenance cost	1.63	1	1.04

The cost was calculated based on time and hourly cost of packaging personnel, operators and technicians respectively, and any spare parts exchanges. Figure 17 and Table 9 shows the distribution between PM and CM. The diagram show CM ratio in relation to total maintenance cost has decreased from 89% to 69% in Q4 compared to Q3, while it increased again to 77% in Q1.

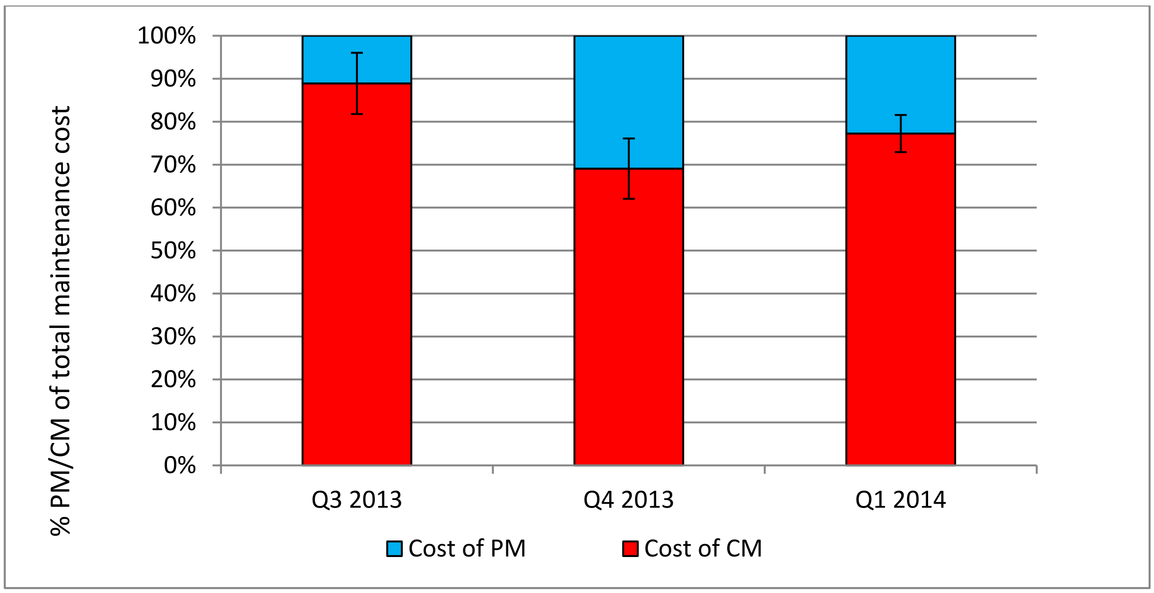

Figure 17: Percentage of cost of PM and CM, of total maintenance cost

Table 9: Table of values presented in Figure 17.

	Q3 2013	Q4 2013	Q1 2014
Cost PM of Total Maintenance cost	11%	31%	23%
Cost CM of Total Maintenance cost	89%	69%	77%

The cost of maintenance activities was divided into cost of personnel and cost of spare parts exchanges. To determine the major cost of maintenance, these were analyzed and compared between the quarters. From Figure 18 and Table 10 it is evident that the major cost factor of CM is personnel costs with 98%, 85%, and 81% of the total maintenance cost respectively. Regarding the cost of PM, cost of personnel was only 56% in Q4 compared to 96% and 84% respectively for Q3 and Q1, see Figure 19 and Table 11.

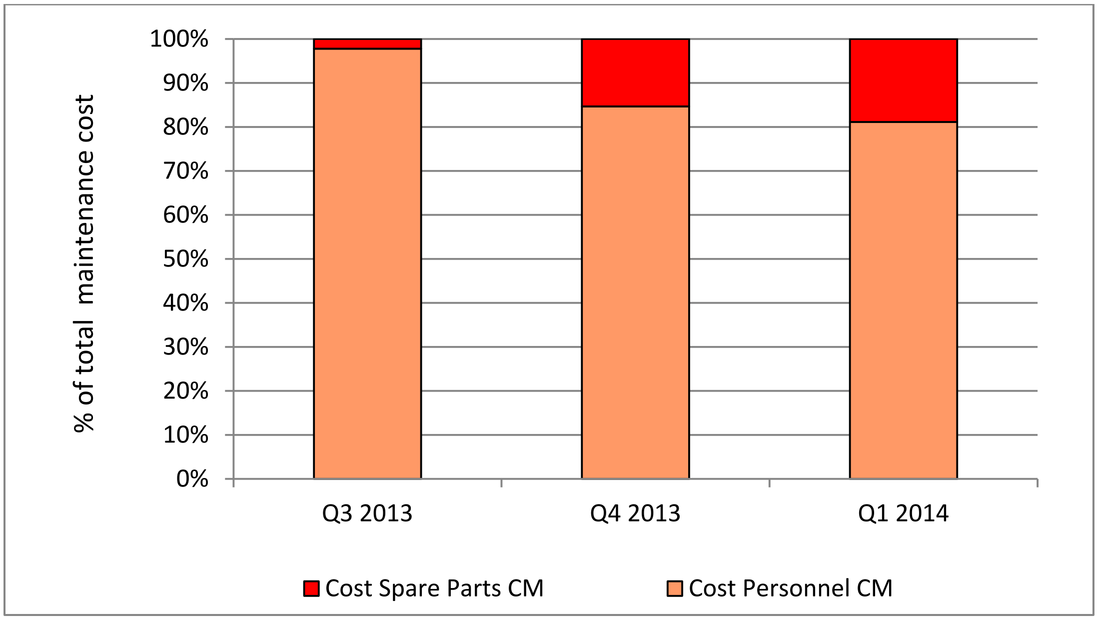

Figure 18: Cost of spare part and cost of personnel compared to total CM cost

Table 10: Table of values presented in Figure 18.

	Q3 2013	Q4 2013	Q1 2014
Cost of spare parts CM	2%	15%	19%
Cost of personnel CM	98%	85%	81%

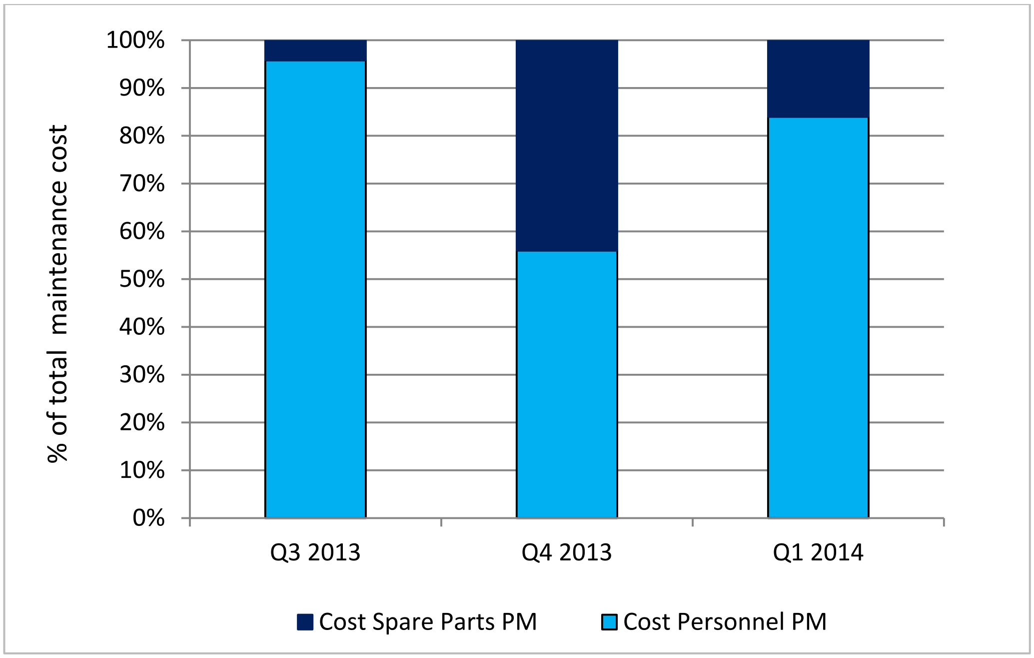

Figure 19: Cost of spare part and cost of personnel compared to total PM cost

Table 11: Table of values presented in Figure 19.

	Q3 2013	Q4 2013	Q1 2014
Cost of spare parts PM	4%	44%	16%
Cost of personnel PM	96%	56%	84%

Even if the relative cost of spare parts exchanged in PM was higher in Q4, total maintenance cost and total fault time was lower compared to the other two quarters. Figure 16 and Figure 17 shows that the major part of total maintenance cost is the cost of CM, which means that a lower total fault time reduces the total maintenance cost. Furthermore, the results show that Q1 had a higher total fault time compared to Q4, but a lower rate of assistance from technicians and MTTR. This suggests that Q1 had more frequent, but shorter stops handled by the operators. The increase in stoppages and decrease in average stop time, indicates that the increase in number of spare part exchanges in Q4 resulted in an increased number of small stoppages in Q1. According to the bathtub theory, these stoppages could be due to installation problems.

A deeper look into personnel costs of maintenance is shown in Figure 20 and Table 12. Before making further analyzis, it is important to state that the model considers technicians as more expensive than operators. Hence, cost of CM by technican per man-hour is more expensive than cost of CM by operator per man-hour. Cost of scheduled PM and cost of service request is divided between operators and technicans and relate to the distribution of finishied PM and service requests reported in Q4. Q4 shows the highest amount of cost of CM by technicians and service requests, which may be explained by the higher proportion of spare part replacements in Q4 as stated above. Figure 21 and Table 13 show the percentage distribution between the maintenance tasks in each quarter. Overall, the results show that personnel cost due to failures (CM by operators and CM by technicians) is most costly.

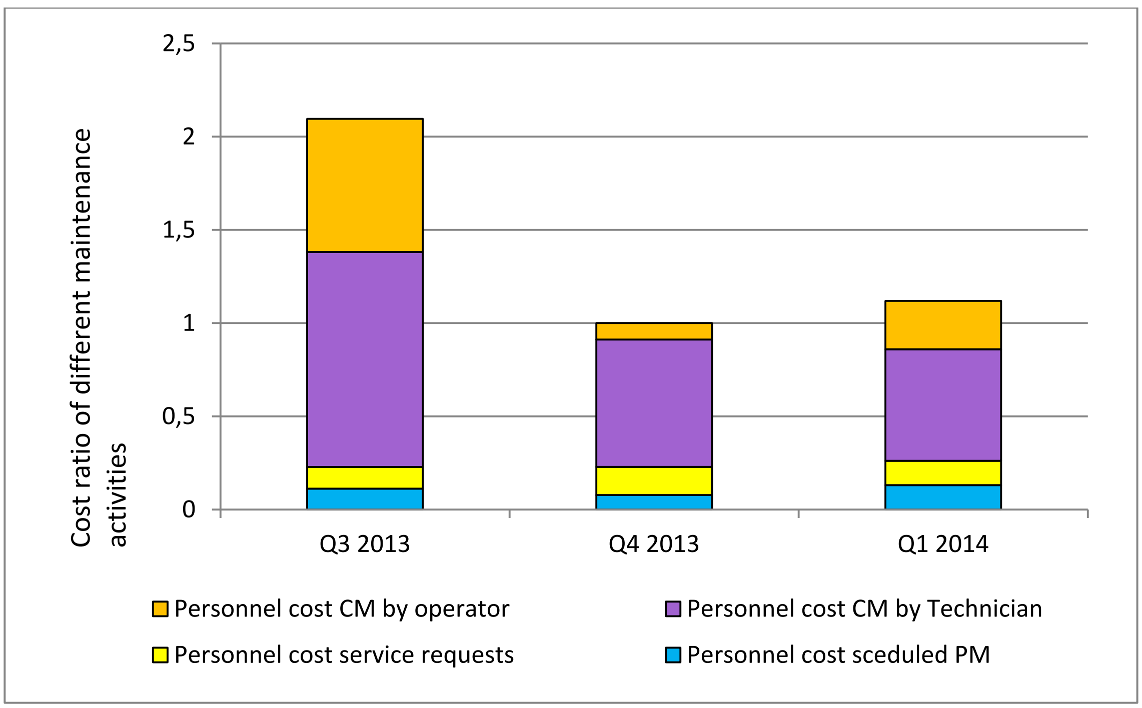

Figure 20: Personnel costs of different maintenance tasks, relative total maintenance cost Q4 2013.

Table 12: Table of values presented in Figure 20.

	Q3 2013	Q4 2013	Q1 2014
CM by operator	0.71	0.09	0.26
CM by technician	1.15	0.68	0.60
Service request	2	0.15	0.13
Scheduled PM	0.11	0.08	0.13

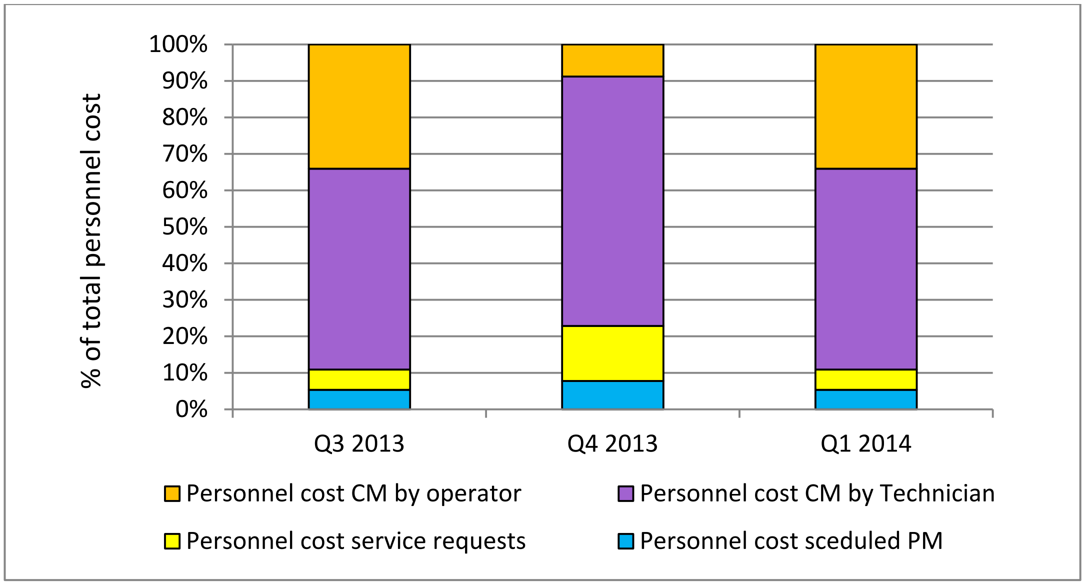

Figure 21: Amount of total personnel cost spent on different maintenance tasks

Table 13: Table of values presented in Figure 21.

	Q3 2013	Q4 2013	Q1 2014
Cost CM by operator	34%	9%	34%
Cost CM by technician	55%	68%	55%
Total cost service request	6%	15%	6%
Total cost scheduled PM	5%	8%	5%

RETURN ON ASSETS

ROA was calculated based on products produced and the cost of CM. Cost and sales prices for one product and the companys total assets was assumed to be the same between the quaters. Products produced affect the ROA in a positive way, while CM affect the result negativetly. The results can be seen in Figure 22 and Table 14. From Q3 to Q4, ROA increased by 31%, and from Q4 to Q1 it decreased by 5%. Assuming that ROA only depends on products produced and cost of CM, the curve of ROA follow the curve of technical availability. The higher technical availability, the higher amount of products produced which generates a higher income. Higher technical availability does also mean a lower cost of CM.

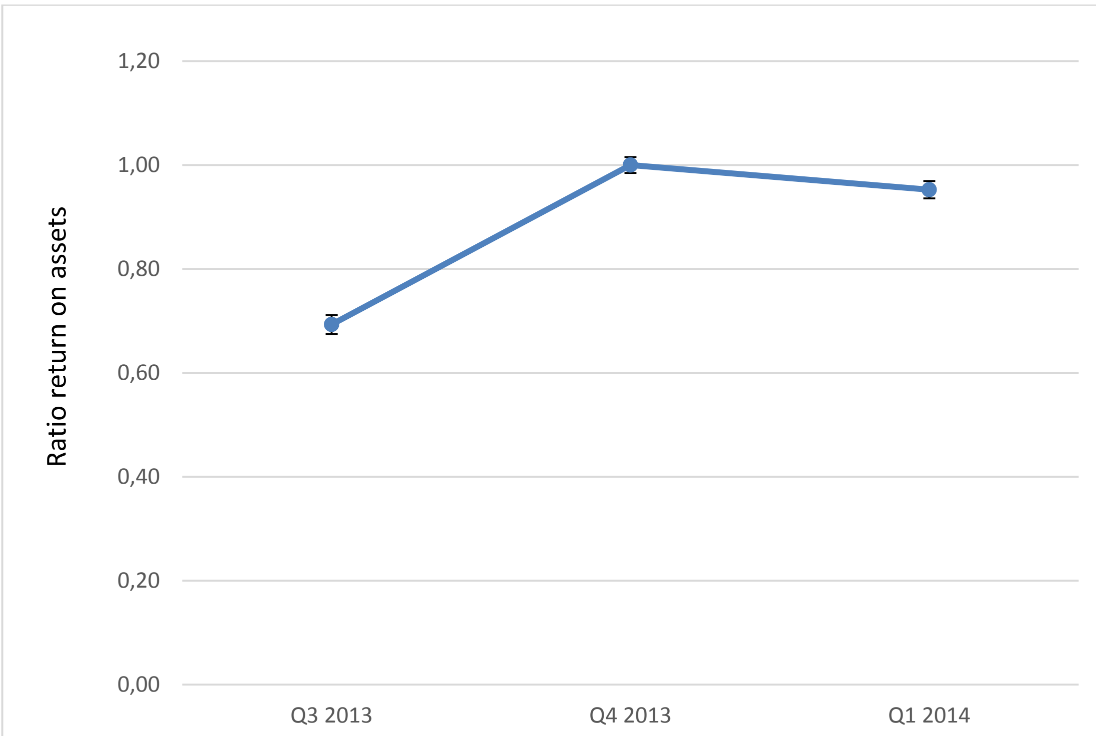

Figure 22: Graph of return on assets, relative Q4 2013.

Table 14: Table of values presented in Figure 22.

	Q3 2013	Q4 2013	Q1 2014
Return on assets	0.69	1	0.95
Standard deviation	0.02	0.02	0.02

SECTIONS

A holistic analysis of the whole production line shows an increase of total fault time between Q4 in 2013 and Q1 in 2014. Since the production line consist of 47 sections, each section was analyzed to evaluate the relation between PM and CM. After comparing total fault time and scheduled PM in Q4 respective Q1, the sections were divided into 7 different groups. Each group consisted of sections with similar or closely similar behavior. The division created four significant groups; increased PM resulting in reduced total fault time, increased PM resulting in increased total fault time, increased PM resulting in total fault time kept at zero, and decreased PM resulting in increased CM.

To find the relation between total PM time and total fault time, a similar comparison was conducted, resulting in the same significant groups. An example of the first group is shown in Figure 23 and Table 15, indicating that increased PM resulted in decreased total fault time. Ten sections demonstrated a similar behavior.

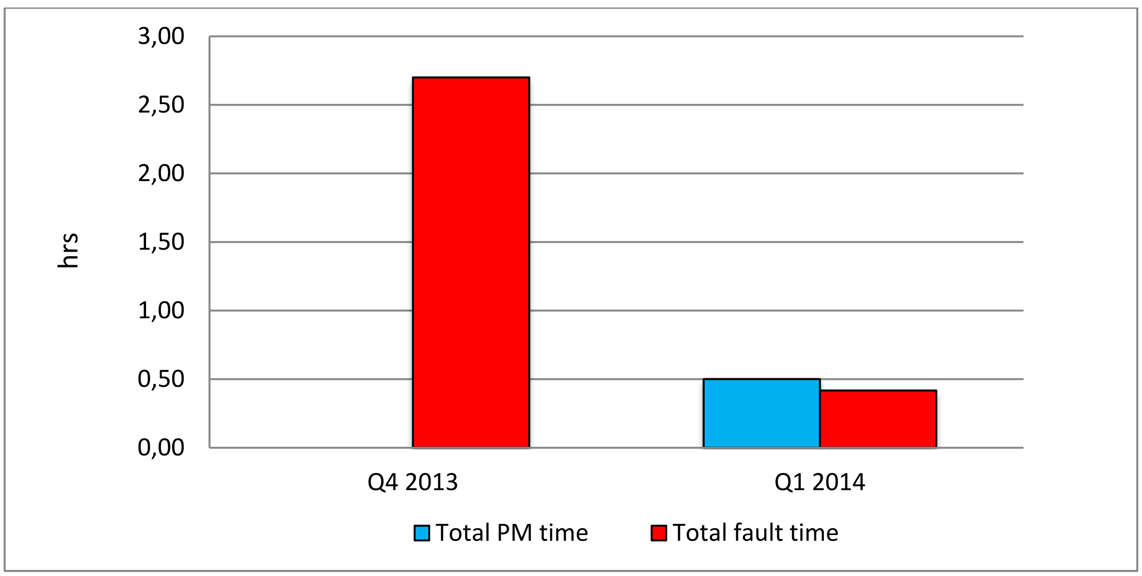

Figure 23: Increased PM resulting in reduced total fault time.

Table 15: Table of values presented in Figure 23.

	Q4 2013	Q1 2014
Total PM time	0.0	0.5
Total fault time	2.7	0.42

An example of the second group is shown in Figure 24 and Table 16, indicating that increased PM resulted in increased total fault time. 12 sections were included in this group. The third group is shown in Figure 25 and Table 17, indicating that increased PM kept total fault time at zero. 12 sections were included in this group. The fourth group is shown in Figure 26 and Table 18, indicating that decreased PM resulted in increased total fault time. 7 sections were included in this group.

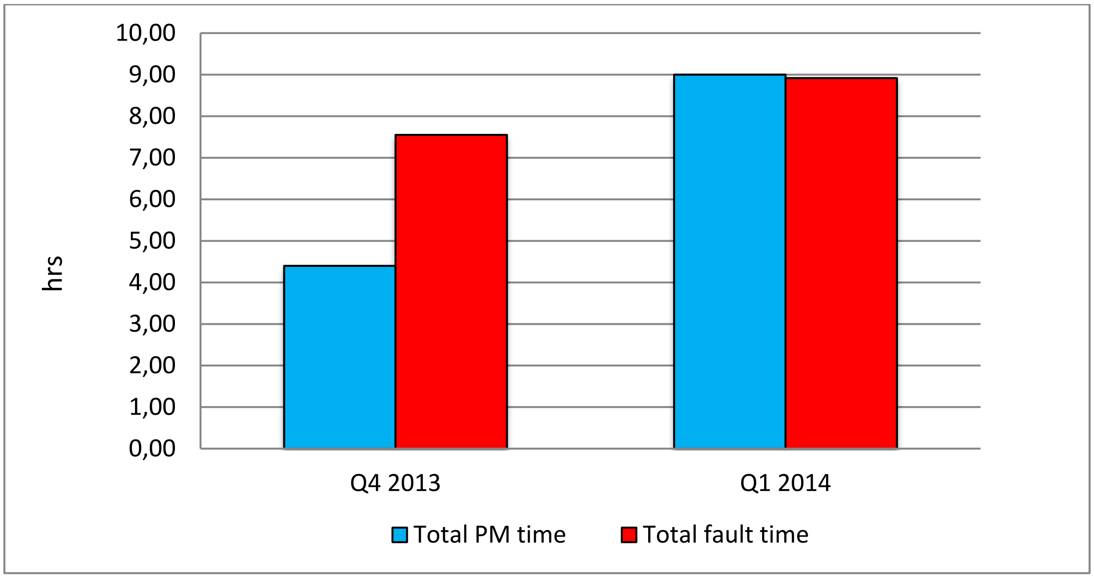

Figure 24: Increased PM resulting in increased total fault time.

Table 16: Table of values presented in Figure 24.

	Q4 2013	Q1 2014
Total PM time	4.40	9.0
Total fault time	7.55	8.92

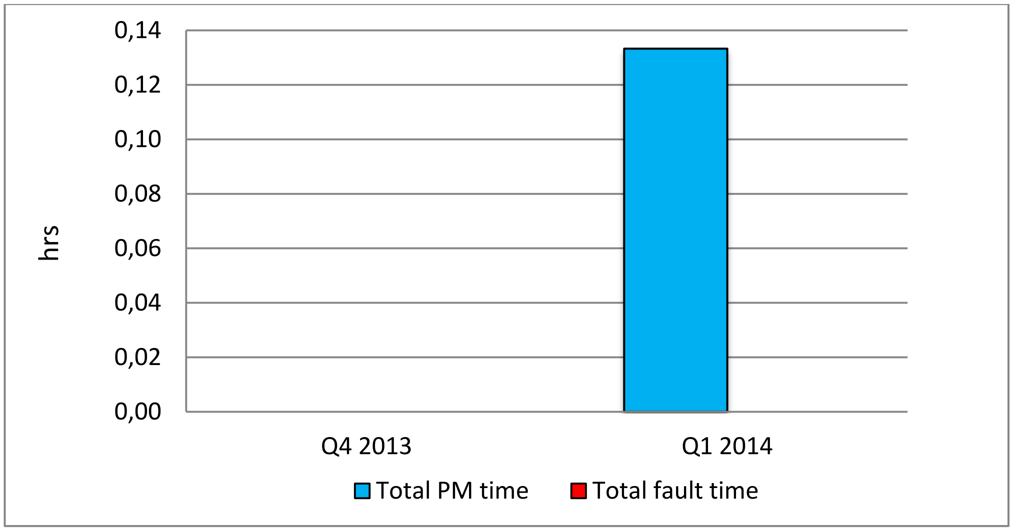

Figure 25: Increased PM Resulting in total fault time kept at zero.

Table 17: Table of values presented in Figure 25.

	Q4 2013	Q1 2014
Total PM time	0.0	0.13
Total fault time	0.0	0.0

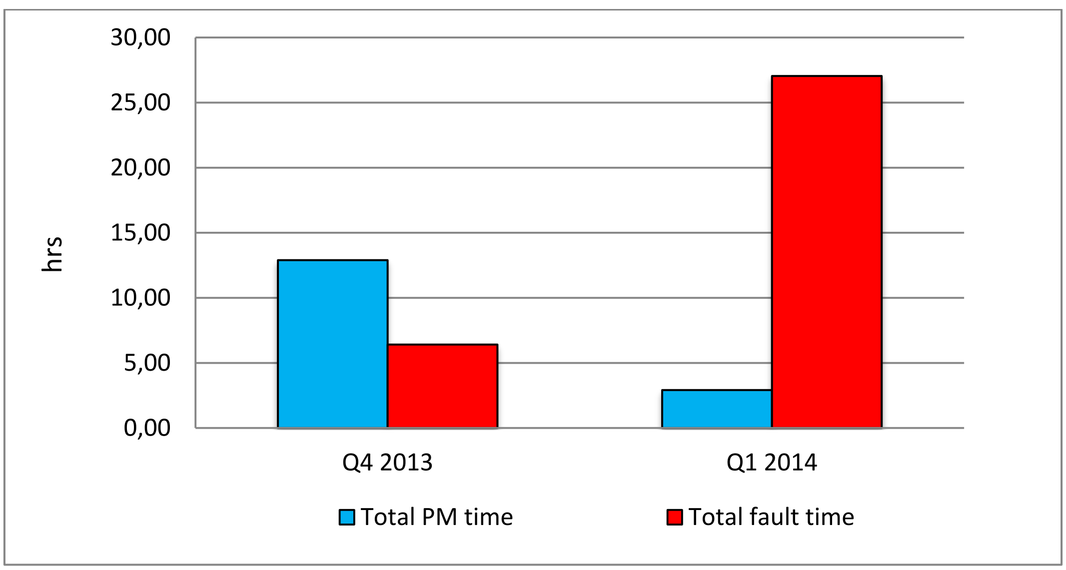

Figure 26: Decreased total PM resulting in increased total fault time.

Table 18: Table of values presented in Figure 26.

	Q4 2013	Q1 2014
Total PM time	12.90	2.92
Total fault time	6.42	27.05

The remaining groups included three, two, respective one section. The behavior of these groups were; decreased PM resulting in decreased total fault time, decreased PM resulting in unchanged total fault time, and unchanged PM resulting in increased total fault time respectively.

Group one and four indicate a direct relation between PM and CM, while group two suggests the opposite. The results will be further discussed in chapter 5.

4.3.2. FUTURE SCENARIO 1

Scenario 1 was simulated to show how simulation could be used to evaluate the effects of using tools to assist operators in troubleshooting for causes to a failure. The main focus was to providing operators with repair instructions; to give them information on how to initiate and prepare for more advanced repairs while waiting on a technician. The time reduction of MTTR was assumed to be 5% for each section. The analysis of scenario 1 was conducted as an overall analysis of the whole line, with the purpose to simulate the effect of increased operator initiative on production performance, production time, cost, and ROA.

PERFORMANCE

Figure 27 and Table 19 shows an increased technical availability compared to Q4, which is explained by a shorter MTTR resulting in more available production time and a higher MTBF. The result shows a potential to decrease total fault time by 4%, described by Figure 28 and Table 19. Involving operators is a key improvement to reducing MTTR. Not only would it allow for operators to contribute with their own knowledge, but it would also stimulate motivation.

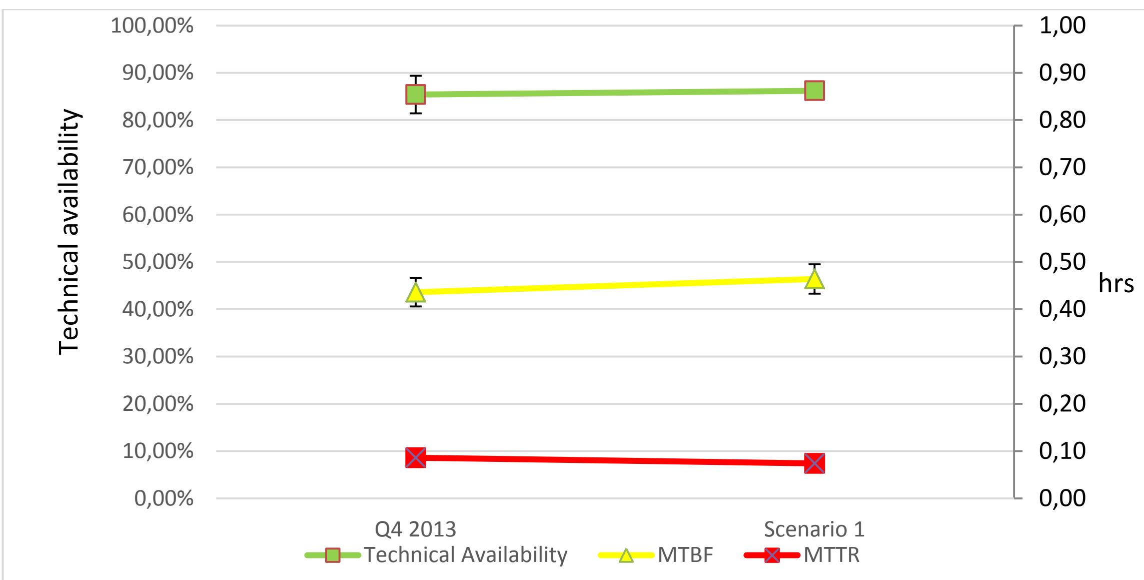

Figure 27: Graphs of technical availability, MTBF and MTTR for Q4 and Scenario 1.

Table 19: Table of values presented in Figure 27.

	Q4 2013	Scenario 1
Technical Availability	85.4%	86.2%
Standard deviation	3.9%	1.1%
MTBF (hrs)	0.436	0.464
Standard deviation (hrs)	0.03	0.031
MTTR (hrs)	0.086	0.074
Standard deviation (hrs)	0.014	0.011

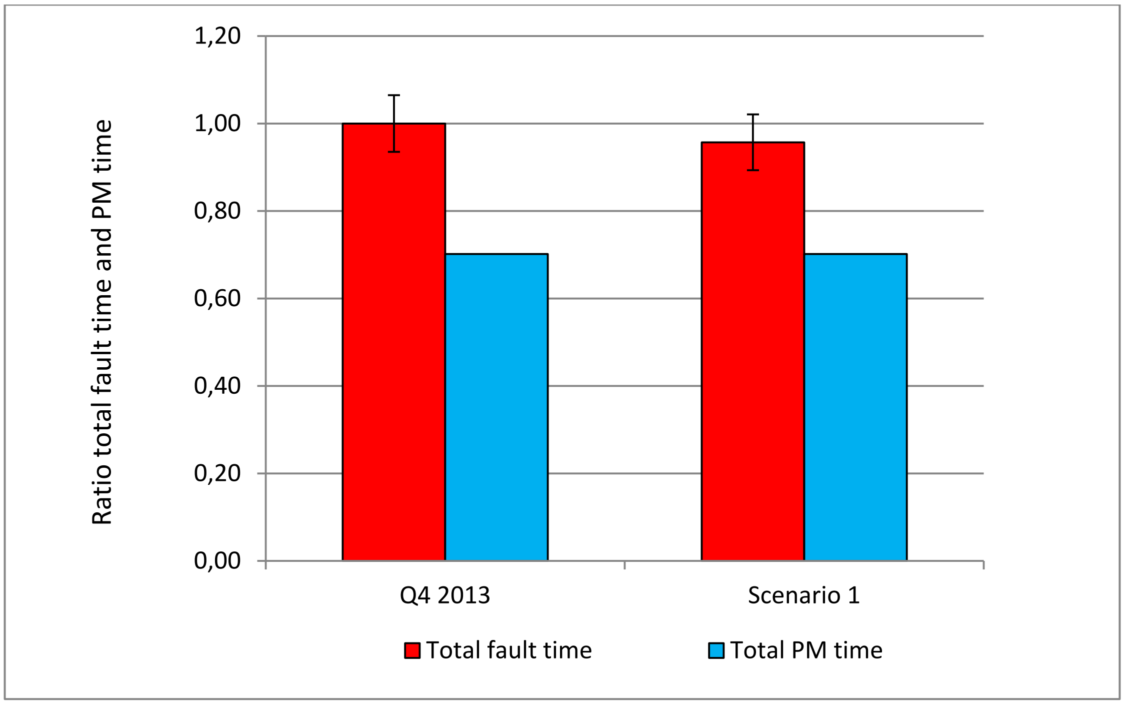

Figure 28: Diagram of total fault time and time spent on PM, relative total fault time Q4 2013.

Table 20: Table of values presented in Figure 28.

	Q4 2014	Scenario 1
Total fault time	1.00	0.96
Standard Deviation	0.06	0.06
Total PM time	0.70	0.70

COST

Same amount of spare parts and total PM has been assumed, meaning that this subchapter will only present the cost of personnel. By decreasing the total fault time by 4%, explained by Figure 28, and increase operator initiative supporting tools, the cost of personnel for CM was decreased by 6%, relative personnel cost of CM in Q4. The results are presented in Figure 29 and Table 21.

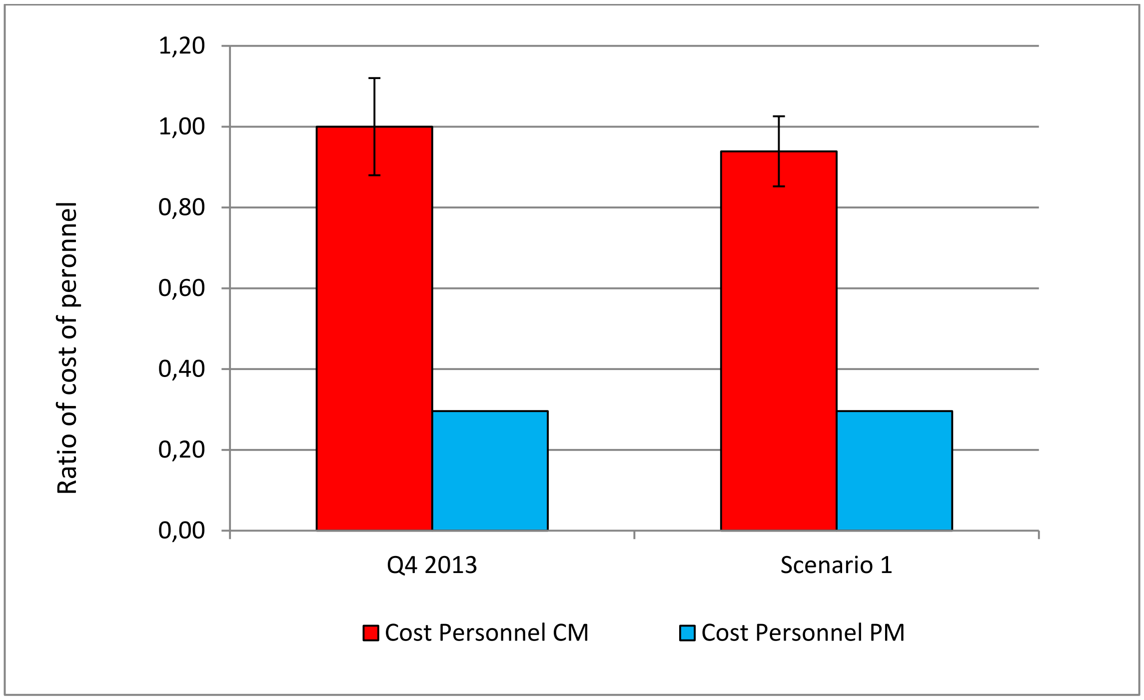

Figure 29: Diagram of personnel costs relative Q4 2013.

Table 21: Table of values presented in Figure 29.

	Q4 2013	Scenario 1
Cost Personnel CM	1.00	0.94
Standard deviation	0.12	0.09
Cost Personnel PM	0.30	0.30

RETURN ON ASSETS

ROA was slightly increased by 0.3% in future scenario 1. In a larger perspective, time saved by using tools to support operators in their work contributes to a small amount relative the total time available time for one quarter. However, results show a decreased personnel cost of CM and an increased ROA, meaning that there is potential for economic benefits of using tools which leads to more operator initiatives.

4.3.3. FUTURE SCENARIO 2

This subchapter describes the results from scenario 2. Scenario 2 is a simulation of a more reliable system, using the lowest downtime and corresponding PM of the two quarters, Q1 and Q4, as inputs. The analysis of scenario 2 was conducted on the whole line to determine the effect on production performance, production time, cost, and ROA.

PERFORMANCE

Figure 30 shows an increased MTBF and reduced MTTR, resulting in increased technical availability compared to Q4. Figure 31 shows a decreased fault time by 15 relative percentages. In addition, total time spent on PM was 12 relative percentages higher in scenario 2. This indicates that right and more PM could reduce the total fault time. All values can be seen in Table 22 and Table 23.

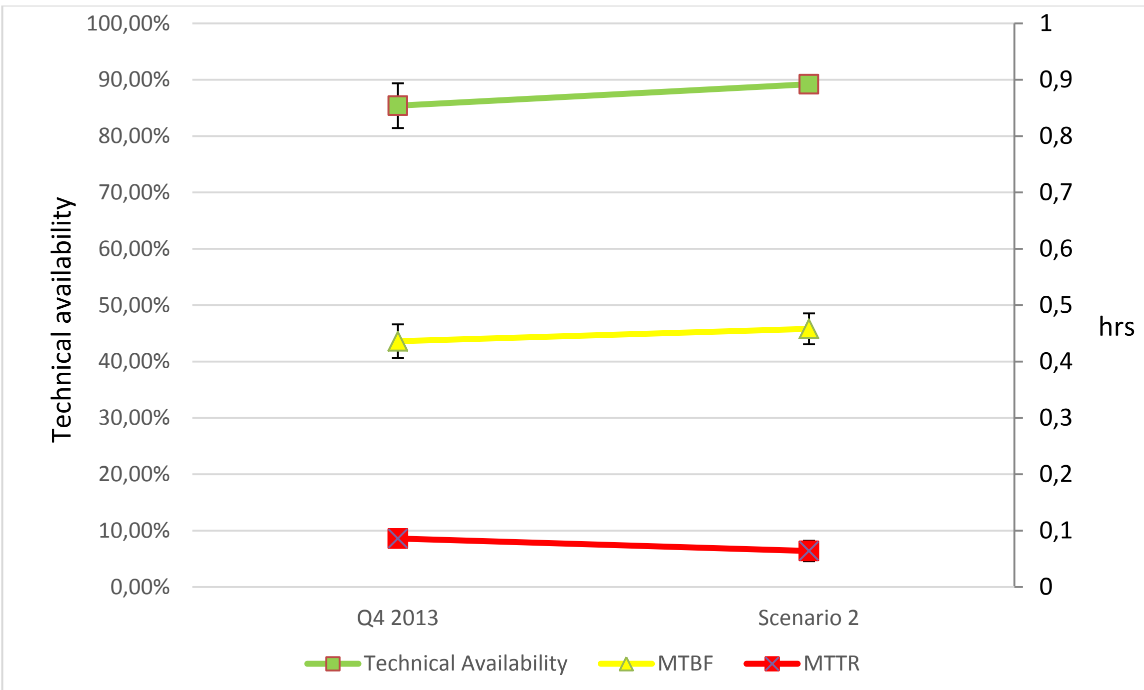

Figure 30: Technical availability, MTBF and MTTR of scenario 2 compared to Q4.

Table 22: Table of values presented in Figure 30.

	Q4 2013	Scenario 2
Technical Availability	85%	89%
Standard deviation	4%	1%
MTBF (hrs)	0.436	0.458
Standard deviation (hrs)	0.03	0.02739
MTTR (hrs)	0.086	0.064
Standard deviation (hrs)	0.014	0.01817

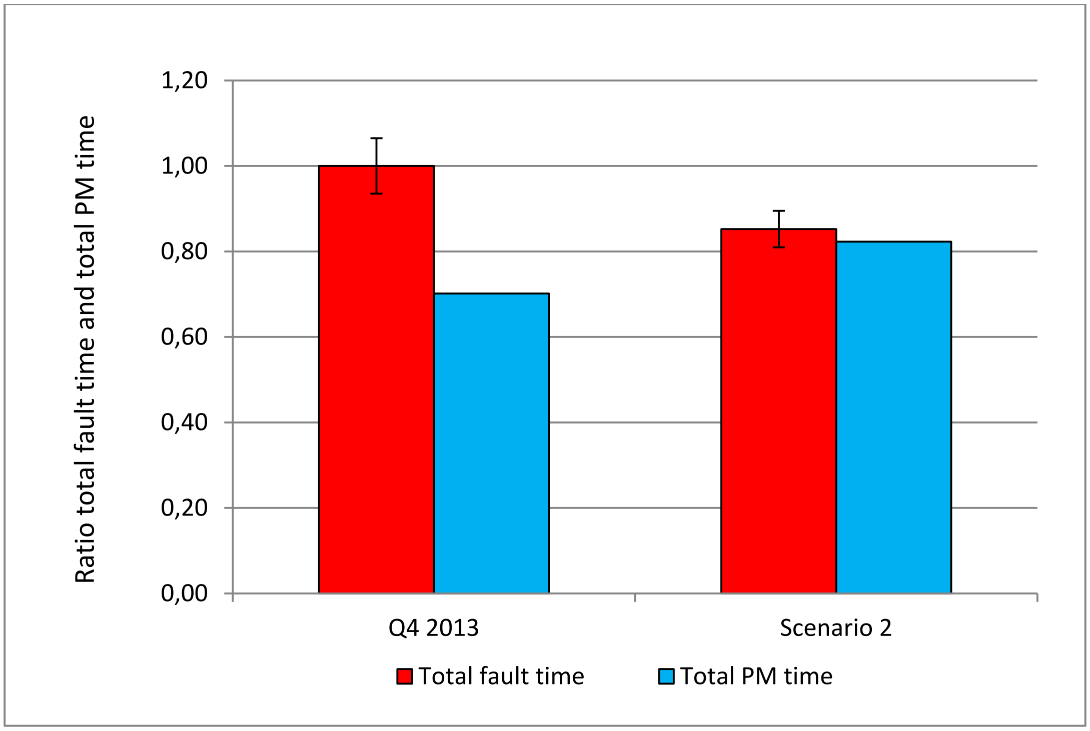

Figure 31: Total fault time and total PM time.

Table 23: Table of values presented in Figure 31.

	Q4 2014	Scenario 2
Total fault time	1.00	0.85
Standard deviation	0.06	0.04
Total PM time	0.70	0.82

COST

Figure 32 shows the total personnel cost of CM and PM, which shows that more money was spent on PM in scenario 2 compared to Q4 2013. Total personnel cost decreased in scenario 2 compared to Q4, which could be explained by reduced total fault time described in Figure 31. The values can be seen in Table 24.

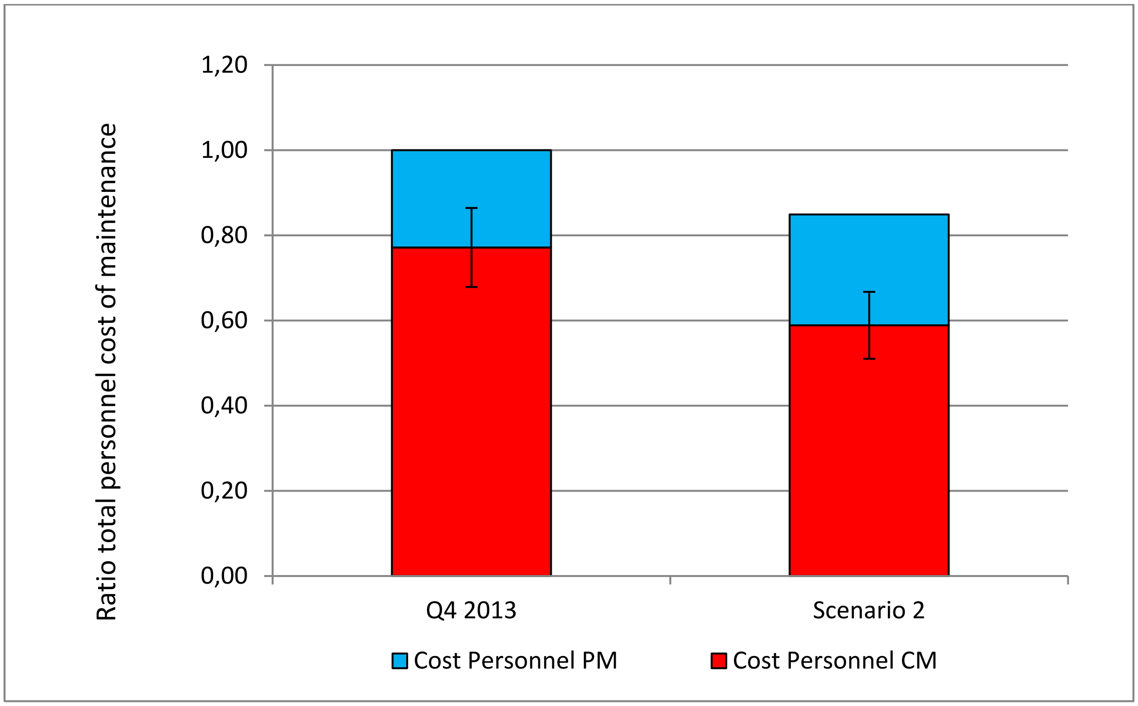

Figure 32: Cost of personnel for PM and CM.

Table 24: Table of values presented in Figure 32.

	Q4 2013	Scenario 2
Cost Personnel CM	0.77	0.59
Standard deviation	0.09	0.08
Cost Personnel PM	0.23	0.26

Return on Assets

A reduced fault time resulted in a higher technical availability. A reduced fault time resulted in lower additional cost (e.g. cost of CM) and increased availability. Figure 33 and Table 24 shows how ROA increases in scenario 2 since the total fault time was reduced, explained in previous subchapter.

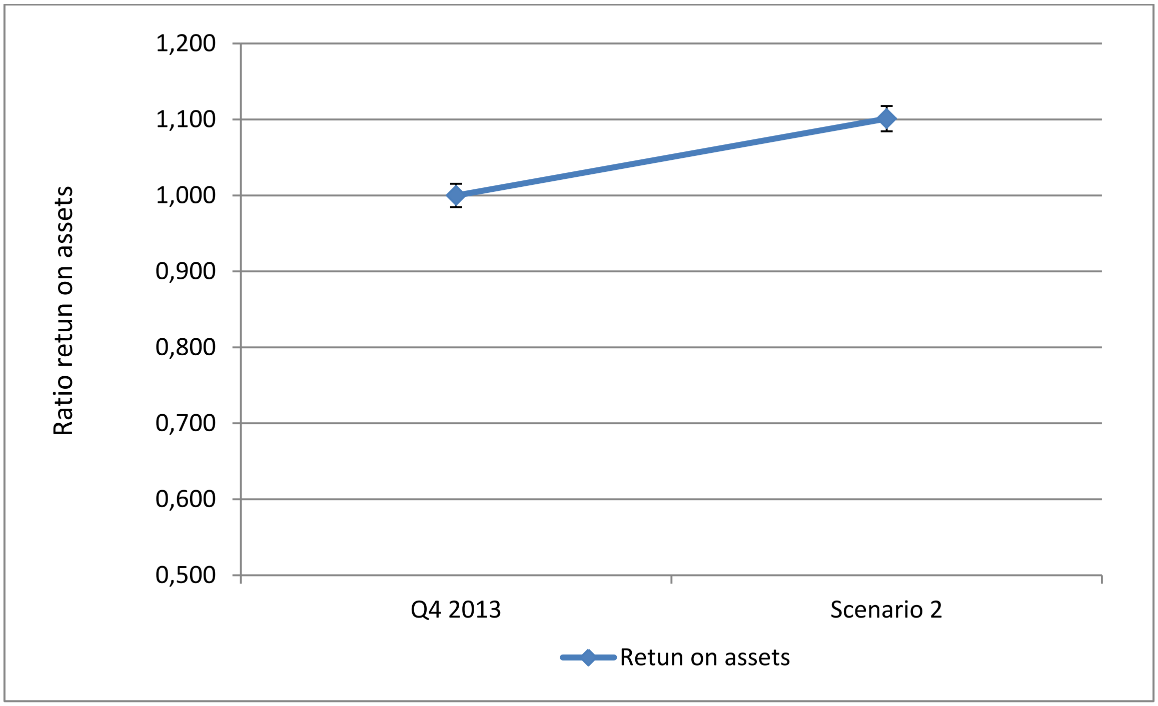

Figure 33: Increased ROA in scenario 2.

Table 24: Table of values presented in Figure 33.

	Q4 2013	Scenario 2
Return on assets	1.000	1.101
Standard deviation	0.015	0.017

5. DISCUSSION

The chapter discusses the result of the thesis and the methods used to answer the stated research questions. Sustainability and a final discussion regarding current and future maintenance work at the company will close this chapter.

5.1. RESULTS

This subchapter discusses the KPIs used in the study and in the simulation model. Furthermore, the results from the case study are discussed.

5.1.1. KPIS TO USE

Simulation can be used to analyze a system on different detail levels. It is therefore important to use KPIs that respond to a company's corporate goals, site goals, and department and individual goals. The KPIs chosen for this study are connected to a specific line but corresponds to a corporate purpose, an effect, and various causes. In this case, return on assets corresponds to the purpose and technical availability corresponds to the effect, while MTTF and MTTR are the main causes. In a future study, additional KPI pathways can be establish starting from top to bottom of the organization to connect activities with the corporate purpose. Through literature review, the authors identified several interesting KPIs related to maintenance. However, the selection of KPIs used in the model was mainly determined by KPIs used at the company today since these were considered sufficient. By measuring these KPIs on a line level instead of on a factory level, it is possible to get a clearer picture of the actual maintenance performance. Measuring MTTR on a line level enables evaluation of repair time of the line in focus, while MTBF will determine how often the line fails. Improved maintenance procedures result in increased MTBF and decreased MTTR. The opposite would indicate that new problems have occurred. One reason for an increased MTBF value may be that root causes have been identified which have eliminated chronic failures. Measuring technical availability on a line level give an indication of how failure rates and repair time affects the availability. In a broader perspective, it can be used to compare different lines in the factory to determine the current bottleneck.

The same analysis can be made on section levels. Analysing KPIs on section levels enables the analyst to determine the effect of variation in PM. By using CM ratio and ratio of PM to CM, sections can be compared to determine the level of reliability and the effectiveness of PM activities between the sections. The ratios can further be compared between industries, but it is important to understand that the ratios are situation dependent.

5.1.2. CASE STUDY

The thesis shows how simulation can be used as a tool to analyze production maintenance in a similar manner as production flows are simulated in industry today. This subchapter will discuss the results based on a comparison between the three quarters.

Real case

The case study includes analysis on the whole line and on the different sections. The study focused on total time spent on PM and CM and how it relates to cost and ROA. Therefore, the number of failures and mean time for each failure was limited to an analysis in terms of MTBF and MTTR. MTTR was reduced through all the quarters, indicating shorter and less complicated stops. Overall, the study showed how technical availability of the line increased from Q3 to Q4, and slightly decreased in Q1. Since there was no direct relation between how time spent on PM affects the need of CM, the authors decided to further study the sections. The study indicated that different sections in the line responded differently to the performed PM. The result shows how important it is to understand different needs of each section in a production line to determine the optimal amount of maintenance. Especially in this specific case since each failure stops the entire line. If the causes of failure are recognized, realistic evaluations can be made on what is possible to expect since the amount of failure prevention has already been applied. Understanding what to expect is therefore crucial for achieving desired level of performance. This includes understanding maintenance and deterioration in order to intervene before a failure occurs (Daley, 2008).

Preventive maintenance should provide tasks that are truly maintainable. Each PM task should include certain steps and provide a certain result (Daley, 2008). Therefore, it exists a limit between the amounts of PM and how it affects the amount of CM. Simulation identified ten sections where increased total PM resulted in reduced CM and seven sections where decreased total PM increased CM. Both these behaviours indicates a relation between PM and CM. Though, ten sections indicated the opposite behaviour; increased PM resulting in increased total fault time. These sections have to be further analyzed to determine if the additional PM tasks have introduced new effects or if these failures are a consequence of a components likelihood of failure according to the bathtub curve. When considering this component failure it is important to understand that even if the bathtub curve is a useful mental model, it includes the simplified assumption that it is possible to know when the end of life will occur. In some cases the most cost efficient strategy is known, where an opportunity to perform PM at a minimal cost exists some time before the expected failure. At other times it is unknown, and the manner in which an asset is used will determine the end of a usable life. An interesting future step to manage the unknown equipment usability is to implement predictive maintenance (PdM) procedures, which enables constant updates on the condition of the assets (Daley, 2008).

The sections in the last significant behaviour group; increased PM resulting in total fault time kept at zero, all show signs of having PM work done when there is little or no risk of failure. Also in these sections the PM has to be further analyzed to determine the effect of PM. Since all sections are synchronized with each other, a failure affects the whole line, meaning that improvements of one section probably result in improvements for the whole line. The authors would find it interesting to study a more dynamic system, with different cycle times for each section and buffers between the sections. Then it would not be as obvious that improvement on a section level results in improvements on a system level, due to the difference in cycle time.

It is important to mention that these results are based on two quarters instead of three, due to inconsistent stop loggings in Q3. The results from a simulation model or any other analysis tool are dependent on a correct input, which is why the authors chose to exclude one of the quarters. The importance of involving operators and increasing the understanding is a key factor in making correct analysis. Communication is therefore required in order to improve and sustain documentation.

Mobley (2004) states that personnel and downtime are important cost factors relating to CM, and identifies personnel costs as the main factors. This study has highlighted a similar result, identifying cost of personnel during downtime as the main factor. The cost calculations relating to fault time was adapted to this specific case study. Failures are assumed to not cause overtime or loss of production since some amount of downtime is included in the planned production time. Furthermore, the current demand does not require 24 hours of production a day, which is why lost production is not added in the cost of failure. If the reliability of the system increases, less planned downtime is required, resulting higher return on assets. Cost of lost production is of interest when the demand requires a constantly running production, and maintenance has to be planned around a window of opportunity (Holmberg et al., 2010). The authors would find it interesting to do a similar study, where a breakdown affects the production more critically than in this particular case. Therefore, the authors suggest studying the economic effect of maintenance on a production line where failures result in production shortage and costly backorders. In this type of production, it would be possible to determine the balance between corrective and preventive maintenance.

Overall, the results of this thesis has shown that maintenance contribute with value for the organization, as stated by Haarman and Delabay (2004). More and improved PM in Q4 compared to Q3 resulted in a higher profit. Since maintenance increased the technical availability, products produced were directly affected. In this thesis, maintenance has shown to affect asset utilisation and cost control; resulting in saved time and increased number of produced products. These two factors are identified as two of the four value drivers in Value driven maintenance. The remaining two value drivers are resource allocation and health, safety, and environment. Since the simulation model is focused on the economical aspect of maintenance, these may be included in a future model to demonstrate the impact of resource allocation and personnel issues on the overall profit.

FUTURE SCENARIO 1

Framtidsoperatören was introduced in this project to evaluate the economic effect of implementing tools to assist and standardize operator maintenance. The company is currently participants in a pilot study regarding use of tools developed by Framtidsoperatören, and was, when this report was written, in an early stage of the implementation. In this thesis, the results show a decreased maintenance cost by 6%. Since the project is still in its early phase, there is no science behind the time reduction of fault time used in the experiments and therefore the results of these tools are considered quite obscure. However, using these tools is assumed to affect the fault time and contribute to optimizing the maintenance staff. Since these factors are two main drivers in Value driven maintenance, these affect the value creation within a company (by Haarman and Delabay 2004). Though, further studies on the effects of using the tools developed by Framtidsoperatören are recommended. Since the user interface enables the user to change data regarding fault time reduction, results from the pilot study can be used as input to the model to evaluate its effect on the specific line.

FUTURE SCENARIO 2

Scenario 2 was tested to evaluate how the system would perform, based on each sections best performance. The scenario assumes that each sections best performance correspond to how reliable the system can be after recognizing the causes of failure in each section, including that equipment is preserved through proper operation and maintenance. Since RCA has not yet been performed, the authors chose to not simulate even better section performances, to avoid making unrealistic assumptions. Results of scenario 2 showed a high reduction of fault time and an increased technical availability, which resulted in lower maintenance costs and higher profitability. The company should in the future start focusing on increasing the reliability of the sections with the highest fault time, since a failure stops the entire line.

5.2. METHODS USED

In this thesis, simulation was used to evaluate how PM related activities could affect production performance, cost, and profit. According to Banks et al. (2010), simulation is a tool suitable to conduct experiments without affecting the real production line, which has enabled the simulation of the future scenarios in this thesis. The strength of using simulation is the possibility to conduct experiments with controlled external conditions (Robinson, 2004). In this thesis, simulation was used to enable a fair comparison between three different periods of time with various external factors affecting the production, such as variation in demand and quality problems from supplier. The authors had to make several assumptions due to incomplete information and to finalize the model building within a reasonable time. An example is missing time setting for a CM, requiring the authors to add times based on similar data. Drawbacks with this assumption are that these times may be extreme, and therefore excluded by the assumption. Another assumption was to label non-coded stops as common failures for the whole line, which is the main reason for not analysing failure rates on a section level in Q3.

In this thesis, Automod® was used to build the simulation model. Compared to other available software, Automod® is limited in graphics. Even if visualization was of high importance in the thesis, the authors found it more important to work with familiar software, due to the complexity around the thesis subject. The effort of visualization was instead put on creating a user interface connected to MS Excel®, which the company primarily use for evaluating data. Autostat® was used to do the simulation runs and determining the standard deviation. The simulations were performed with five replications and with a confidence interval of 90%. Only five replications were used, since the whole line fails if one section fails. Furthermore, each run was 13 weeks, which was the major reason for selecting a relative low number of replications.

In general, the authors find simulation to be a suitable tool to get a general idea of possible scenarios, and also to understand the cause and effect relation. Since it is possible to update the model through the user interface, it can be a useful tool to do further analysis on the sections. Furthermore, the effects of possible improvements can be simulated before implementation. However, further experimentation of the line was not included in the thesis, and the authors cannot assure that the results of a future state will be valid. The model was validated in the current state, mainly by looking at previous production data. Too many and radical changes in inputs to the model increases the inaccuracy of the model.

The cognitive walkthrough was used to evaluate how to simplify the interface and to determine which part should be included in the instruction sheet. From a user perspective, it may have been better to involve the users earlier, thus eliminating unnecessary re-work. In terms of the output, the users were greatly involved in determining what KPIs they considered relevant. Even if several interesting KPIs for maintenance were found during the thesis, the cognitive walkthrough showed that user actually preferred less information. The purpose of using the most important KPIs was to simplify decision making by reducing noise of less important KPIs.

Reflect in action was an important method for the authors to critically review documentation of maintenance. Reflection during the thesis made the authors more alert during interviews and discussions when determining the reasons behind gaps in the documentation. Reflection also enabled the authors' to critically review their own assumptions. During the thesis, new knowledge came to light on various occasions, untimely changing several assumptions. Without thorough investigation and reflection of gathered information, the model would not have been validated.

The thesis included both quantitative and qualitative data collection. The interviews had an un-structured approach when gathering a general understanding of the current maintenance work. Semi-structured interviews were preferred when identifying work procedures in maintenance and when finding possible improvements. From a retrospective point of view, the authors would prefer to have more qualitative data from technicians. Regarding the quantitative data, Axxos® and Aretics® enabled an extensive opportunity for data collection. Besides aforesaid assumptions, it was not possible to separate waiting time and repair time during a stop. The authors would find it interesting to evaluate how much of the total stop time was spent on waiting for a technician. A suggestion from the authors would be to further develop the stop time monitoring to separate waiting time and repair time. Moreover, it would also be more preferred to synchronize the two systems to remove the occurrence of possible gaps. Though, before making further changes, it is important to inform the operators and technicians of why it is important to document in order to improve. To make sustainable changes, it is important to recognize who will be affected and to involve them in the decision-making. Sustainability will be further discussed in the next subchapter.

5.3. *SUSTAINABILITY*

This thesis was carried out with a major financial focus, and to show how different amount of time spent on PM and CM affects the total cost of maintenance and profit of the company. According to Holmberg et al. (2010), maintenance is critical for organizations to maintain competitiveness. Analysis of the effects of maintenance contributes to a sustainable development regarding environment, safety, and economy.

The thesis has not included a safety perspective, which is of interest when discussing social and economic sustainability. Still, creating standardized procedures would not only help the operators identify and correct errors, but also ensure that procedures are performed in accordance with stated safety regulations. The involvement of Framtidsoperatören enabled interesting discussions and contributed to a social aspect of the thesis, by focusing on the operators. In a retrospective, the authors have the impression that operator involvement is highly valued at Wellspect HealthCare and that further improvements in this area will be a successful factor. Wellspect HealthCare is aware of how operators can contribute to a sustainable production, resulting in more responsibilities and trust, thus generating a virtuous cycle. However, operator’s initiative differs between individuals, which suggest that a standard needs to be defined. In addition, operators are not allowed to perform more advanced maintenance tasks. This thesis enables Wellspect HealthCare to evaluate how various degrees of operator involvement affect the performance. Based on interviews with technicians, the authors got the impression of stressful work conditions. Improved planning and more operator initiative would not only contribute to reduced fault time, it would also contribute to a potentially better work place for both operators and technicians. Finally, there is potential to enable more time for improvement work, both regarding production and maintenance.

The production at Wellspect HealthCare is critical in perspective of the quality of the product. Operating in the healthcare business requires perfect quality with a zero tolerance to product impact. Minimum effects on a product results in scrap, making failures that affect the products extra important to eliminate. By decreasing these kinds of failures, the environmental impact of the production may be decreased. Furthermore, less scrap contributes to a more sustainable and economic development. However, this thesis has not evaluated specific failures and has therefore not analysed failures with direct product impact.

Maintaining equipment may lead to increased utilization of equipment that reduces equipment down time and prevents wastes of tools and spare parts (Gupta, 2009), thus contributing to economic and environmental sustainability. This thesis has not included analysis of the necessity of spare part replacements in PM. It is unknown how long a spare part can be useful, and therefore not possible to compare the cost of replacements for preventive purposes.

5.4. *Current and Future Maintenance work at Wellspect HealthCare*

While working with the simulation model, the authors realized the importance of documentation. The authors found several maintenance activities that were not time-reported, which therefore affected the accuracy of the model and its calculations. In addition, causes of stops in production were documented differently between the quarters. Though, in previous quarter, the authors have observed an increased consistency in the coding of stop causes. The increased accuracy was a result of higher documentation demands from the line manager. Furthermore, the company has during the progress of this thesis started standardizing the documentation of maintenance work in Aretics®.

The company has also started to attain to several improvement areas associated with Lean maintenance (Idhammar, 2013). Even if the production support department is still in its initial stages, the maintenance manager is aware of the importance of manufacturing reliability by trying to reduce stoppages, developing partnership between departments, reflecting on root causes, reducing storage value by reducing number of spare parts, and by trying to find new tools and methods to gather knowledge of new procedures.

Results from this thesis show the potential of using simulation for further improvements of the company's maintenance activities. The idea with the model is to simplify the detection of which sections fail the most, and to identify how it relates to performed PM and CM. The aim should be to increase the reliability of these critical sections. Since fault time, time spent on PM, and responses to performed PM differ between the sections, the authors emphasize the importance of understanding specific section needs. This is in accordance with the statement of Hinchcliffe and Smith (2004), which focuses on the importance of understanding a system and equipment's failure mode in order to determine PM activities. RCA is a recommended method to further evaluate a system by identifying root causes and to specify truly maintainable activities. Since RCA affects the value drivers in production, it will affect the overall profit. Furthermore, Idhammar (2013) identifies the elimination of root causes as one of the biggest improvement opportunity in production today according to Lean maintenance.

In order to understand a section's specific needs, the analyst has to determine in what way the critical section behaves when generating a failure. The section's machine might stop turning or is able to turn but cannot lift the batch to the next section, thus the machine is not locked from rotating but is not able to perform its required function. Both are possible behaviours, but each significant behaviour leads to a different failure mode and repair procedure. After defining these paths, it’s possible to separate data into various paths. From this step, the analyst is able to identify paths in the data, and map their frequency of occurrence. The analysis then has the means to diagnose the most likely problem and its recommended corrective action. This data may further be used in statistical-based PdM to predict future stoppages and failures (Holmberg et al., 2010).

The simulation model was designed so that the user is able to change input variables and update the model based on current production data. Thus, the user will be able to use updated results and compare these with previous results in order to discover a relation between PM and CM and to identify a trend in how each station reacts to performed maintenance procedures. After analysing maintenance activities, the user will also be able to detect equipment deterioration. Furthermore, the simulation model was constructed so that the user is able to test possible improvements before implementation.

6. Conclusion

This thesis presents an approach to demonstrate and analyze the development of maintenance and its effect by using DES. The simulation model showed how three quarters could be compared with equity external factors to compare time spent on PM and the need of CM. A direct relation between PM related activities and its effects of production performance, cost, and profit could not be determined, but the importance to analyze the need of PM of the different sections. Since the model is connected to an interface, the user is able to update various input parameters in order to receive an updated version of current KPIs values. KPIs received from the model; MTTR, MTBF, CM ratio, technical availability, and ratio service requests/scheduled PM/CM by technician/CM by operators, and ROA are determined based on interviews, cognitive walkthroughs, and on KPIs used at a factory level. Through simulation, one could also determine the potential of production improvements by more operator initiative, and by right performed PM.

Apart from being used as a decision tool, the thesis concludes the importance of documentation, communication, and involvement to achieve maintenance targets. Overall, the thesis shows the importance of a greater understanding of the company's resources and the relation between cause and effect will have a sustainable impact throughout the factory.

7. FUTURE RESEARCH

As discussed in previous chapter, there is potential for further research. Further research suggested by the authors is summarized in the following lines:

- Further experiments of additional quarters should be conducted. This would result in more data to analyze different section behavior, which can be used to determine a trend in the relation between PM and CM.
- A similar study of a system where sections/stations are not synchronized with each other.
- A similar study of a more critical production, where more time is valued production time. This would enable an analysis of the tradeoff of closing down production for PM compared to CM. In addition, failures then result in lost production, which could cause lost sales and expensive backlogs.
- Analysis of the time a spare part is usable; to evaluate the economic effects of preventive exchanges compared the risk of failures and production stops.
- Including safety in the cost analysis, to see how accidents and incidents affect the cost.

REFERENCES

Ali, A., Chen, X., Yang, Z., Lee. J, Ni, J. 2008. ”Optimized Maintenance Design for Manufacturing Performance Improvement using Simulation”. In: *Proceedings of the 2008 Winter Simulation Conference*, edited by S.J. Mason, R.R. Hill, L. Mönch, O. Rose, T. Jefferson, J.W. Fowler, 1181-1819.

Altuger, G., C. Clhassapis. 2009. “Multi criteria preventive maintenance scheduling through Arena based simulation modeling”. In: *Proceedings of the 2009 Winter Simulation Conference,* edited by M.D. Rossetti, R.R.Hill, B.Johansson, A.Dunkin and R.G. Ingalls, 2123-2134.

American National Standard 2000. *ANSI/ISA–95.00.01–2000 Enterprise-Control System Integration Part 1: Models and Terminology.* (ANSI/ISA–95.00.01) North Carolina, 2000.

American National Standard 2005. *ANSI/ISA–95.00.01–2000 Enterprise-Control System Integration Part 3: Activity Models of Manufacturing Operations Management.* (ANSI/ISA–95.00.03) North Carolina, 2005.

Anderson, J. D. (2006). Qualitative and Quantitative researchSuperintendent of Schools. pp 3.Imperial COE. Retrieved from http://www.icoe.org/webfm_send/1936 (2014-01-23)

Aretics (2014). Retrieved from http://aretics.com/ (2014-04-22)

Armstrong, M., Atkins, D., (1996) Joint optimization of maintenance and inventory policies for a simple system, IEE Transactions, vol. 28, no. 5, pp. 415-424.

Arnold, J.R.T. (1996), *Introduction to Materials Management,* Prentice-Hall, Upper Saddle River, New Jersey

Axxos (2014), Retrieved from http://www.axxos.com/ (2014-04-22)

Banks, J., Nelson, B. L., Nicol, D. M., Carson, J. S. (2010) Discrete-event system simulation 5 ed. Pearson Education, Uppser Saddle River, New Jersey

Chakravarty, A.K., (1981), **Multi-item inventory aggregation into groups**, J. Oper. Res. Soc., 32 (1981), pp. 19–36

Dhillon, B.S (2002), *Engineering Maintenance – A modern approach*, CRC Press LLC, Florida, United Stated of America

DiCicco-Bloom, B., & Crabtree, B. F. (2006). Making sense of qualitative research: the qualitative interview. *Medical Education, 40*(4), pp 314–321. doi:10.1111/j/1365-2929.2006.02418.x

Edwards, D., U.S.A. (2011), "The 80/20 Rule", *Defense Transportation Journal,* vol. 67, no. 5, pp. 59.

Engle, P. (2013) Understanding gross margin. Industrial Engineer, 45(4), 20.

European Committee for Standardization (2001). Maintenance terminology - EN 13306.

Fixed costs. (2006) Encyclopedia of Finance, Springer, Germany

Forbes, C. (2011) *Statistical distributions*. 4th ed. Hoboken: Wiley.

Foote-Lennox, T. (1996) *Ergonomic Guidelines for Computerizes User Interfaces*, Minneapolis, USA

Finkelstein, M. (2008) Failure Rate Modelling for Reliability and Risk, Springer Verlag London Limited.

Gebraeel, N., Lawley, M., Li, R., Ryan, J., (2005) Residual-life distributions from component degradation signals_ A Bayesian approach, IIE Transactions, vol. 37, pp. 543-557.

Gopalakrishnan M., Skoogh A., Laroque C. 2013. Simulation-based planning of maintenance activities in the automotive industry. In: *Proceedings of the 2013 Winter Simulation Conference*.

Groppelli, Angelico A.; Ehsan Nikbakht (2000). *Finance*, 4th ed. Barron's Educational Series, Inc. pp. 444–445.

Gupta A.K. (2009) Reliability, Maintenance and Safety Engineering. [Electronic] Laxmi Publications.

Haarman, M., Delahay, G. (2004) VDM: Value Driven Maintenance New Faith in maintenance. Amstelveen:Mainnovation.

Hansen, R.C. (2002) Overall equipment effectiveness. A powerful production/maintenance tool for increased profits. USA: Industrial Press Inc., U.S. E-book.

Hederson, S., Nelson, B., (2006) *Handbooks in Operation Research and management science*: *Simulation.* North Holland.

Heizer, J. and Render, B. (1996), *Production and Operations Management: strategic and tactical decisions*, Prentice Hall, Upper Saddle River, New Jersey

Hinchcliffe G. R. and Smith A. M. (2004) RCM – Gateway to world class maintenance. [Electronic] Elsevier Inc.

Holmberg, K. et al. (2010), E-maintenance, Springer-Verlag London Limited

Idhammar (2014). Retrieved from http://www.idhammar.se/konsulttjanster/operatorsunderhall.html (2014-04-01).

Idhammar, C. (2013), "How does your maintenance organization use time?", *PPI*, vol. 55, no. 12, pp. 10.

International Standard (2011). *ISO/DIS 22400-2 Automation systems and integration - Key performance indicators for manufacturing operations management - Part 2: Definitions and descriptions (ICS 25.040.01)* Geneva, 2011.

Kaiser, K., M., (2007) A simulation study of predictive maintenance policies and how they impact manufacturing systems, University of Iowa.

Keister, R. S., and Gallaway, G. R. (1983). Making software user friendly: An assessment of data entry performance. *In Proceedings of the Human Factors Society 27th Annual Meeting* (pp. 1031-1034). Santa Monica, CA: Human Factors Society.

Levitt, J. (2008), Lean maintenance, 1st ed..Industrial press New York, United states of America

Lewis, C., Polson, P. G., Rieman, J., Wharton, C. (1990) Testing a walkthrough methodology for theory-based designed of walk-up-and-use interfaces. Institute of Cognitive Science, University of Colorado, Boulder.

Lind, H., Muyingo, H (2012). *Building maintenance strategies: planning and uncertainty*, Property Management, vol. 30, pp. 14-28

Lu, C., Meeker, W., (1993) Using degradation measures to estimate a time-to-failure distribution, Technometrics, vol. 35, pp. 161-174.

Lynch, M. (1996). 'Preventive versus corrective maintenance', *Modern Machine Shop*, No. 69, Vol. 6, p. 144, *Business Source Premier*, EBSCOhost, reviewed on the 12th January 2014.

Mobley, K.R. (2004) Maintenance Fundamentals (2Nd edition). Oxford: Elsevier Inc. E-book.

Moubray, J. (1997) RCM II – Reliability-centered Maintenance (2nd edition). Elsevier Butterworth-Heinemann.

Niebel, B.W. (1994), *Engineering Maintenance Management*, Marcel Dekker, New York

Opdenakker, R., (2006). Advantages and Disadvantages of Four Interview Techniques in Qualitative Research. *Forum : Qualitative Social Research,* **7**(4),.

Piper, C. & Sumukadas, N. (1994), "Continuous improvement in manufacturing", *Business Quarterly*, vol. 58, no. 3, pp. 42-51.

Polson, P. G., Lewis, C., Rieman, J., Wharton, C. (1992) Cognitive walkthroughs: a method for theory-based evaluation of user interfaces. *Man-Machine Studies* Vol. 36, 741-773.

Rohrer, M.W. (2002), Planning & logistic solutions, Simulation Conference, 2002. Proceeding of the Winter, Brooks-PRI Automation, McGregor, I.W, p. 173-181, vol. 1, Salt Lake City, UT, USA;

Rohrer, M. (1999), AutoMod product suite: AutoMod tutorial, WSC ‘00 *Poceedings of the 32nd conference on Winter simulation*, p. 170-176, Society for Computer Simulation International, San diego, CA, USA

Salonen A. (2011) Strategic Maintenance Development in Manufacturing Industry. School of Innovation, Design and Engineering. Västerås: Mälardalen University Dissertations No. 99

Sargent, R.G. 2010. Validation and verification of simulation models. In: *Proceedings of the 2010 Winter Simulation Conference*, pp.166-183.

Sharda, B., Bury, 2008. A discrete event simulation model for reliability modeling of a chemical plant. In: *Proceedings of the 2008 Winter Simulation Conference*: 1736-1740.

Scholl, W., M. Mosinski, B.P: Gan, P. Lendermann. 2012. “A Multi-Stage Discrete Event Simulation Approach for Scheduling of Maintenance Activities in a Semiconductor Manufacturing Line”. In: *Proceedings of the 2012 Winter Simulation Conference*, edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A.M. Uhrmacher. 4673-4781

Suliman S.M.A. and Jawad, S.H. (2012): Optimization of preventive maintenance schedule and production lot size. *Int. J. Production Economics,* vol 137, pp 19-28.

Sullivan, A., Sheffrin, M. (2003) Economics: Principles in action. Upper Saddle River, New Jersey, Pearson Prentice Hall, p. 272

Smith, S. L. (1982). "*User-system interface"*. Human Factors SocietyBulletin, 25(3), 1.

Smith R. and Hawkins B. (2004) Lean Maintenance. Oxford: Elsevier Inc. E-book.

Smith, S. L., and Mosier, J. N. (1984). *Design Guidelines for User-System Interface Software* (Technical Report ESD-TR-84-190). Hanscom Air Force Base, MA: USAF Electronic Systems Division.

Soliman, M. T. (2008), The use of DuPont analysis by market participants. *The Accounting Review*, 83(3), 823-853.

Stanely, B. (2001), The AutoMod product suite tutorial, *Proceedings of the 2001 Winter Simulation Conference*, Brooks Automation, AutoSimulations Division

Stapleton D., Hanna J. B., Yagla S., Johnson J., Markussen D., (2002) "Measuring Logistics Performance Using the Strategic Profit Model", *International Journal of Logistics Management*, The, Vol. 13 Iss: 1, pp.89 – 107

Tsang, A. H (2002), Strategic dimensions of maintenance management, Journal of Quality Maintenance Engineering, Vol 8, No 1, pp 7-39

Variable costs. (2006) Encyclopedia of Finance, Springer, Germany

Värmlands Landsting (2013). Upphandlade Urinavledande produkter, Tappningskatetrar. Retrieved from https://www.google.se/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CC8QFjAA&url=http%3A%2F%2Foldwww.liv.se%2Fsidkat%2F21824%2FUpphandlade%2520Urinavledande%2520produkter%2520130830.xlsx&ei=5PB5U8TGH4bDygOQjYG4CA&usg=AFQjCNEFg-wjjcbQ8bmBK4s4Q53F0XQFvA&sig2=oF-CfdUF3yQploF2Z_bezw (2014-05-19)

Wellspect HealthCare (2014) Retrieved from http://www.wellspect.se/ (2014-06-09)

Wireman,T. (2005) Developing performance indicators for managing maintenance (2nd edition) [Electronic] New York: Industrial Press Inc

Wireman, T. (2010) Benchmarking Best Practices in Maintenance Management (2nd edition). [Electronic] New York: Industrial Press Inc

APPENDICES

A. Questions for Semi-Structured Interviews

1. **What tools do you use for scheduling/planning and calculate cost of maintenance?**
   For Maintenance: MS excel, analytical methods (lean boards), CMMS (IFS, SAP)

2. **What are the methods you use for scheduling/planning activities and calculate cost?**
   For Maintenance: Condition-based, Simulation models

3. **What kind of analysis do you make to support your decisions?**
   For Maintenance: bottleneck analysis, risk analysis, criticality analysis, stock levels etc

4. **What decisions you make using these tools and analysis?**
   For Maintenance: planning or scheduling activities, any special kind of planning or scheduling?

5. **What are the KPIs you use for the above scheduling/planning and cost analysis to realize the organization goals? (ask for machine level and system level individually)**
   For Maintenance: Organization goals could be increase throughput, reduce waste, high quality, energy consumption reduction. KPIs could be MTTR, MTTF, cycle time, Takt time, etc

6. **Are current KPIs adequate according to you? (1: inadequate, 10: highly adequate)**

   ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨ ⑩ □**Don't know**

7. **Do you use simulation to plan maintenance and repair? How?**

8. **Do you prioritize maintenance activities? If yes, how?**
   Example: loudest operator, ABC classification, cost of machine based

Gap Analysis:

9. **What are the current problems with the existing practices?**

10. **Do you think you need more KPIs or right KPIs for better scheduling/planning?**

B. QUESTIONS TO COMPLEMENT COGNITIVE WALKTHROUGH

1. **What do you think of the model? How do you see it being used in your work?**

2. **What do you think is the best and what more you would like to see in this model?**