Condition Based Maintenance at Marel Poultry?

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It should be noted that all numbers and costs are altered due to confidentiality reasons

Abstract

Providing service contracts is becoming more important for Original Equipment Manufacturers (OEMs). This leads to maintenance increasingly being offered as an after-sales service. In order to keep differentiating from competitors, continuously improving the offered maintenance is needed. A way to improve the maintenance offered may be implementing Condition Based Maintenance (CBM) policies, which has become extra interesting lately with the rapid developments in sensor technology. This increased interest in CBM results in research projects such as the ProSeLoNext project, which focusses on predictive maintenance and service logistics. This research is part of the ProSeLoNext project. Marel Poultry (MP) is an OEM within the ProSeLoNext group that wants to add CBM policies to its maintenance concept. MP has developed a maintenance concept to help its customers. According to MP, "a maintenance concept is a gathering of maintenance activities for a particular asset to maintain its intended function" (Laurijs & Lemmens, 2016). In this thesis, a maintenance concept for a whole machine consists of multiple different maintenance policies for each of the parts within the machine. This research focuses on improving the maintenance concept of Marel Poultry by applying CBM policies.

The first step at MP is to select the parts most interesting for CBM. Parts with more relevant costs are more interesting. A selection method is developed to select these parts. This method starts with identifying the most interesting machines, followed by identifying the most interesting parts in these machines, and finally selects the part most interesting for CBM. The selection method strives to select in a data-driven manner and to need expert input only when really necessary. The selection method is applied to a case. The case resulted in the recommendations that Marel Poultry should start logging the data needed for the selection method in a way that allows this data to be combined and used for the selection method. Relevant process and condition data are identified during the selection of a part. This data can be combined with the other data for a smooth transition to a CBM policy. The case resulted in selecting the part Ratchet within the legend Unit-Pushover of the machine TRDE as the part most interesting. A CBM policy has been developed for the Ratchet. The potential costs savings are calculated. Sensitivity analysis shows that the costs savings are heavily dependent on the input values. Small changes in the input values eliminate the cost savings. The input values are not expected to be able to be estimated with enough accuracy, and it is thus recommended not to pursue this CBM policy further. However, MP should first put its effort in deriving the input values to allow proper implementation of the selection method. Such that a better selection can be made, for which CBM policies can then be developed, that might turn out to be promising.

Management summary

This report contains the research on how Marel Poultry (MP) can apply Condition Based Maintenance (CBM) to improve its current maintenance concept. MP produces and develops poultry processing lines. Next to producing and selling these lines, MP offers after-sales services such as maintenance. MP's service strategy is to generate as much as possible added value for its customers with its maintenance concept. The added value of MP's maintenance concept is to support the customers preferred balance between Throughput, Yield and Cost of ownership (CoO), as indicated by the 'Golden Service Triangle' (Figure 1.3). The throughput is maximized by high processing speeds and low downtime, and the yield is maximized by minimizing the waste and losses such that as much as possible from the incoming products result in an end product. MP wants to add CBM policies to its current maintenance concept to further improve its added value. We research how MP can do this, which leads to the main research question:

"Can MP apply CBM policies to improve its current maintenance concept?"

Deliverable 1 – the selection method

Before MP can apply CBM, effort and investments are needed. It makes sense to only make an effort and investments for the parts most interesting for CBM. The first step at MP is selecting the parts most interesting for CBM. Currently, MP does not have a standardized way to identify parts interesting for CBM. Maintenance policies are assigned to parts via the AE-coding, but this does not yet include CBM policies. Selecting the part most interesting for CBM in a standardized way can be done by using the selection method developed (Chapter 3). This method starts with identifying the most interesting machines, followed by identifying the most interesting parts in these machines, and finally, the part most interesting for CBM is selected. In order to identify which parts are interesting, the yearly impact of failures expressed in costs is taken into account rather than the number of failures or downtime upon a single failure. Also, the yearly Preventive Maintenance (PM) costs, which could be reduced with a CBM policy, are taken into account. The selection method aims to do the selection in a data-driven manner and to need expert input only when really necessary. Although the selection method selects the most interesting parts as a starting point, it also identifies the next interesting parts, allowing a continuous improvement process. These features differentiate our selection method with the currently available selection methods. The selection method is expected to be generic as the steps likely apply to most OEMs (Original Equipment Manufacturers) providing maintenance, that want to apply CBM.

Deliverable 2 – the selected part

The developed selection method is applied to a customer of MP (Chapter 4). Applying the selection method to MP resulted in selecting the part Ratchet within the legend Unit-Pushover of the machine TRDE as the part most interesting for CBM. Applying the selection method resulted in identifying the data that are currently missing at MP, as well as the impact on the selection.

Deliverable 3 – the CBM policy for the selected part

A CBM policy for the Ratchet has been developed (Chapter 5), which improves detection. This policy showed yearly costs savings of €1074 for the Unit-Pushovers for one customer (16% of the PM costs of the Unit-Pushovers and 7% for the whole machine TRDE). These costs savings might apply to more customers. However, these costs savings are dependent on the input values. Sensitivity analysis showed that the input values are very critical; small changes in the critical input values eliminate the costs savings. Given the small costs savings and the level of detail needed for the input values to be sure these costs savings hold, it is recommended not to pursue the CBM policy developed for the Ratchet further. However, a modification of the Ratchet, for instance, the Sharp Edge identified at the end of Section 5.6, can turn out to be interesting dependent on its technical feasibility.

Main conclusion

When developing the three deliverables mentioned above, we identified gaps at MP to apply CBM policies to improve its current maintenance concept. We concluded that, at the moment, applying the selection method at MP is possible, but improvements are desirable as data is missing. The developed CBM policy was also constrained by missing data. Getting the data that is currently missing will improve the application of the selection method and smoothen the development of future CBM policies of parts selected. Therefore, the main steps recommended to MP regard getting the critical data (Chapter 6). The overall answer to the main research question is that MP should first put its effort in deriving the input values to allow proper implementation of the selection method. Such that a better selection can be made, for which CBM policies can then be developed, that might turn out to be promising.

Main recommendation selection method

The most critical limitation in the current application of the selection method is the inability to assign downtime to parts due to the data that lacks. We tried to solve this by combining the repair list and the downtime list. However, this proved difficult to do as the data is not registered on the same time interval making it difficult to assign parts to downtimes. It was also unclear which of the parts registered in the repair list are the actual cause of the failure (and downtime) or registered for another reason. Parts can be registered in the repair list when they are repaired as a consequence of other failing parts, replaced opportunistically as the machine is down and the legend is disassembled anyway, or replaced auxiliary (for example bolts). We recommend combining the data in a 'combined data list', see Table 6.7.

Recommendation CBM policy

The developed CBM policy is not deemed beneficial enough to pursue further. This is partial because the application of the selection method at MP currently falls short by focusing primarily on the PM costs and not the downtime costs (which are most critical at MP). However, also, because basic input for the CBM policy is not known at MP. A CBM policy, as any maintenance policy, decides upon the optimal replacement moment. This is a trade-off, at any moment, between the costs of replacing at that moment and the costs of delaying replacement. For this, the costs of replacing and the cost of delaying the replacement need to be known. The costs of delaying are the increased risk of failure multiplied by the cost of failure. The probabilities of failure for a CBM policy are based on the condition measurement(s), thus it makes sense these are not yet known. However, the probability of failure based on time or usage could be known and used as input for the PMS (Preventive Maintenance Schedule). Besides these failure probabilities, the costs are also not known. This is partial because currently the downtimes cannot be assigned to parts. However, this could be solved with the ′combined data list′. Moreover, the other costs of failure (like emergency order costs) are also not known. Therefore it is recommended to MP to determine the failure distributions of the parts using the failure data provided by the 'combined data list' and to determine the costs of replacing preventively and replacing correctively.

Other recommendations

The remainder recommendations are given in order of importance.

1. Downtime costs machines

The downtime costs are critical for the selection method. However, at MP, the downtime costs are not precisely known. MP uses €300/minute as a ball-park figure as this is indicated by the customer with whom MP cooperates with the most. However, no differentiation is made between the machines, lines, and customers. Further investigation in the downtime costs per customer per machine is recommended.

2. Costs amongst multiple customers

The CBM policy developed for the Ratchet only leads to small costs savings, but these could be increased if applied to multiple customers. The costs of only one customer were considered. Ideally, the selection method would combine the costs of customers to identify the parts most interesting for MP as a whole. Therefore it is recommended to combine the costs data, for both the machines and the parts, for multiple customers. This would, of course, require registering the costs of more customers (which is currently not done).

3. Intermediate result of the selection method

The intermediate result of the selection method identifies costly machines that do not allow data handling, which are the Vakuumtrichter, JLR, and Tipping-Section. It would be interesting to look into the possibilities of projects resulting in the capacity to handle the data for those machines. All three machines would have been considered before the TRDE if they had the data handling capacity.

4. Further research in in-depth failure analysis

Detailed consideration of the in-depth failure analysis is out of scope for this thesis. However, the 'combined data list' provides the data needed for the analysis. Therefore, further research on in-depth failure analysis using the data obtained by the 'combined data list' is recommended, which should focus on the relevant characteristics of the failure modes. The failure modes should have an increasing failure rate as well as variation in time till failure such that a CBM policy can provide benefits over the current (time- or count-based) PM policy.

5. Costs data

The most critical costs at MP are the downtime costs. However, to make the best selection, all relevant costs should be taken into account. It is currently problematic to take all costs for all machines into account in a data-driven manner. It is recommended to get the labor time data for all machines, get the corrective maintenance (CM) costs data, and automate the calculations of the costs for all machines.

6. Long troubleshooting time

Another option for condition monitoring to reduce downtime would be not to focus on preventing the failure but decrease the troubleshooting time. The current selection method focusses on wear parts. Therefore the B-coded parts are not considered as they fail randomly. However, some subassemblies it is not clear which of the B-coded parts failed, and troubleshooting time is needed, while in the meantime there is downtime. Condition monitoring could be used to shorten the troubleshooting time and reduce the downtime. This would be interesting for parts with a lot of yearly downtime due to troubleshooting time. It is recommended to look into this option after the main costly wear parts have been considered.

7. Soft failures

The current selection method focusses on hard failures. This is done as hard failures lead to downtime, which is critical. After the main hard failures and a lot of the downtime are tackled, the next step would be to focus on the soft failures. These soft failures reduce the performance that leads to costs as well. Especially the Process data is handy for this. The reduced performance can be used to determine a cost rate. This costs rate could be compared to the costs of replacing to reset the performance to decide upon the replacement moment. Replacement should be done when the break-even point (between the increased revenue from the performance improvement and the replacement costs) is surpassed.

8. Validate AE-coding

Currently, AE-coding is used to indicate the higher level failure behavior. This is assumed to give an accurate representation of the failure behavior as it is based on mechanical knowledge and validated at the customer. However, this could still use validation from the data to be sure. We recommend validating the failure behavior of parts using the data obtained with the 'combined data list'. Extra interesting to validate are the B-coded parts. It is assumed that these fail random and do not wear, and thus have a constant failure rate. It could, however, turn out that the parts do wear but that the variation in time till failure is such that it is perceived random by MP. These parts would be interesting for CBM as this would allow predicting the failures, which is currently perceived impossible.

9. Modification data-driven or expert input?

For the modifications, expert input is assumed always to be needed, and therefore this is taken into account (late) in the selection method. This can lead to iterative steps, as shown in Chapter 4. It is deemed not possible to register the modifications such that a purely data-driven approach is possible. For this, it should be registered exactly what the impact (which problems are solved and for how much) of the modifications are, including all the dependencies of the production line. However, we recommend checking if this is really impossible, otherwise, the modifications should be taken into account in a data-driven manner when assigning costs to both the machines and the parts.

Preface

This document contains my master thesis, which is conducted at Marel Poultry in Boxmeer. The master thesis is the final step to my Master degree in Operations Management and Logistics at the University of Technology in Eindhoven. I would like to thank everybody who played a role during my study, but especially during the thesis project as this was the most difficult part of the study. A special thank you goes to Simme Douwe Flapper for all your detailed and critical but constructive feedback. Also, a special thank you goes to Robert Lemmens for supervising me at Marel Poultry.

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Term	Abbreviation	Description
# Empty Shackles		Number of empty shackles [shackles/year]
# Hammering$_j$		Amount of hammering in situation *j* [number of hammer strikes]
A-coded parts	A	'Consumable' parts often in direct contact with the product
AE-coding		Coding of the service parts of MP in order to cluster these parts into overhaul kits
Age-Based Maintenance	ABM	Preventive maintenance policy which uses a time limit to base its maintenance decisions on
Auxiliary		Parts that have to be replaced because of a maintenance task performed on the machine or subassembly of the part
BC-coded parts	BC	'Small overhaul' parts with an increasing failure rate and random failures
B-coded parts	B	'Breakdown' parts with a constant failure rate
BD-coded parts	BD	'Major overhaul' parts with an increasing failure rate and random failures
BE-coded parts	BE	'Total overhaul' parts with an increasing failure rate and random failures
CBM Candidate		A part-machine combination or a part in a specific application in a machine which is interesting for CBM
C-coded parts	C	'Small overhaul' parts with an increasing failure rate
Censored data		Censored data is data of which the value of a measurement or observation is only partially known
Condition Based Maintenance	CBM	Maintenance policy which uses condition measures to base its maintenance decisions on
Corrective Maintenance	CM	Maintenance task performed such that the failed machine can fulfill its intended function
Cost of ownership	CoO	Total costs of machines during its lifecycle; for instance, next to the acquisition costs the operating costs are also taken into account
Costs$_j$		The yearly costs in situation *j* [€/year]
D-coded parts	D	'Major overhaul' parts with an increasing failure rate
Delay time		Time period from defect initiation to failure
Downtime	DT	Time a machine is out of service and not able to perform its function during operation time
Downtime list		Customers tracks how long, when, why, and which machine was down during operation
Duration Detection$_j$		Duration between start of 'the hammering' and detection in situation *j* [years]
Duration$_{j,k}$		Duration 'the hammering' takes place in situation *j* due to failure mode *k* [years]
Duration Till Next Opportunity$_k$		Duration from detection of 'the hammering' until it is solved for failure mode *k* [years]
E[Effect hammering$_{i,j}$]		Expected effect hammering on part *i* in situation *j* [effect]
E-coded parts	E	'Total overhaul' parts with an increasing failure rate
Effect Hammering$_i$		Effect per hammerstrike on part *i* [effect/hammer strike]
Expected Time Till Failure$_k$		Expected time till failure of failure mode *k* [years]
Failure		Breakdown causing the machine or part not to be able to perform its intended function
Failure mode		The specific manner by which a failure occurs
Frequency$_{I,j}$		Frequency of kit *I* in situation *j* [1/year]
Frequency$_k$		Frequency of failure mode *k* [1/year]
Golden Service Triangle		Preferred balance between the three needs of the customer: throughput, cost of ownership, and yield

Grower to Processor system	GP-system	System that handles the arriving live birds (from the grower)
Hard Failure		Type of Failure that prevents the machine from doing its intended function. The machine does not perform at all and is therefore down
JLR	JLR	Anatomic leg cutting module
Knowledge Information System	KIS	Information system of Marel
Labor Costs$_I$		Labor costs of kit *I* [€]
Labor time		The time spent by engineers on executing a task. During this project, labor time is only considered for executing a maintenance task. The labor time of the maintenance task includes disassembly and reassembly as well as the actual repair time
Labor time customer$_I$		Labor time of the customer's engineer of kit *I* [hours]
Labor time MP$_I$		Labor time of the MP's engineer of kit *I* [hours]
Legend		Subassembly or subset of a machine containing multiple parts. Every hierarchy level between the highest (machine) and the lowest (part).
Maintenance concept		Maintenance strategy for a whole machine, which is a combination of multiple different maintenance policies
Maintenance policy		Maintenance strategy for a single part
Major overhaul kit	M-kit	Planned maintenance overhaul for all C- and D-coded parts
Marel Poultry	MP	Brand of Marel that specifically focuses on the Poultry industry
Minimal Time Limit$_{I,j}$		Minimal time limit of kit *I* in situation *j* [years]
Operational maintenance		Minor maintenance that does not require detailed technical knowledge
Opportunistic replacement		Using the downtime or repair moment of another part to replace a part
Overall Equipment Effectiveness	OEE	OEE is an industry standard method for measuring the utilization of a machine
Part cost		Cost of part for a customer of Marel
PM Costs$_I$		Preventive maintenance costs of kit *I* [€]
Preventive Maintenance	PM	Maintenance task performed such that a part is replaced with an as good as new part before the replaced parts actually failed.
Preventive Maintenance Schedule	PMS	Schedule of the planned preventive maintenance for the lifetime of the machine
Primary Processing		Processing from Live bird handling till Chilling is considered primary processing
Proactive Service Logistics for capital goods - the Next steps	ProSeLoNext	Consortium of companies and universities researching predictive maintenance and service logistics, service business models, and service control towers
Product Detection System	PDS	Marel's detection system that detects its broilers on the line during production in order to operate
Product Lifecycle Management	PLM	Information system of Marel focusing on the lifecycle of their products
Programmable Logic Controller	PLC	Digital computer adapted for the control of manufacturing processes
Ratio Empty Shackles		Ratio empty shackles [empty shackles/total shackles]
Repair data		Spare part usage list. For every part replaced it tracks when it is replaced, which part is replaced, and in which machine it is put
Repair time		Time of the repair of a machine, legend or part
Secondary Processing		Processing from Grading and Distribution till End processing a Packaging are considered secondary processing
Service parts		Parts that are expected to need to be replaced during the lifetime of its machine
Small overhaul kit	S-kit	Planned maintenance overhaul for all C-coded parts

Soft Failure		Type of Failure that only partly reduces the intended function, such that, although the machine can still operate, only a reduced speed or quality is achieved
Statistical Process Control	SPC	Method of quality control in which statistical methods are employed
Systems, Applications, and Products	SAP	Information system of Marel focusing on the logistics
Tariff		Cost rate of the labor time of engineers
Tariff customer		Tariff of the customer's engineer [€/hour]
Tariff MP		Tariff of the MP's engineer [€/hour]
Throughput		Rate of production
Time Hammering Empty Shackles$_j$		Time of hammering in situation *j* [year]
Time limit		Maximum time between replacements of a part such that a certain customer satisfaction is achieved.
Time Limit$_{i,j}$		Time limit of part *i* in situation *j* [years]
Tipping-Section		Systems that tips over the crates with live birds
Total # Shackles		Total amount of shackles [shackles/year]
Total overhaul kit	T-kit	Planned maintenance overhaul for all C-, D- and E-coded parts
Transfer system	TR1G	Transfers broilers from the PDS line to the Cut-up line
Transfer system	TRCS	Transfers broilers from the Cooling Selection to the Grading product carrier Identification
Transfer system	TRDE	Transfers broilers from the Defeathering line to the Evisceration line
Vakuumtrichter		Vacuum funnel
Yield		Amount of the incoming products that actually result in end products

1. Introduction

This report contains the thesis of my master project at Marel Poultry (MP). This project is part of the ProSeLoNext project, where ProSeLoNext is an abbreviation for Proactive Service Logistics for capital goods – the Next steps. ProSeLoNext consists of the following three work packages: Predictive maintenance and service logistics, service business models, and service control towers. This project is part of the first work package.

Marel's main business tasks are to produce and develop food processing lines, which are considered capital goods. These lines consist mostly of standard modules, which are assembled to fit the customer specific needs. Marel's products vary from standard stand-alone products to full-line solutions. Marel is the market leader and very innovative (Marel, 2015). Marel continuously innovates and improves its products. Next, to producing and selling these lines, an important part of Marel's business is to provide after-sales services, such as maintenance. At the moment the maintenance at Marel's customer is done via a combination of failure based and preventive maintenance policies. The preventive maintenance policies are periodic time-based maintenance, which is based on Marel's Preventive Maintenance Schedule (PMS). Marel would like to also implement Condition Based Maintenance (CBM) policies, to improve its current maintenance concept.

Marel is divided into three industries; Poultry, Meat, and Fish. This project is conducted for Marel Poultry (MP) specific. MP has a lot of overlap with both Marel Meat and Marel Fish for which this project can be useful as well.

The goal of the ProSeLoNext project at MP is to add CBM policies to its maintenance concept for the high-end customers. However, before this is achieved, some intermediate steps need to be taken. This master thesis project is a first step towards the goal of ProSeLoNext.

Before CBM policies can be added to the maintenance concept, it should be known which parts are interesting for CBM. This master thesis project develops a selection method, which can be used to identify the parts interesting for CBM. The selection method identifies the most interesting machines, after which the most interesting parts of the machine are identified. The selection method is the first part of the master thesis, which can be found in Chapter 3. The selection method is applied to a case. The case study can be found in Chapter 4. The case resulted in the selection of a part. For this part, a CBM policy is developed, which can be found in Chapter 5. To answer the main research question: "How can MP apply CBM policies to improve its current maintenance concept?" the next steps for MP are given in Chapter 6.

To understand the situation of MP, essential background information is discussed in this chapter. Section 1.1 starts with a layout of a typical poultry processing line. Section 1.2 explains how a customer typically operates. Section 1.3 describes MP's product structure. Section 1.4 describes the customer's need. Section 1.5 describes MP's maintenance concept.

1.1 Poultry processing layout

To better understand the situation of MP, first, a typical poultry processing plant layout is explained shortly. Poultry processing has developed itself during the last century into a highly automated process. Production speeds are increasing, which makes automating operations necessary. For this automating process new high-tech complex machinery is needed to maintain the throughput of the factory, and keeping the production costs low. The layout of a poultry processing plant of MP is divided into separate departments for hygienic purposes, see Figure 1.1. The processing steps executed in the various departments are: Live bird handling in A, Killing and Defeathering in B, Evisceration and Organ handling in C, Collection and Processing of several by-products in D, Giblet handling in E, Chilling in F, Grading and Distribution in G, Cut-up and Deboning in H, and End processing and Packaging in J. A (Live bird handling) till F (Chilling) are considered primary processing. G (Grading and Distribution) J (End processing and Packaging) are considered secondary processing. MP distinguishes three different processing steps, which are primary, secondary and further processing. Further-processing entails, for example, marinating and cooking.

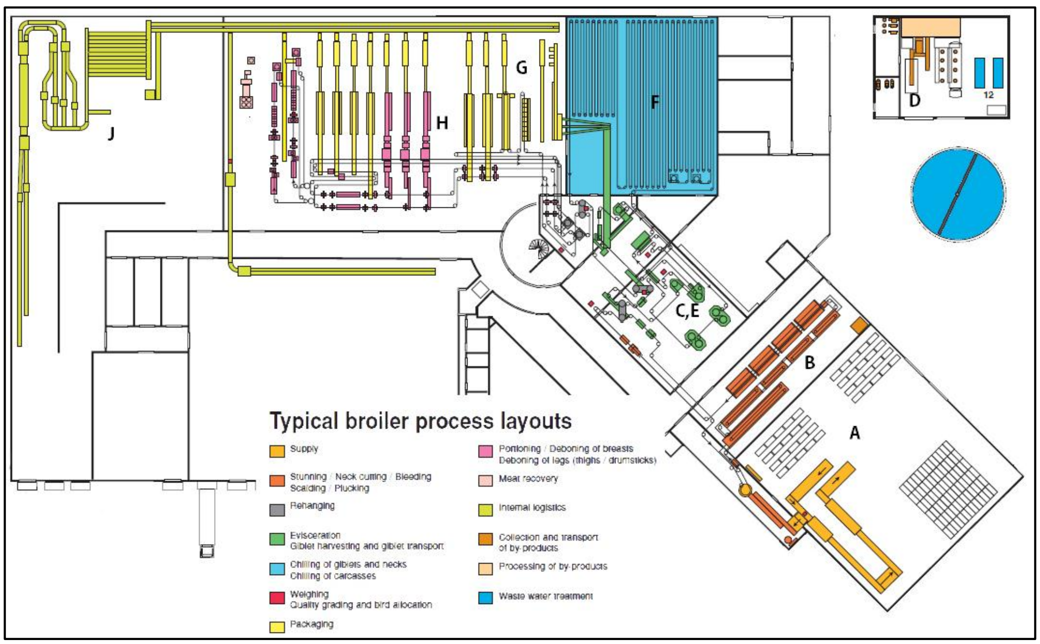

Figure 1.1: Typical poultry processing layout MP

1.2 Processing characteristics

This section discusses the processing characteristics. These processing characteristics apply to most of MP's high-end customers. The characteristics of the high-end customers are interesting because these are the customers to which MP will offer CBM solutions first. Most of these customers work six days a week and 20 hours a day. In the morning the first shift begins with primary processing. The Chilling line takes up to 3 hours to chill the broiler. Because of this delay, the first shift at secondary processing starts later. The same applies to the second shift. Every shift has a break. Customers want their systems to operate as much as possible, which requires maintenance. Working the hours mentioned above only leaves the breaks, a few hours each night, and one day in the weekend of non-operating to do maintenance. Therefore, preventive and planned maintenance is done during these non-operating moments, and corrective maintenance is done as soon as something breaks down. This unplanned breaking down of machines leads to downtime.

Downtime is the time a machine is out of service and not able to perform its function during operation time. The downtimes result in downtime costs as the customers encounter many problems when this happens. For example, the line is full of broilers that cannot be processed during this downtime. With a tight schedule, the time lost can result in the customer not meeting their deadlines. Also, the personnel working on the line are idle while they still need to get paid. Currently, high-end customers process with speeds up to 13,000 – 15,000 broilers per hour. Because of these reasons, downtime costs are considered very significant by the customers. To give some context, according to experts, high-end customers assign €300,- per minute to their downtimes.

1.3 Product structure

MP structures its machines in multiple hierarchy levels, as can be seen in Figure 1.2. The different poultry plants are divided into different production lines. Each production line consists of multiple machines. Each machine consists of various legends or single parts. Legends are assemblies of parts. Each legend can consist of multiple legends and parts. Machines are considered level 0, the first level of legends and parts are considered level 1, these levels of legends and parts typically do not exceed level 4.

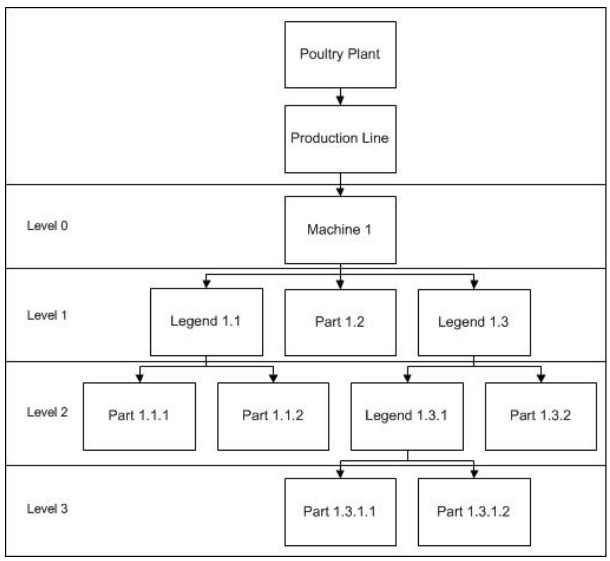

Figure 1.2: Product structure

1.4 Customer's need

MP's customers have three needs, which MP helps to provide via service. The first need is to maximize the throughput or rate of production. While higher processing speeds lead to a higher throughput, this is only the case when the machines can operate. The second need is to maximize the yield. This means that the waste and losses are minimized such that as much as possible from the incoming products result in an end product. The last need is to achieve the first two needs with minimal costs of ownership (CoO). MP's service strategy is to create a preferred balance between the three needs that results in the 'Golden Service Triangle', see Figure 1.3. To achieve this preferred balance, MP offers a maintenance concept, which is explained in more detail in Section 1.5.

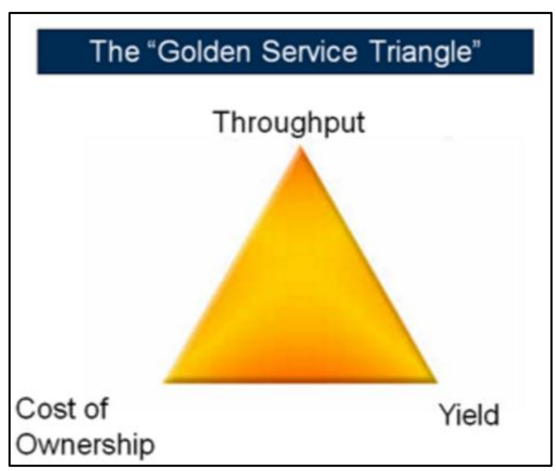

Figure 1.3: Golden Service Triangle

1.5 MP’s maintenance concept

MP has developed a maintenance concept to help its customers. According to MP, “a maintenance concept is a gathering of maintenance activities for a particular asset to maintain its intended function” (Laurijs & Lemmens, 2016). In this thesis, the maintenance strategy for a whole machine is called a maintenance concept that consists of maintenance policies for each of the parts within the machine. MP’s maintenance concept is a combination of corrective maintenance policies and proactive maintenance policies for the parts within a machine (asset). The proactive maintenance policies are divided into operational maintenance, periodic preventive maintenance, and predictive maintenance (CBM). Operational maintenance is minor maintenance that does not require detailed technical knowledge; e.g., cleaning, lubricating, and adjusting. Periodic preventive maintenance is preventive maintenance done at fixed moments that are planned in advance on time or count bases. Predictive maintenance is maintenance that aims to replace only when needed based on a prediction. To decide upon the maintenance policies for each of the parts within the machine, MP has developed its service part coding. The service part coding is called the AE-coding as the codes A till E are used. The following is based on MP’s AE coding guidelines (AE-coding guidelines, 2015). For the parts of the machines of the high-end customers, it is decided on by service engineers whether these parts should be service parts. Service parts are parts that are expected to need additional maintenance during the lifetime of its machine. Parts subject to an operational maintenance policy are coded A.

Parts subject to a corrective maintenance policy are coded B. Parts subject to a periodic preventive maintenance policy are coded C, D, or E. Some of the parts that wear are also subject to random failures. These parts are coded BC, BD, or BE and are also subject to a periodic preventive maintenance policy but are also stored at the customer. Currently, no parts are subject to a predictive maintenance policy. Every service code and its type of parts are explained.

A-coded parts are "consumables". These are parts that often make direct contact with the product processed and have an immediate effect on the technical performance of the machine. A-parts must be replaced very frequently on the judgment of and by the operator and therefore need to be easily accessible and changeable. These parts are considered to be part of the first line operational maintenance, which has to be done daily. To indicate the exchange frequency of an A-coded part, the annual consumption of the A-coded part is given to MP’s customers by MP.

B-coded parts are "breakdown" parts. These are parts or assemblies of parts that, when they become defective, make the production difficult (performance reduction) or impossible to continue (downtime). B-coded parts fail suddenly, and their failure is considered unpredictable in time for MP.

C- and BC-coded parts are “small overhaul” parts. These are parts that are subject to gradual and predictable wear and tear and are replaced preventive, time or count (as in broilers processed) based, to safeguard the correct operation of the machine. The C-coded parts have the shortest lifetime of the service parts within a subassembly, apart from A-coded parts.

D- and BD-coded parts are “major overhaul” parts. These are parts that are subject to gradual and predictable wear and tear and are replaced on preventive, time or count based, to safeguard the correct operation of the machine. The lifetime of the D-coded parts is at least twice that of the C-coded parts within the same subassembly. D-coded parts are similar to C-coded parts but have a longer lifetime.

E- and BE-coded parts are “total overhaul” parts. These parts are also subject to gradual wear and tear. However, two types are distinguished within this group. The normal E- (or BE-)coded parts are replaced on preventive, time or count based, to safeguard the correct operation of the machine. The expected lifetime of the E-coded parts is at least twice that of the D-coded parts within the same subassembly. The second type of E-parts is the so-called condition-dependent E-part also coded as Ei-part. The condition of the part can be assessed during inspection and or overhaul. The replacement time is anticipated to be similar to ‘normal' E-parts during the total overhaul. However, because it concerns expensive parts, an extra check is done on the condition to check if replacement is needed, such that it is not replaced too early.

PMS

While explaining the service codes, C-, D-, and E-coded parts were named overhaul parts as they are subject to periodic preventive maintenance policies. MP has developed the Preventive Maintenance Schedule (PMS) for these parts. The idea behind the PMS is to cluster parts based on their failure behavior into different overhaul kits. This preventive maintenance schedule can be classified as a block replacement policy with a minimal repair. Upon failure, the parts are minimally repaired, if possible, to survive till the next replacement opportunity. This next replacement opportunity is either the planned overhaul or an extra emergency overhaul. During planned overhauls, the parts are replaced preventively regardless of the previous corrective repairs (replacements or minimal) except the Ei parts. For the Ei parts, an inspection can lead to delaying the planned replacement if the part is expected to last till the next planned overhaul as a result of a corrective replacement done prior.

The clustering of the parts into the different overhauls based on their code (C, D, or E only) is explained next. Currently, the maintenance is done at different frequencies based on these codes. Every fixed amount of time (dependent on the customer and part) only the C-coded parts are replaced, which is called the small (S) overhaul kit. Every second time (or another multiple dependent on the customer and part) the C-coded parts are replaced, the D-coded parts are also replaced, and this is called the major (M) overhaul kit. Every second (or another multiple dependent on the customer and part) time D-coded parts are replaced, the E-coded parts are also replaced as the total (T) overhaul kit. For a typical schedule, see Table 1.1. The frequencies or time intervals are decided upon based on a combination of the minimal lifetimes of the parts within each overhaul and the relation of the minimal lifetimes between each overhaul (the overhauls have to be done in an integer multiple frequencies of each other). As can be seen, some parts follow the pattern described above entirely, while others deviate a bit. Legend 2 and 3 only have infrequent major overhaul (denoted with a red M) for example. Moreover, Legend 5 only has infrequent total overhaul (denoted with a blue T). Legend 9 has many small overhauls (denoted with a green S) before a major overhaul is done.

					Year :	1				2				3				4				5			
	TRDE				Quarter :	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Level	Pos	Item Type	Quant	Part Name	PMP :	1,1	1,2	1,3	1,4	2,1	2,2	2,3	2,4	3,1	3,2	3,3	3,4	4,1	4,2	4,3	4,4	5,1	5,2	5,3	5,4
0		N	1	TRANSFER SYSTEM,TRDE																					
.1	18	L	1	Legend 1				S			M			S			T			S			M		
.1	20	L	1	Legend 2													M								
.1	22	L	16	Legend 3													M								
.1	25	L	1	Legend 4				S			M			S			T			S			M		
.1	26	L	32	Legend 5													T								
.1	32	L	1	Legend 6				M			M			M			M			M			M		
.1	33	L	1	Legend 7													T								
.1	44	L	1	Legend 8				S			M			S			T			S			M		
.1	45	L	1	Legend 9				S			S			S			M			S			S		
.1	46	L	1	Legend 10													T								
.1	64	L	1	Legend 11																					

Table 1.1: Typical Preventive Maintenance Schedule (PMS)

2. Research design

This chapter discusses the research problem in Section 2.1, the research questions in Section 2.2, the research deliverables in Section 2.3, the methodology in Section 2.4, the research scope in Section 2.5, and the literature review in Section 2.6.

2.1 Research problem

Marel Poultry's (MP) service strategy is to generate added value for its customers with its maintenance concept. The added value of MP's maintenance concepts is to support the customer's preferred balance between the throughput, the cost of ownership (CoO) and the yield as dictated by the 'Golden Service Triangle', explained in Section 1.4. CBM policies are expected to allow a better balance between the three elements of the triangle. MP wants to add CBM policies to its current maintenance concept to further improve its added value. We research how MP can do this, which leads to the following main research question:

"Can MP apply CBM policies to improve its current maintenance concept?"

2.2 Research questions

This section presents the research questions that are required to answer the main research question.

Research Question 1

Before being able to apply CBM policies, investments to get the right data, and effort to analyze the data, are needed to get the optimal maintenance policy. It only makes sense to make investments and effort for parts which likely lead to benefits. This leads to Research Question 1:

RQ1: "How can MP select the parts most interesting for CBM?"

Parts are interesting for CBM when CBM is possible and can improve the current maintenance concept by decreasing the customers' costs, increasing their uptime, and increasing their yield. To answer Research Question 1, three steps have to be taken, which follows from the research sub-questions described hereafter.

Research Sub-Question 1.1

Although we are interested in the parts, we start with the machines as the parts cause the machines to be down. The downtimes of the machines are what the customers experience and are interested in as that is what results in a decreased throughput. Therefore, the first thing looked at is which machines are the most interesting for CBM. This leads to Research Sub-Question 1.1:

RQ1.1: "What are the machines most interesting for CBM?"

Research Sub-Question 1.2

After the most interesting machines have been selected, it is time to look at the parts within those machines. Although we already selected the most interesting machines we are interested in the actual parts in those machines. This leads to Research Sub-Question 1.2:

RQ1.2: "What are the parts most interesting for CBM within a selected machine?"

Research Sub-Question 1.3

After the most interesting parts are selected within an interesting machine, the failure behavior should be considered more in depth. We are interested in failure modes of parts that have a proper failure behavior and condition measurement(s) that allow CBM policies. Only when the condition can be measured, the parts are genuinely interesting for CBM. Checking the failure behavior of the parts leads to Research Sub-Question 1.3:

RQ1.3: "What is the failure behavior of the parts?"

This answers RQ1 leading to the selection method, which can be found in Chapter 3. The selection method is developed such that the input required is as much as possible from databases and only need expert input when necessary. The selection method is applied to a case at MP, which can be found in Chapter 4, resulting in a part selected.

Research Question 2

After the part most interesting for CBM has been selected, the next step is to apply CBM to this part to improve its current maintenance concept. This thesis considers the part selected during the selection method. This leads to Research Question 2:

RQ2: "How to apply CBM for the selected part and what are its costs savings?"

Research Sub-Question 2.1

The selection method has selected a part for which CBM is interesting. However, before the CBM policy is considered, it should become clear how the current maintenance concept operates for the specific relevant parts. Because the new CBM policy is part of this maintenance concept and to make a comparison to identify the possible costs savings. This leads to Research Sub-Question 2.1:

RQ2.1: "What is the current maintenance policy of the selected part?"

Research Sub-Question 2.2

When the current situation is clear, the new situation, with a CBM policy using the condition measure, is considered. This leads to Research Sub-Question 2.2:

RQ2.2: "What can the CBM policy of the selected part be?"

Research Sub-Question 2.3

After both the current and the new situation are clear, it is interesting to look at the difference regarding costs. We are interested in the potential costs savings, leading to Research Sub-Question 2.3:

RQ2.3: "What are the expected costs savings of the CBM policy?"

The CBM policy for the selected parts and its costs savings answers RQ2. This can be found in Chapter 5.

2.3 Research deliverables

Three deliverables follow from answering the research questions. To answer RQ1, a selection method is developed. This selection method is a generic method. This results in the first deliverable, which can be found in Chapter 3.

D1: The selection method

The implementation of the selection method to a customer of MP leads to a part selected. This results in the second deliverable, which can be found in Chapter 4.

D2: The part most interesting for CBM

To answer RQ2, a CBM policy is developed for the selected part for the customer for the current situation. This results in the third deliverable, which can be found in Chapter 5.

D3: The CBM policy for the selected part and its costs savings

Developing the three former mentioned deliverables identifies gaps at MP to apply CBM policies to improve its current maintenance concept. These gaps result in steps recommended to MP, which can be found in Chapter 6.

2.4 Methodology

The methodology of RQ1:

First, the selection method is developed as it would be used in the ideal situation where all desired data would be available. The development of the selection method is based on a combination of literature and expert input. To validate the selection method, it is applied to a case for MP. Implementation of the selection method requires input from the databases as much as possible and to need expert input only when necessary. The implementation of the selection method identifies data gaps at MP. Those gaps result in steps recommended to MP to take to utilize the selection method optimally.

The methodology of RQ2:

The current implementation of the selection method leads to a part selected for which the interesting condition measurement(s) are identified. First, the current situation (as-is) is described based on discussions with experts. This is followed by the development of a CBM policy for the selected part (to-be), also based on discussion with experts. The developed CBM policy is constrained to what is currently possible. Mathematical modeling is used to determine the benefits. The difference regarding costs is identified by expressing the relevant costs in formulas. The needed input values are mainly based on expert estimated input. The resulting costs savings is tested by a sensitivity analysis on the input values.

2.5 Scope

The main research goal is to apply CBM at MP. However this is a large task. This research focuses on the first steps towards that goal, which are the selection method and a CBM policy for the selected part. Currently, no data is representing the condition of interesting parts that can be used to predict a specific failure mode. The scope of this thesis is to be able to select the most interesting parts such that the required condition data can be acquired.

The selection method identifies parts interesting for CBM, but it should be defined for whom it is interesting. The focus of the research is to improve the maintenance concepts to increase the added value for the customers of MP. Therefore when costs are considered these are the costs of the customer. MP is interested in what is best for its customers because of customer relations alone. However, MP also wants to know what a service solution brings the customer, to know for how much to sell those services. Lastly, MP would like to be prepared for the future as MP might end up taking over the responsibility of the maintenance from the customers via service contracts. Therefore the costs of the customers are considered rather than the costs of MP.

Failure behavior (based on failure data) and condition measurement(s) for failure modes are both master theses on its own, and therefore only taken into account at a high level. Because these two steps require the most effort, they are considered last. Also during the implementation, we are dependent on the MP's experts input when data is missing.

2.6 Literature review

In this section, the essentials for this thesis of the literature study (van Sprang, 2016), preceding this thesis, are recapped. First, the past master theses at Marel Poultry (MP) concerning CBM are shortly discussed. This identifies the need to invest in sufficient data and also a necessity of a selection method to determine where to invest. Therefore, literature for several criteria for CBM is shortly discussed. This section finishes with discussing the relevance of the selection method for ProSeLoNext.

Theses at MP

Hussein (Hussein, 2012) started in 2012 with a master thesis at MP concerning CBM. A CBM situation was assumed with a hypothetical condition as there was no condition data available. This CBM policy was compared with the current policy at MP, a 95% age based maintenance policy, and a frequency constraint clustering model (van Dijkhuizen & van Harten, 1997) showing that the CBM-policy performs best. This was followed with van Dorst (van Dorst, 2014) in 2014 trying to predict the remaining useful life with condition monitoring of a chain. The model could predict the pitch as a condition of the chain. However, no threshold value could be determined as the chain was replaced before failure. Also, Houben (Houben, 2014) tried to predict the remaining useful life of the GP (Grower to Processor) system with performance monitoring using Statistical Process Control (SPC). No deviating trend could be spotted during the project. These theses at MP identify the problem that data lacks. There either is no data, censored data, or no sufficient history that allows for trends. MP wants to invest in data, but also want to know where to invest. Literature concerning criteria for CBM to identify when investments in the required data are interesting is discussed next.

Criteria CBM

Arts (2015) explains that CBM is interesting if either the timing or the content is unknown. Also, CBM and Age-Based Maintenance (ABM), thus preventive maintenance in general, is interesting for expensive components that degrade. When a component degrades, it means it has an increasing failure rate. Arts also mentions that CBM is chosen over ABM only if the condition can be measured relatively easy and cheap. De Jonge, Teunter, & Tinga (de Jonge, Teunter, & Tinga, 2016) investigated the relative benefits of CBM over ABM. They state that the relative benefits are dependent on the behavior of the degradation, the severity of failures, required setup time, the accuracy of condition monitoring, and randomness in the degradation level leading to failure signal, but CBM almost always outperforms CBM. The criteria used for the selection method are increasing failure rate and relevant costs. The remaining criteria related to the behavior of degradation, the accuracy of condition monitoring, and randomness in degradation level leading to a failure signal will only become apparent after a more in-depth investigation.

Relevance

We believe that our selection method is an improvement or extension of the existing selection methods. We explain the main differences with the most relevant existing selection methods below. Within ProSeLoNext, Teeuwsen (2016) and van Elderen (2016) both researched selecting suitable maintenance policies for parts at Océ. Their focus was to divide all the parts into different maintenance policy categories, without necessarily identifying the most interesting part to start with. Our focus is to select the part most interesting for CBM out of all parts, such that a start can be made to improve the current maintenance concept via CBM policies. The parts to continue with next are also identified, which allows a continuous improvement process of the parts most interesting for CBM.

Also, the focus of the research at Océ was limited to a single new machine for which they are interested in applying CBM policies. This means that both a machine is already selected and that this machine is rather new in the field and thus not yet been subjected to changes. These changes (at MP) can outdate the data used for the selection method. These changes could make the machine as 'new', but it is not clear which of the machines can be seen as new. Also, unlike the new machine at Océ, older machines already in the field could be lacking the capacity to handle the data needed for CBM. These are the first differences with MP and likely many other companies, as they are interested in which of the multiple machines already in the field are the most interesting.

Teeuwsen (2016) started with a selection method taking into account the 'failure rate', 'whether deterioration measurable', 'severity of consequences at a breakdown of parts', and 'need to learn about behavior'. The importance of the 'need to learn about behavior' is unique for the situation where the machine is new in the field, and thus not taken into account in our selection method as did van Elderen. Van Elderen (2016) built upon Teeuwsen's research by extending the selection method into a three step method. This method first takes into account the failure rate. Each part with an increasing failure rate is then categorized based on part costs and failure frequency. The categorizing is based on Scarf (2007), who, however, uses downtime and failure frequency.

Scarf (2007) categorizes parts into a matrix based on the criteria downtime and failure frequency. The matrix differentiates five different policy types. One of these policy types is CBM. Parts with low failure frequency but long downtime are categorized as CBM parts.

Van Elderen developed for each of the quadrants a decision tree taking into account things as 'condition detectable', 'severity of consequences at a breakdown of parts', 'deterioration measurable with data'. The decision trees can result in parts being recategorized into other quadrants. The need to recategorize leads to doubt the criteria used are correct in the first place. The main reason for recategorizing parts is the 'severity of consequences at a breakdown of parts'. This is taken into account in his project at a later stage because expert's input is needed at Océ. This is understandable as it minimizes the expert input needed. Our selection method tackles this by taking this into account data driven, such that this can be addressed earlier and easier.

Van Elderen uses high failure frequency as a criterion to categorize in matrices as Océ gets penalties for the number of failures (called errors at Océ). At MP, and likely many other companies, not the number of failures per se but the impact of these failures is what is of interest. Therefore rather the total downtime is taken into account which is a result of the number of failures and the downtime per failure.

Scarf (2007) does take into account the downtime, but only the downtime itself and not the costs. We also take into account the downtime costs as we multiple the total downtime with its cost.

Van Elderen takes into account the part costs as an indicator of the costs of preventive maintenance. Preventive maintenance wastes lifetime of the parts and thus more expensive parts make this wasted lifetime more expensive. However, next to the part costs, also the labor costs should be taken into account as the same applies. Therefore this is included in our selection method.

Our selection method is different as it results in a continuous improvement process that takes into account:

- multiple machines already in the field rather than one new machine;
- the consequence of failure data-driven such that recategorization due to inadequate criteria is not needed;
- the impact of failures rather than the failure frequency or the downtime alone;
- the preventive maintenance costs more thoroughly by including labor cost and look at yearly costs.

3. The selection method

This chapter answers Research Question 1.

RQ1: "How can MP select the parts most interesting for CBM?"

A generic selection method is developed to answer this research question. The selection method consists of steps that filter the parts most interesting for CBM. The selection method starts with RQ1.1 concerning the machines, in Section 3.1. This is followed by RQ1.2 concerning the parts within the interesting machines, in Section 3.2. This is followed by RQ1.3 concerning more in-depth failure behavior of the interesting parts, in Section 3.3. At any point of the selection method, iterative steps can be taken, which is explained in Section 3.4. This results in D1: the selection method, seen in Figure 3.1.

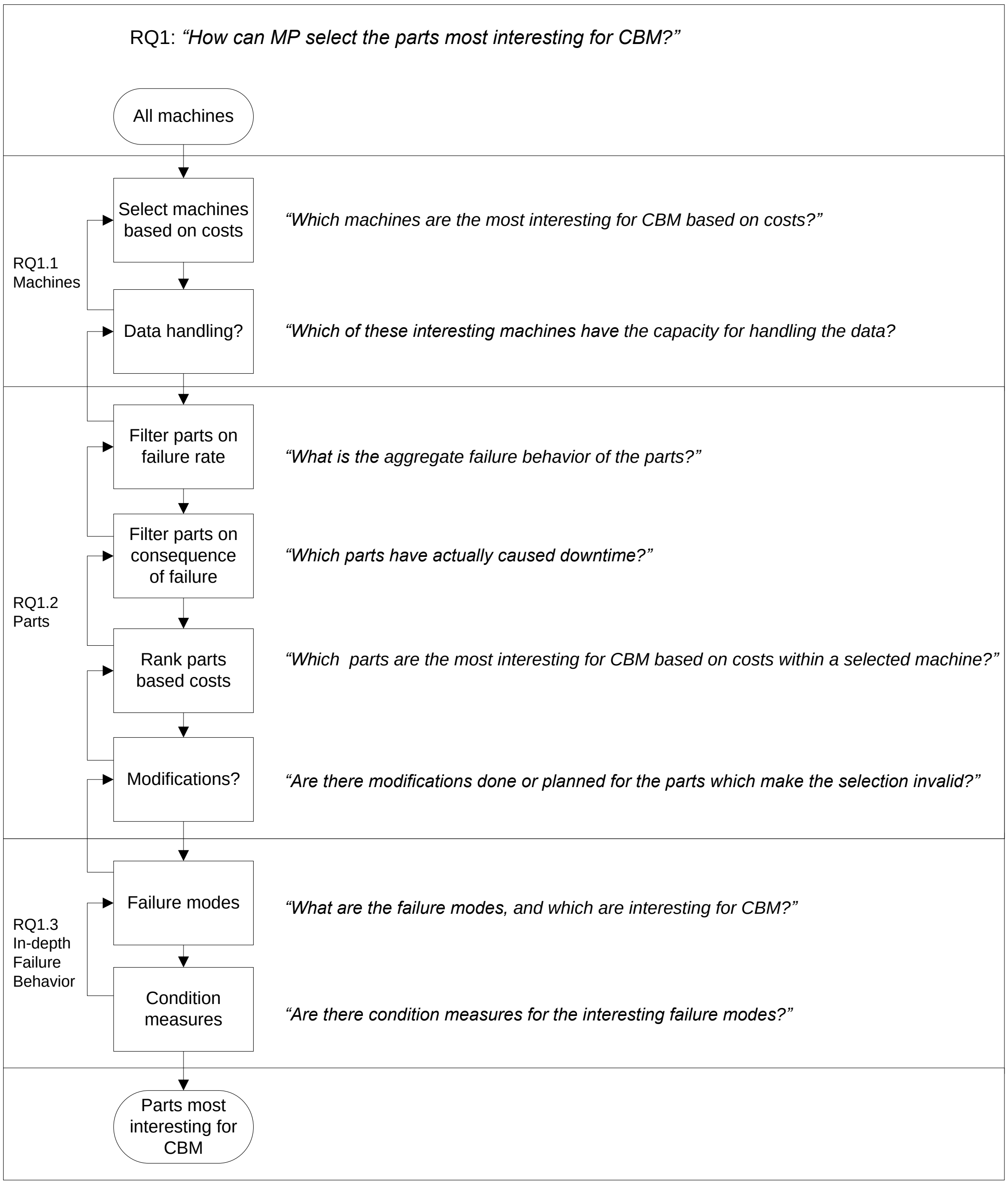

Figure 3.1: The selection method

3.1 Select machines

This section answers Research Sub-Question 1.1.

RQ1.1: "What are the machines most interesting for CBM?"

The selection method starts with the machines. To select the most interesting machines, the first thing looked at are the relevant costs of the machine. The more costs, the more room there may be to improve the current maintenance concept. The relevant costs are the preventive maintenance (PM) costs and the costs due to failures consisting of the corrective maintenance (CM) costs and the downtime costs. These costs are calculated with Formula 3.1.1.

$$Yearly\ Relevant\ Costs\ [€/year] = \tag{3.1.1}$$
$$Yearly\ PM\ Costs\ [€/year] + Yearly\ CM\ Costs\ [€/year] + Yearly\ Downtime\ Costs\ [€/year]$$

Next to costs, the capacity of the machines to handle the data is checked. To apply CBM policies, handling much data is needed, and the machines can be differentiated in their capacity to handle this data.

Preventive maintenance costs

The aim of the PM is to reduce the downtimes, but this means the lifetime of the parts is not utilized fully. This waste of lifetime can be seen as investments for reducing the downtime, and thus interesting to see whether this could be improved with CBM. PM leads to more replacements, which results in more part and labor costs. The part costs of the machine are the costs the customer pays. This is likely to be registered. Labor costs consist of the labor time and the tariff of the labor time. The labor time is the total time engineers from both the customer and Marel are needed to perform the preventive maintenance. The labor time includes disassembly, repair, and reassembly of the machine. The labor time results in labor costs consisting of the labor time multiplied by the engineer's tariff. Labor time and tariff should be registered to be able to take this into account data driven. Also, the frequencies of the PM actions should be known and registered. The yearly PM costs per machine, calculated with Formula 3.1.2, are the part and labor costs per PM action multiplied by the yearly frequency of the PM actions.

$$Yearly\ PM\ Costs\ [€/year] = \tag{3.1.2}$$
$$Yearly\ PM\ actions\ [PM\ actions/year] * PM\ Costs\ [€/PM\ action]$$

Although the customers perform PM, for which the machine has to be down as well, this is planned to be done during non-operating hours. Thus the PM does not lead to downtime.

Costs due to failures

For the PM costs, the part and labor costs are taken into account as lifetime is wasted. While upon failure, no lifetime is wasted. Therefore these costs are not taken into account as the costs due to failures. However, plannability is an extra advantage of PM over corrective maintenance (CM). CM costs consist of the extra costs of maintenance due to the unplannable nature of the replacements. For instance, the parts are not present and still have to be ordered, which costs more than normal orders. This could be tackled by storing the parts, which also has costs. Both the number of failures and the extra CM costs per failure should be registered to be able to take this into account data driven. To rank the machines based on their costs, in the end, the costs need to be compared. The average yearly costs per machine are used for this. The yearly CM costs per machine, calculated with Formula 3.1.3, are the yearly number of failures multiplied by their CM costs per failure.

$$Yearly\ CM\ Costs\ [€/year] = \tag{3.1.3}$$
$$Yearly\ Failures[failure/year] *\ CM\ Costs\ [€/failure]$$

Next, to the costs of maintenance, there are downtime costs. The downtime costs are the costs of the machines being down during operation due to a failure of a part or parts. The downtime costs consist of the actual time the machines are down and the costs the downtime of the machine brings. Both the downtimes and the downtime costs should be registered for this to be taken into account data driven. The yearly downtime costs per machine, calculated with Formula 3.1.4, are the yearly downtimes in minutes multiplied by their costs per minute.

$$Yearly\ Downtime\ Costs\ [€/year] = \\ Yearly\ Downtimes[minutes/year] * Downtime\ Costs\ [€/minute] \tag{3.1.4}$$

Rank based on costs

The machines are ranked based on the relevant costs (mentioned above) to find the most interesting machine. A graph like Figure 3.2 is useful to get an overview of the rank of the machines. The most expensive machine is also the most interesting and thus considered first (Machine 1 in the example). After the most expensive machine has been considered, the next most expensive machine is considered, and so forth.

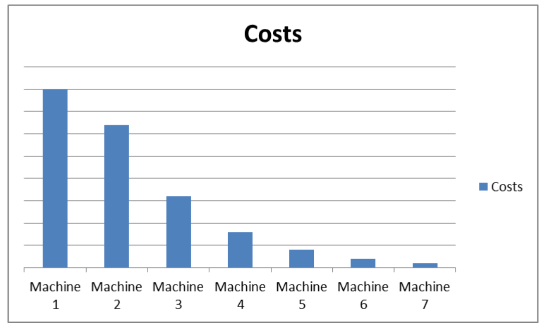

Figure 3.2: Resulting rank of the machines based on costs

Capacity for handling data

After the machines are selected based on their costs, the machines can be distinguished from each other in another aspect. Some of the expensive machines do not allow handling the data likely needed as input for a CBM policy, while other machines do. The capability of the machines to handle condition data that might be required as input for a CBM policy facilitates an easier implementation of the CBM policy. In this step, it is considered what is needed to handle the required condition data. The required data needed to be able to predict the failure consists of failure data, maintenance data, process data and (possibly several) condition measurement(s) for the parts considered. This data should be able to be put together and be timestamped on a fine enough grid. Process data contains, for instance, the input and output of processes in the line, as well as line speeds, quality, and losses. Condition measurement(s) should indicate the condition of the parts considered for CBM. The condition measure would likely need to be continuously monitored to allow for the best CBM policy. The failure and maintenance data likely needs to be logged manually. To understand which parts fail and are maintained and also how they are maintained human knowledge is needed. However, the process data and the condition measurement(s) would likely need to be logged automatically. The reason for this is that the condition data required would be too time- and labor-consuming to handle manually. How the machines differ in meeting the requirements to handle the data is company dependent. To give an example, at MP, they state that new PLCs (Programmable Logic Controller) are needed to handle the condition data. Although these new PLCSs are quite cheap (€500), they need a waterproof (machine specific) case, sensors, software, and a wireless Ethernet connection to allow handling the amount of data likely needed as input for a CBM policy. These extra requirements, to use the new PLCs adequate, are quite expensive. Currently, none of the machines have the new PLCs or an alternative. However, for some machines, there are already projects running to get the new PLCs that can handle (almost any) condition data that would be required as input for a CBM policy. For other machines, it would require quite some money, effort, and time to get the new PLCs. This differentiates the machines. For the capacity of the machine to handle the data to be taken into account, a discussion with experts is needed to identify the requirements of the machines. Ideally, whether machines meet the requirements is registered. If not, expert input is needed.

Priority classes

The interesting machines can be assigned to different priority classes based on the degree they meet the requirements for the capacity of the machines to handle the data. Likely three, but possibly more, priority classes can be differentiated. For instance, the first priority class contains the machines currently meeting the requirement. These machines are considered first in order or their costs rank. The second priority class contains the machines expected to meet the requirements soon. These machines are considered after the first priority class and in order or their costs ranked. The third priority class contains the machines expected not to meet the requirements soon. These machines are considered last and in order of their costs ranked. The example in Figure 3.2 could result in Table 3.1. Machines 2 and 4 are assigned to the 1st priority class, machines 1 and 5 to the 2nd, and machines 3 and 6 to the 3rd. This means that the order in which the machines are considered is 2, 4, 1, 5, 3, and 6.

Table 3.1: Machines assigned to priority classes

1st Priority Class	2nd Priority Class	3rd Priority Class
Machine 2	Machine 1	Machine 3
Machine 4	Machine 5	Machine 6

3.2 Select parts

This section answers Research Sub-Question 1.2.

RQ1.2: "What are the parts most interesting for CBM within a selected machine?"

Now that the most interesting machines are selected, that have the highest costs and the capacity to handle data, it is time to look at the parts within those machines. The first step is to filter parts suitable for PM, as only those parts are interesting. The second step is to filter parts with a severe consequence of failure, as this is a possible indicator that the current maintenance policy (aimed at reducing the consequence of failure) is underperforming. The third step is to again look at the costs, only now at part-level. Although we already selected the most interesting machines based on costs as a result of the parts, we are now interested in the parts that have contributed the most to these costs. Also for the parts, it applies that the more costs, the more likely there is room to improve the current maintenance concept. The fourth step is to check for modifications. Each step is discussed hereafter.

Failure rate

CBM is PM that aims to replace parts based on the condition just before failure to prevent failure from happening. The repairs of CBM should ideally be done during planned downtimes. These planned downtimes are the opportunities for the repairs. When parts need replacements during every planned downtime, CBM does not provide benefit as no repairs can be delayed (if not necessary) or done earlier (to prevent failure). When this is the case, the parts are removed from further consideration. Furthermore, PM only makes sense for parts with a wearing behavior (or increasing failure rate). If the part does not have an increasing failure rate, replacing the part does not reduce the probability of failure. The failure behavior of parts does not always have a purely increasing, constant, or decreasing failure rate. The failure behavior of parts could follow a typical bathtub curve, as shown in Figure 3.3. Parts following this bathtub curve have a decreasing failure rate in the beginning due to "infant mortality" failures, a constant failure rate in the middle due to random failures, and an increasing failure rate in the end due to "wear out" failures. When the part follows this curve, it makes sense to only replace it in the latter stage where the failure rate is increasing. A graph is useful to identify such relations in the failure rate. Expert and failure data can be used to derive whether the failure rate is increasing.

The expert knowledge would indicate if the part indeed 'wears' and has an increasing failure rate based on the mechanical machine- and part-knowledge the expert has. Next, to the expert input, the failure data can be used to determine the failure rate or validate the expert input. The time between two repairs of a part is considered as the failure times. A lot of these repairs are preventive replacements and thus need to be considered as censored data. Data is censored as the failure time is only partially known, for a preventive replacement it is only known that the part survived until the repair moment but it is unknown when the part would have failed without this preventive replacement (right censoring). Going into more detail on how to determine whether a part has an increasing failure rate based on failure data is considered out of scope for this project. Kaplan-Meiers's non-parametric estimation deals with censored data (Kaplan & Meier, 1958).

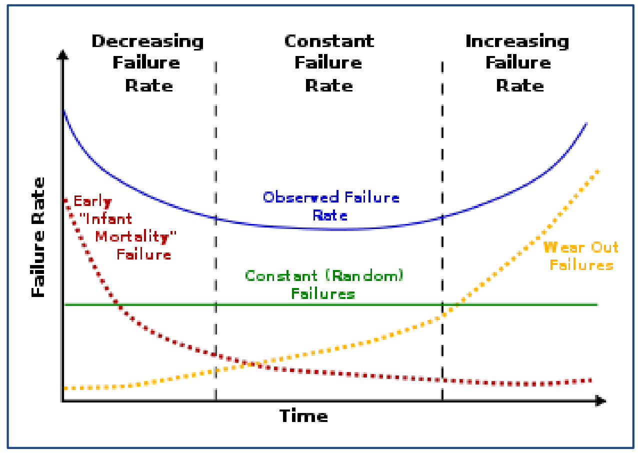

Figure 3.3: Typical bathtub curve

Consequence of failure

The primary reason for maintenance policies to prevent failures to happen is the consequence of a failure. So far, the parts are already filtered on their failure rate, and we expect those parts to be subject to a PM policy. Failures still happening could be seen as an indicator that the current PM is underperforming. In some situations wearing parts that also fail might not be subject to a PM policy. This might be due to the costs of the PM outweighing the consequence of failures. A CBM policy could be a way to reduce the costs of the PM, allowing a reduction in the number of failures and their consequence. Thus for wearing parts with severe consequence of a failure, regardless if they are currently subject to a PM policy, it is interesting to look into CBM policies. Therefore, the parts are filtered on severe consequences of failure. Dependent on which consequence of failure is most important, the downtime or the CM costs, the focus is on whether the parts caused downtime or caused CM costs. In order to take into account if parts led to failure that led to downtime, the downtime should be registered. It should be registered is such a way that it is able to deduce the parts causing the downtime. Thus, either the downtimes should be registered on part-level, or the failure data and downtime data should be registered such that downtimes can be linked to parts replaced. In order to take into account that parts led to failures that led to CM costs, the CM costs should be registered. This should be combined with the failure data. When data lacks, expert knowledge could be used. Experts could indicate the likelihood of failure of the part as well as its consequence.

Costs

After the parts are filtered on their failure rate and consequence of failures, we want to rank the parts on their costs. The consequence of the failures can indicate that the current policy is underperforming, but the costs identify which of the remaining parts has likely the most room to improve. The same costs (PM part- and labor costs and CM and downtime costs) are taken into account similarly as done with the machines. Some costs are registered on machine-level, which will have to be assigned to parts. Other costs are registered on part-level, which can be used directly. However, an extra challenge arises with assigning costs to parts. When doing maintenance, some parts are the root cause of the maintenance action, while other parts are replaced consequential. This did not matter when the costs were considered on machine-level as the costs were aggregated for all the parts within the same machine. When trying to identify the part that actually causes costs, allocating these costs to parts becomes important. Therefore, ideally, the failure data, maintenance data, and downtime data also register the root cause parts and the consequential parts.

Validate for modifications

Now that the parts have been ranked based on their costs, it should be considered whether these costs still represent the parts (in the future). There might have been modifications that already solved the issues causing the high costs. These modifications would make the data used for the costs invalid. Besides modification already being done, it can also be that a modification is planned that changes the near future. It can even be concluded that the solution is a modification rather than a change in the maintenance policy. This step validates if the selected parts are still 'problematic' (causing high costs) in the near future. We do not expect that the modifications can be registered in a way that allows a purely data-driven approach. Modifications can have multiple kinds of impact on many different parts, machine, or even lines. This would require registering the modification in a way that allows concluding whether a certain part is affected by any of the possible modifications done in the whole plant. Therefore, expert input is needed, and thus this step is done last in the part selection before the more in-depth failure behavior analysis of the remaining parts. The selection is discussed with a group of experts that have knowledge about the machine (and its parts) and the problems customers experience.

Resulting part selection

During the part selection, the four steps mentioned above have been taken into account. In order to give an example of how the part selection looks like, Table 3.2 gives an example of the machine selected in the machine selection example (Figure 3.2 and Table 3.1.). Part 1 is removed as it has no increasing failure rate. Part 2 is removed due to its failure frequency. Part 4 is removed as it has no severe failure consequence. Part 5 is discussed first for modifications due to costs. Part 5 is removed due to a modification. Part 3 is the selected part as it did not have a modification.

Table 3.2: Example of the resulting part selection

Machine 2					
Part	**Increasing Failure rate (1/0)**	**Frequency Failure - Opportunity (1/0)**	**Severe Failure Consequence (1/0)**	**Costs (€)**	**Modification (1/0)**
1	0	1	0	0	0
2	1	0	1	7965	0
3	1	1	1	15464	1
4	1	1	0	15341	0
5	1	1	1	41756	0
…	…	…	…	…	…
Filtered on Failure rate					
3	1	1	1	15464	1
4	1	1	0	15341	0
5	1	1	1	41756	0
…	…	…	…	…	…
Filtered on Severe Failures					
3	1	1	1	15464	1
5	1	1	1	41756	0
…	…	…	…	…	…
Ranked on Costs					
5	1	1	1	41756	1
3	1	1	1	15464	0
…	…	…	…	…	…
Filtered on Modification					
3	1	1	1	15464	0
…	…	…	…	…	…

3.3 Failure behavior

This section answers Research Sub-Question 1.3.

RQ1.3: "What is the failure behavior of the parts?"

After the parts are filtered, ranked on their costs, and the costs are validated and expected to represent the future, it is time to look at the failure behavior more in-depth. First, the failure behavior is split into the different failure modes, and each failure mode is considered. Hereafter, the potential condition measurement(s) for the interesting failure modes are considered.

Failure modes

The failure behavior is already partly considered as the parts are checked whether they have an increasing failure rate. However, this failure rate is likely a result of multiple failure modes of which the aggregate failure behavior is observed. In this step, the failure modes are identified, and it is considered which of these failure modes are interesting. Only failure modes that wear and have variation in time till failure are interesting for CBM. The failure modes should result in wear as they should have an increasing failure rate which makes them interesting for PM, and the wearing process is likely what can be detected. The failure mode should have variation in time till failure, as otherwise periodic PM could be planned perfectly without the need of CBM. It should, however, be noted that we do not mean a higher variation in the degradation level that leads to failure, as this variation is a disadvantage for CBM (de Jonge, Teunter, & Tinga, 2016). Upon failure, the reason of failure (and thus the failure mode) could be registered in the failure data. This would enable a data-driven approach as the failure data could be used to determine the failure rate of a part and the variation of time till failure for each failure mode. However, even if the failure data is sufficiently registered, this is likely quite challenging as the failure modes censor each other. Upon failure because of a failure mode, it is uncertain how long it would have taken before any of the other failure modes would have arrived. An alternative would be to discuss the failure modes with a group of experts that have knowledge about the parts and insight in the actual failures happening at the customers.

Condition measurement(s)

After the interesting failure modes have been identified, potential measurement(s) that represent the condition should be considered. Only when the condition can actually be measured, the parts are truly interesting for CBM. This would likely have to be done with a group of experts similar to the group potentially needed for the failure modes. This is done as the condition measurement(s) are specific for the failure modes and the part, and expert input is needed. Ideally, the condition measure allows continuous monitoring as this would provide the most detailed and direct information. Also, the condition measure should allow for sufficient delay time. The delay is the time between detection of a defect (or need for replacement) and the actual failure of the part. The delay time should be long enough to allow the planning of the maintenance tasks for CBM to be interesting.

3.4 Iterative steps

At any point during the selection method, it can be decided that none of the remaining candidates considered at that step be interesting. This leads to iterative steps in the selection method. For example, for the most interesting failure mode, there is no condition measure. Therefore the second most interesting failure mode is considered. However, it could be that none of the failure modes are interesting. Thus the second most interesting part of the same machine has to be considered. It is possible none of the parts in the first machine are interesting, thus the second machine has to be considered. Iterative steps are done until the most interesting part is selected or concluded that CBM is not appropriate for any part.

4. Implementation of the selection method at MP

The selection method is executed for a customer as a case at MP, resulting in a part selected with an interesting condition measure. Per step of the selection method, it is indicated what data is available and how the available data is used. This chapter is concluded with the main results.

Case introduction

The customer used for the case study is the one with whom MP cooperates most. This customer can provide most data needed for the selection method. The customer divides its plant (as many other customers) into primary- and secondary processing. For primary processing, the lines until chilling are considered, and for secondary processing the lines after chilling (see Figure 1.1 for a typical poultry processing layout MP). It should be noted that at the customer, not only is there relatively a lot of data available, but also that the customer performs well, the customer achieves the highest line speeds (13000-15000 broilers/hour) with the relative little downtime.

4.1 Select machines

In order to select the machines, data or expert input about the PM costs, costs due to failures, and the capacity of machines to handle the data is required.

Preventive maintenance costs

The yearly PM costs consist of the part and labor costs per PM action that have to be multiplied by the yearly frequency of the PM actions, as calculated with Formula 3.1.2. The part costs of the machines can simply be retrieved from SAP (Systems, Applications, and Products) and extracted to Excel. In order to get the part costs per PM action, the part costs are summed for the parts in each overhaul kit. The parts in each overhaul kit follow from the AE-code that can also be retrieved from PLM (Product Lifecycle Management) and extracted to Excel. The labor times are only known for a few machines and only for legends (and parts) level 1 in the product structure (see Section 1.3) for each overhaul kit. Thus the labor times are known for each PM action, but not for each part. The labor times include the required labor time of the customer's engineers that execute the overhaul and also the labor time of MP's engineers that oversee the overhauls. The labor tariffs for each type of engineer are known as this is registered in MP's Service Tariffs documentation. The frequencies of the PM actions follow from the PMS, which can be retrieved for KIS (Knowledge Information System). The PMS indicates the planning of the overhaul kits per machine for each legend (or part) level 1 in the product structure. The actual frequency should still be deduced manually. Retrieving and combining these data to get the PM costs for a machine requires several actions. The customer has 231 machines (231 unique machine codes) of which some machines have 25 legends. Calculating the PM costs for all the 231 machine is quite time and labor consuming. Also, the data is not completely available for all the machines. Because of this, we can either only take into account the machines for which data is available or disregard the PM costs for now. Only taking into account the machines for which the data is available could mean that some machines with much downtime would be ignored. However, otherwise, the PM costs are ignored. This can have an impact on the order of the top critical machines. Thus it is checked which of the two contributes to the most costs. For two machines, of which MP expects the PM costs to be the highest, and the labor times and downtimes are known, the PM costs are calculated. Table 4.1 shows these costs. TRCS has €47400 downtime costs due to 158 downtime minutes in 2016, €4234 labor costs, and €21571 part costs. TRDE has €68550 downtime costs due to 228.5 downtime minutes in 2016, €4446 labor costs, and €11498 part costs. Based on this, the downtime costs are considered most important, and thus all machines of which the downtimes are known are taken into account.

Table 4.1: Costs TRCS and TRDE

	DT (minutes)	DT costs (€)	Labor costs (€)	Part costs (€)	Total Costs (€)	% PM costs of Total costs (%)
TRCS	158	47400	4234	21571	73205	35%
TRDE	228.5	68550	4446	11498	84494	19%

Costs due to failures

The costs due to failures consist of the extra corrective maintenance costs (CM costs) and the downtime costs. At MP, the extra CM costs are not readily known, they differ for each situation as they are dependent on multiple factors (including the moment in time). However, the extra CM costs are expected to be less significant compared to the downtime costs. For the downtime costs, the customer keeps a downtime list. In this list, they track when downtime happens, at which line, machine, how long, the reason (mechanic, electric or organizational), and a short description of the reason. The customer started this downtime list at the end of 2011, meaning the downtimes of almost five years are registered. The downtimes of the year 2016 are used for the current average downtime, as these are the most recent.

The downtimes of the downtime list are assigned to the machines. However, due to human error, for some downtimes, the machine entry is not filled in (blank). The blanks grouped together has the most downtime. Therefore further investigation is needed for these blanks. First, if the machine could be deduced from the description, it is assigned to that machine. If it could not be assigned to one of the other machines, they are grouped together based on the description. The biggest new group consisting of blanks does not make the top ten, and thus is not considered further. Next to blank entries, there are also entries which actually are not machines, but rather whole lines. These lines are split up and based on their descriptions. These new groups also don't make the top ten, and thus are not considered further. Some of the machines entries not from MP. These entries are removed and not considered further too.

It is important to note the difference between the primary processing line and the secondary processing line when comparing machines within these lines. The primary processing line is more standardized and developed which allows it to perform better. However, there is only one line and all the broilers coming in are processed the same. So, although maybe performing better, downtime likely has a bigger impact. When a machine in primary processing is down, the arriving broilers cannot be processed, and the secondary line cannot be supplied. The secondary processing lines are more redundant than the primary processing lines. In secondary processing, the broilers are cut-up in different ways dependent on the demand. Therefore there are multiple options for operations that can be done, leading to more variation which is harder to control. However, on the other hand, there are also more options to cope with downtime. When a machine in the secondary processing is down, modules can be bypassed. While the preferred root may not be possible, broilers arriving at secondary processing can still be processed. Also, the broilers at primary processing can still be processed. Secondary processing can still process a part of the demand that does not require the particular machine that is down. As mentioned before, high-end customers typically assign €300/minute of costs to their downtime. This was input from the customer considered in this case. The customer does not differentiate in costs assigned to the different lines. However, because the primary processing line impacts the whole plant and the secondary processing line only a part, the downtime costs of secondary processing are probably lower than the downtime costs of primary processing. This is also seen in the downtime list; the downtime at secondary processing is typically higher than the downtime at primary processing. In Table 4.2 both the top three in downtime of both primary and secondary processing are shown.

Table 4.2: Top three in downtime of both primary and secondary

#	Machine	Downtime/ year (minutes)	Downtime frequency/ year	Average Minutes per Downtime (minutes)
Primary Processing				
1	Tipping-Section	389.5	119	3
2	TRDE	228.5	30	8
3	TRCS	158	11	14
Secondary Processing				
1	TRIG	2876	30	96
2	Vakuumtrichter	2535	14	181
3	JLR	1661	24	69

Table 4.3: Top reduced downtime costs

#	Machine	Downtime costs/year (€)
1	TRIG	215700
2	Vakuumtrichter	190125
3	JLR	124575
4	Tipping-Section	116850
5	TRDE	68550
6	TRCS	47400

Secondary processing as a whole has nine times as much downtime as primary processing with primary processing having slightly more downtime moments. This leads to the question: are the machines in the secondary processing leading to more downtime and thus more interesting for CBM or are the machines in secondary processing leading to more downtimes but not more downtime costs? The downtime costs of secondary processing are likely less than primary processing, but the customer does not differentiate. Therefore the impact of conservative assumptions for the downtime costs of secondary processing on the machine selection is checked. The €300/minute will be used for the downtime costs of primary processing, as downtime at primary processing impacts the whole processing plant. Because downtime at secondary processing only impacts the latter half of the processing plant, it is likely that the downtime costs are only half the downtime costs of primary processing. However, next, to only impacting the latter half, secondary processing also has more options to bypass machines that are down. Therefore, the downtime costs might even be a quart of the downtime costs of primary processing, meaning the downtime costs for the primary could be €300/minute (100%) and the downtime costs for secondary could be only €75/minute (25%). Applying these costs to the above top 3 of both primary processing and secondary processing will lead to Table 4.3. Table 4.3 shows that the top remains the same even though the conservative assumption of the downtime costs. Based on this, just as the customer, no differentiating in downtime costs is done between the machines.

Rank based on costs

The machines are ranked based on their costs. Only the downtime costs are currently taken into account as these are the highest costs. The first step in the machine selection results in the machine top based on downtime costs in Table 4.3.

Capacity for handling data

The requirements for the machines that enables the capacity to handle the data are discussed with the experts. This would require new PLCs and the accompanying implementation to allow the data handling. The top machines are discussed with experts whether they meet the requirements. None of the machines already has the new PLCs. However, the three transfer systems (TRIG, TRDE, and TRCS) will get the new PLCs in the near future as there are already projects running to get the new PLCs for these machines. The TRIG, TRDE, and TRCS are assigned to the 2nd priority class. The remaining machines in the top (Vakuumtrichter, JLR, and Tipping-Section) are assigned to the 3rd priority class. This results in Table 4.4. The machines TRIG, TRDE, and TRCS, are considered first and in that order, respectively.

Table 4.4: Machines assigned to priority classes

1st Priority Class	2nd Priority Class	3rd Priority Class
…	TRIG	Vakuumtrichter
	TRDE	JLR
	TRCS	Tipping-Section

4.2 Select parts

Now, the parts within the TRIG are considered for selection. The parts are filtered on failure rate and consequence of failure, ranked on costs, and checked on modifications.

Failure rate

The available repair data consists of a repair list of the customer. This repair list tracks the repairs (both preventive and corrective) on the TRIG of the year 2014. This was a result of a one-time initiative in the past to assess the troubling machines. Seven machines were selected that MP and the customer considered the most interesting (costly) to discuss, the TRIG was amongst these seven. For this thesis, the most recent repair list was requested at the customer, which resulted in a repair list of the corrective repair of the years 2015 and 2016. Some problems arise when analyzing the repair list for the failure behavior. Parts are replaced preventive between every 0.25 and 7.5 years and the parts subject to PM typically didn't fail often in the time frame. Some parts are present often in the list because they are replaced every shift. Other parts fail often, but this is a result of multiple of the same parts in the TRIG. These parts, however, are not registered separable, meaning that parts are registered under a certain part number. Multiple parts with the same part number cannot be differentiated from each other. Normally the time between repair (preventive or corrective) and failure can be used for the time till failure. However, since it is not clear which specific part is repaired or fails, the times between repair and failure are not known and the time till failure is also not known. Because of the lacking repair data, expert input is used. The AE-coding is used to represent the failure behavior. A-coded parts are replaced daily between shifts, and removed from consideration due to this high failure frequency. B-coded parts are removed from consideration as they follow a random failure behavior. C-, D-, E-, BC-, BD-, and BC-coded parts follow a wear behavior (and do not fail too often) and are considered further. Un-coded parts are also removed from consideration as they are not coded due to a combination of lack of standardization of the part and the expectation that the parts outlast the (economic) lifetime of the machine.

Consequence of failure

The consequence of failures at MP with the highest impact is the downtime. The downtimes are, however, registered on machine-level. The repair data is registered on part-level, and we are interested in the downtime as a result of a part failing. Only downtimes as a result of failing parts (that should be registered in the repair data) and failing parts that caused downtimes are interesting. Downtimes due to other reasons than failing parts are not interesting as are failing parts that do not cause downtime. In order to identify the parts with downtime (as consequence of failure), the downtime list and the repair data are combined, as shown in Figure 4.1. The 'Combined list' contains per part the part costs, the downtimes (amount of moments) and downtime in minutes. Only parts that had downtime as consequence of failure are considered further.

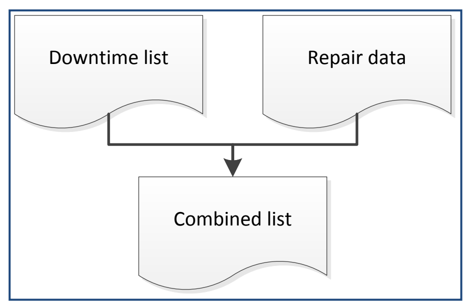

Figure 4.1: Combined list

Costs

After the parts are filtered on downtime upon failure, the parts are compared based on their costs. For this, the costs relevant for the benefits of a CBM policy are taken into account. The relevant costs are the PM part and labor costs, the extra CM costs, and the downtime costs. The labor times are unknown for the TRIG and thus not taken into account. The same applies for the extra CM costs. The PM part costs follow the part cost multiplied by the PM frequency of the part, calculated with Formula 4.2.1. The part costs are retrieved from SAP, the AE-code from PLM, and the PM frequency is deduced (manually) from the PMS, which is retrieved from KIS.

$$Yearly\ PM\ part\ costs\ [€/year] = Part\ cost\ [€] * PM\ frequency\ [/year] \qquad (4.2.1)$$

The downtime costs follow from the downtime costs per minute (€300) multiplied with the downtime minutes of the year 2016, calculated with Formula 4.2.2. The combined list, created for the consequence of failure, is used to determine the downtime minutes of parts.

$$Yearly\ Downtime\ costs\ [€/year] = \\ = Downtime\ costs\ [€/minute] * Downtime\ 2016\ [minutes/year] \quad (4.2.2)$$

Table 4.5 shows the parts, with the appropriate AE-code and consequence of failure, ranked on their PM part costs and downtime costs. Part A is the most interesting part. This Part A together with Part F, Part H, and Part I, which are also filtered as interesting, are part of Legend A.

Table 4.5: Ranked remaining parts

Rank	Name	AE-Code	Total Costs (€)
1	Part A	C	40833
2	Part B	D	4575
3	Part C	D	4555
4	Part D	E	4543
5	Part E	C	4521
6	Part F	C	3997
7	Part G	E	1641
8	Part H	C	1570
9	Part I	D	1507

While we are interested in a single part, the whole Legend A with their interesting parts is considered further, due to its dependency. Next to the parts filtered as being interesting, the costs of parts already removed from consideration, also show some other interesting results. Part J, which is an A-coded part and thus removed from consideration, has almost the same costs as Part A. Upon further investigation, it is seen that Part J and Part A are always replaced together. This also results in assigning the same downtime costs to the parts. It, however, is not clear which of these parts is the actual root cause of the downtime, which part might just be a consequence of the failure of the other part, or if a part is replaced opportunistic during the downtime. Part J, although it was removed from consideration, is still interesting to discuss with experts in regards of its relation with Part A. Also, Part K in Legend B results in high costs. These costs are mainly due to a single downtime event. The part is un-coded and not expected to fail, and thus no PM is done, while the part itself is quite cheap. Part K is also discussed further to check whether the part failed more often even though it is un-coded (and thus not expected to need PM)

Validation for modifications

The input of experts is used to validate and get a complete and correct picture of the selected parts. The TRIG and its identified interesting parts have been discussed with a group of experts within MP. The discussion was done with 2 Process Technologists who know the TRIG and the problems customers experience with the machine, and a Service Coordinator who knows the customer and the maintenance (and the problems). When discussing Legend A, and Part A in Legend A, with the experts, it turned out that Part A was indeed problematic. However, the problem was already known for a while, and even a technical improvement was done, which improved the whole Legend A. Thus a modification was already executed to solve the problem. During the discussion, it was stated that the replacements of Part A are used as an opportunity to replace Part J. Part J is not the cause of the downtimes, and thus the 'Combined list' wrongly assigned the downtimes to Part J. According to the experts, Part K in Legend B is not expected to fail, and Part K had to have failed due to an incidental extremity. To check this, the orders of Part K, amongst all customers, are checked to see if Part K indeed hasn't failed more often. It turns out that, besides this instance, Part K is never re-ordered by any customer. It is only included in the purchase orders of the whole machine upon purchase of the TRIG. Concluding Part K does not fail outside of extreme incidents, and therefore is not interesting for CBM. At this point, it was concluded that no parts in the TRIG are interesting for CBM.

Selection 2

Since no parts of the TRIG are considered interesting for CBM, the next machine has been considered. According to Table 4.4, the TRDE is the next machine.

Select parts 2

When redoing the selection, we take into account some of the things we learned in the first selection. Ideally, the downtime is taken into account based on the combination between the downtime list and the repair list. However, this turns out to be somewhat problematic. It is not clear whether the parts involved are the actual cause or simply replaced as a result. Also, only for a small fraction of the downtime, parts could be assigned. Moreover, only for a small fraction of the failed parts, downtime could be assigned. Also, mistakes are made in the downtime lists; some downtimes are registered wrongly, which could be concluded from the description. For instance, some downtimes are registered under a mechanical cause, while the description indicates it was organizational. While the problems with assigning downtime to parts were apparent with the selection of the parts of the TRIG, they became even more apparent with the TRDE. The few downtimes that could be matched to parts with the 'Combined list' are considered incidents and not recurring failure modes. Therefore, it has to be concluded that, at this point, it is not possible to assign downtimes to parts. The downtime cannot be used to identify parts interesting for CBM. However, selecting the most interesting part is still desired. The whole PMS is based on known recurring failure modes (and prevent these from happening). The selection method's goal is to select a part for which a CBM policy can be developed in order to predict a certain failure mode (and prevent these from happening). It makes sense to focus on the failure modes that currently costs the most to be prevented. These costs are the PM costs, which will be the main focus for now, and the downtime and CM costs are not taken into account. Therefore the part selection is based on the failure rate and PM costs only.

Failure rate 2

Again, the parts are filtered on their failure rate based on the AE-coding. C-, D-, E-, BC-, BD-, and BC-coded parts are considered further.

Costs 2

The PM costs play a larger role now and the labor times of the TRDE are known. Thus next to the parts costs, also the labor costs are taken into account. The part costs are taken into account the same way as with the parts for the TRIG. However, the labor times are only known for legends (and parts) level 1 in the product structure. In order to take into account the labor costs, the costs (part and labor) of legends level 1 are looked at first. After which the costs of the underlying parts are looked at.

The Unit-Pushover is the most expensive legend and has yearly PM costs of €6824, which is about 40% of the yearly PM costs of €15944 for the TRDE. These PM costs consist of yearly labor costs of €2243, which is about 50% of the yearly labor costs of €4446 for the TRDE, and the yearly part costs of €4581, which is about 40% of the yearly parts costs of €11498 for the TRDE. The most expensive part within the Unit-Pushover is the Ratchet with yearly part costs of €1309.

Legend C is the second most expensive legend and has yearly PM costs of €2771, which is only about 40% of the yearly PM costs of the Unit-Pushover. Therefore, only the Unit-Pushover will be considered further.

Validation for modifications 2

The Unit-Pushover of the TRDE and the Ratchet are discussed with experts to validate for modifications. It could be concluded that no modifications that will reduce the PM costs are done, planned or considered as the main solution.

4.3 The failure behavior

Now that Ratchet within the Unit-Pushover of the TRDE is considered to be the most interesting part due to its failure rate and costs it is time to take a more in-depth look at the failure behavior. The TRDE, Unit-Pushover, Ratchet, failure modes, affected parts, action, and detection are discussed in more detail in Chapter 5. In this section we focus on the characteristics of the failure modes and if condition measurement is possible, as mentioned in Section 3.3.

Failure modes

The aggregate failure behavior of the Ratchet is already considered with the AE-code concluding it has an increasing failure rate. However, now, the underlying failure modes are discussed with experts. The main failure mode is the result of wear and thus has an increasing failure rate. The failure mode has variation in time till failure. The variation in time till variation is such that MP currently has difficulty planning the replacement moment. A CBM policy is likely better at predicting the failures, and thus planning the replacement moments. Therefore, a CBM policy is likely more beneficial than the current PMS. The main failure mode is interesting for further consideration.

Condition measurement(s)

The possible condition measurement for the main failure mode is discussed with experts. The actual wear of the Ratchet is considered hard to measure or monitor. However, currently, the failure is not self-announcing and continuous monitoring can allow the failure to be detected (close to) immediately. This improved detection is expected to be interesting as it can decrease the wear on other parts as well.

4.4 Results of the implementation of the selection method

This section discusses the main results of the selection.

Main result

The main result of the implementation of the selection method at MP is the selection of the Ratchet within the Unit-Pushover of the TRDE, which has an increasing failure rate due to wear.

Intermediate result

Intermediate results of the selection method are the costly machines that do not allow data handling; the Vakuumtrichter, JLR, and Tipping-Section. It would be interesting to look into the possibilities of projects resulting in the capacity to handle the data for those machines. All three machines would have been considered before the TRDE if they had the data handling capacity.

4.5 Lacking data and its impact on the selection

The lacking data and its impact on the selection are discussed in the order when the data is needed for the selection method.

Labor times

The data of the PM labor times lacks for most machines. However, the labor costs are only a small part of the total costs, as the downtime costs contribute to the most costs. Taking into account the labor times would improve the selection, but this is not critical for the selection that can be done without.

PM costs machines

The data of the PM costs of the machines lacks. Calculating the PM costs for all the 231 machine is quite time and labor consuming. The PM costs are only a small part of the total costs, as the downtime costs contribute to the most costs. Taking into account the PM costs would improve the selection, but this is not critical for the selection that can be done without.

CM costs

The CM costs are not known. However, the CM costs are expected only to be a small part of the total costs. These extra CM costs are only made to reduce the downtime costs, which are also the bigger contribution to the costs. Taking into account the CM costs would improve the selection, but this is not critical for the selection that can be done without.

Downtime costs for machines

The downtime costs per minute of the machines are not exactly known. Also, there is no difference made between the machines in primary processing and the machines in secondary processing. The downtimes of the current top machines in secondary processing are high enough that even conservative assumed downtime costs per minute do not change the current order of machines. Although the downtime cost per minute did not influence the current selection of the machines, these costs are considered quite critical as these are the biggest part of the total costs. For future selection, the actual downtime costs per machine should be known.

Aggregate failure data and analysis

The failure data lacks as it does not allow analysis that is sufficient for an adequate understanding of the failure behavior. The data does not register the parts as unique parts, but multiple of the same parts are aggregately registered. Besides this, the volume of data per part is not enough to do sufficient analyses on. There are only a few corrective failure data inputs as a result of PM policy. To give an example, if the PM policy achieves a 90% performance by replacing four times a year (one of the higher frequencies within MP), you would expect one corrective failure every 2.5 years. At least multiple failures and thus more years are needed to do analysis on. In order to cope with the lacking data, the AE-coding could be used as input for the aggregate failure behavior. Although ideally, the AE-coding would be validated with failure data, this is not critical for the selection that can be done without.

Downtime for parts

The downtime data for the parts lacks as this is only registered for the machines. The available failure data could be used to link the failing parts with the downtimes. However, this currently lacks as it is not clear which parts are the root cause of the failure and downtime and which parts are replaced as a result of the failure and downtime (consequence, opportunistic, or even auxiliary). This has the biggest impact on the selection method as the downtimes costs are the most critical costs and the parts are what we are interested in. Currently, it is impossible to take the downtime costs per part into account adequately. Although it is still possible to select a part interesting for CBM, this is not ideal as it likely is not the most interesting part.

Failure data and in-depth analysis per failure mode

The failure data for more in-depth failure behavior per failure mode lacks due to similar reasons as the aggregate failure behavior analysis. Next, to the problems with the failure data mentioned before, the failure data also lacks a distinction between the different failure modes. Because each of the failure modes censor the failure data for the other failure modes, even more data volume would be required. Although the data currently lacks, the expert input is currently sufficient to base the selection method on.

5. The CBM policy for the Ratchet and its costs savings

This chapter answers Research Question 2.

RQ2: "How to apply CBM for the selected part and what are its costs savings?"

A CBM policy is developed for the selected part for the customer for the current situation to answer the research question. The part selected in Chapter 4 was the Ratchet in the legend the Unit-Pushover in the machine TRDE. The CBM policy is guided by the input from discussing the failure modes and condition measurement with the experts. The idea is that with improved detection the increased wear, due to a soft failure, can be reduced. A soft failure is a type of failure, which negatively influences the intended function, but still, allows the machine to operate. The negative influences could be a reduced speed or quality, or in this case, increased wear. The reduction of the increased wear can lead to higher lifetimes of the parts affected, which could decrease the frequencies of the current PMS. This decreased frequency will result in costs savings. The situation considered is the situation of the same customer as used for the selection of the part. RQ 2.1 is answered in Section 5.1, which gives the gives the current situation. RQ2.2 is answered in Section 5.2, which gives the new situation and the expected benefits that follow from the difference. RQ2.3 is answered in Section 5.3, which gives the calculations and formulas, in Section 5.4, which gives the input values, and in Section 5.5, which gives the results. Section 5.6 concludes the chapter with a sensitivity analysis.

5.1 Current situation

This section answers Research Sub-Question 2.1.

RQ2.1: "What is the current maintenance policy of the selected part?"

The TRDE, Unit-Pushover, Ratchet, failure modes, affected parts, current maintenance concept rules, action upon failure, and detection are discussed in this section to get an understanding of the current situation.

TRDE

The TRDE (Figure 5.1) is a system, which transfers broilers (Figure 5.2) from the Defeathering line to the Evisceration line. The name TRDE has the TR in it to refer to it being a transfer system, the D to refers to the Defeathering line and the E to refers to the Evisceration line. The TRDE connect the two different lines by transferring the broilers. Broilers have to be transferred due to hygienic reasons and because different shackles are needed in the different lines.

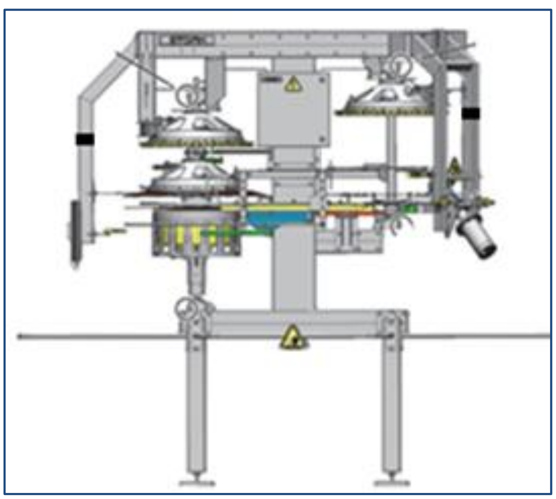

Figure 5.1: Picture of TRDE

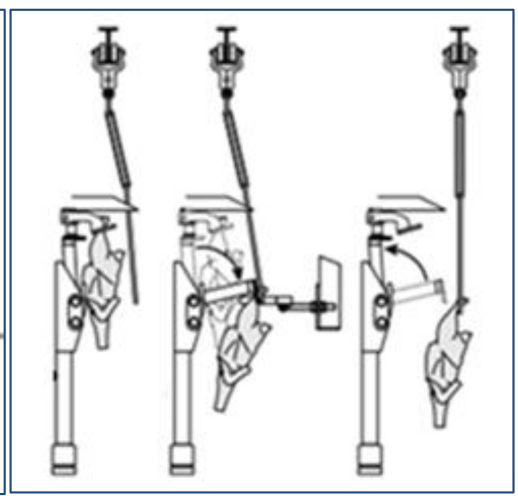

Figure 5.2: Picture of transfer

Unit-Pushover

The Unit-Pushover (Figure 5.3) rotates with the shackles, and it has a hammer which slams the broilers from a shackle of the Killing line to a shackle of the Evisceration line. The TRDE contains 16 of these Unit-Pushovers. The Unit-Pushover should only slam if there is an actual broiler on the shackle; here the Ratchet comes into play.

Ratchet

The Ratchet (Figure 5.4) locks the tensioned hammer with a sharp edge on the one side of the Ratchet. The other side of the Ratchet sticks out. If the shackle passing has a broiler on it, the broiler pushes Ratchet which releases the hammer. When there is a broiler on the shackle, the broiler dampens the impact of the slamming.

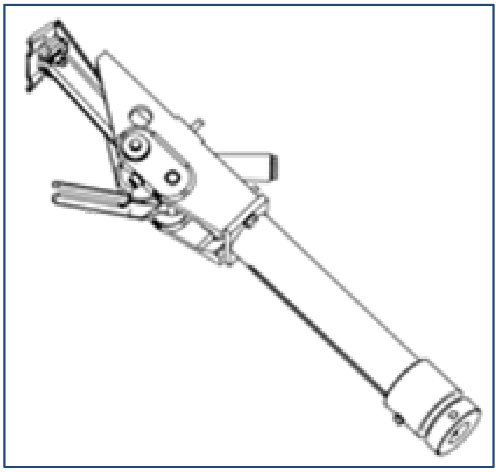

Figure 5.3: Picture of Unit-Pushover

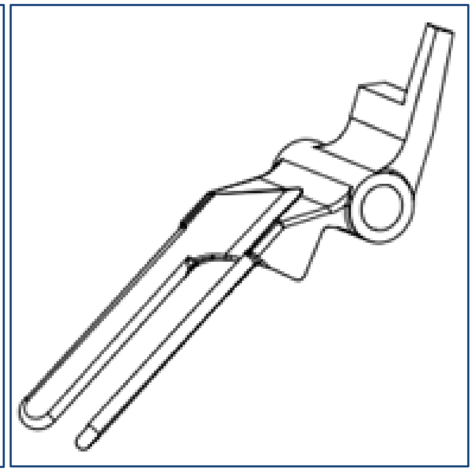

Figure 5.4: Picture of Ratchet

Failure modes

When the Ratchet is worn, the sharp edge becomes dull. This can cause the Ratchet to lock the hammer improper as it loses traction and slips. This will lead to the hammer slamming on empty shackles, which, without the damping from the broiler, will increase the wear of Part L, Part M, and Part N the Unit-Pushover (explained under affected parts). This also makes much noise, which can be noticed by the customer, but only after it has already been happening. There is another failure mode causing the Unit-Pushover to hammer on empty shackles. This is still related to the Ratchet, but not to the wear of the part itself. The height settings of the Curve, on which the gears are assembled on, have to be set to a certain height for the machine (and Ratchet) to operate properly. The actual height will start to deviate from the set height over time, and at some point in time, the height deviation is enough to prevent the Ratchet to lock properly. The first considered failure mode, due to the wear of the Ratchet itself, will hereafter simply be called: 'Failure mode Ratchet'. The second considered failure mode, due to the deviation in the height of the Curve, will hereafter simply be called: 'Failure mode Curve'.

Affected parts

Since hammering on full shackles is needed to transfer the broilers, this is considered normal operating. Thus also the wear resulting from hammering on full shackles is considered normal wear and thus not taken into consideration. Only the extra wear caused by hammering on empty shackles is of interest and therefore also only the hammering on empty shackles is of interest. From now on: 'hammering on empty shackles' is simply called: 'the hammering' from now on. The parts affected by 'the hammering' are Part L, Part M, and Part N. Appendix 1 shows Figure A1 which is an 'exploded' overview of the parts.

Current maintenance concept rules

The CBM policy will not change the current maintenance concept. According to the PMS structure (discussed in Section 1.5), the overhauls are done in a nested frequency, during planned downtimes. These overhauls remain the opportunities for preventive maintenance. The current clustering of the parts in the overhaul kits also remains the same. However, the parameters of the PMS structure, which are the frequencies of the overhauls, can change. This is interesting as a reduced frequency leads to reduced PM costs. The frequencies of the overhaul kits will only change if the reduced wear on the parts is such that the minimal time limit of the parts within the overhaul kit changes enough to delay the overhaul kit. The time limit is the maximum time between replacements of a part. Usually, to optimize time-based maintenance, the failure distributions of the parts need to be known. The failure distributions would enable determining the optimal time limit for replacing the parts based on the costs and failure probabilities. However, at MP, the failure distributions are not known. The time limits are initially set based on experience and intuition. Afterward, the time limits are validated and set iteratively based on the interaction between an expert and the customer until a certain customer satisfaction is achieved. Increased time limits due to decreased wear can decrease the frequency of the overhaul kits which saves PM costs. The CM costs are left out of consideration as the time limits are only allowed to change when the same customer satisfaction can be achieved. In order to explain the implications of the current maintenance concept rules, the PMS of the Unit-Pushover is given, and its implications are discussed. The PMS of the Unit-Pushover is shown in Table 5.1.The parts that wear (C, D, and E-coded) are clustered into the overhaul kits. The Small overhauls (S and green in Table 5.1) contain only the C-parts, the Major overhauls (M and red in Table 5.1) contain the C- and D-parts, and the Total overhauls (T and blue in Table 5.1) contain the C-, D- and E-parts.

Table 5.1: PMS of the Unit-Pushover

					Year :	1				2				3			
	TRDE				Quarter :	1	2	3	4	1	2	3	4	1	2	3	4
Level	**Pos**	**Item Type**	**Quant**	**Part Name**	**PMP :**	1,1	1,2	1,3	1,4	2,1	2,2	2,3	2,4	3,1	3,2	3,3	3,4
.1	22	L	16	UNIT PUSHOVER-			S		S		M		S		S		T

According to the PMS in Table 5.1, the C-parts are replaced every half year, the D-parts every 1.5 years, and the E-parts every three years. Thus, the C-parts are replaced three times as often as the D-parts, and six times as often as the E-parts. The D-parts are replaced twice as often as the E-parts. The frequency of the S-kit is 4/3 a year, the frequency of the M-kit is 1/3 a year, and the frequency of the T-kit is also 1/3 a year. The parts are clustered because to replace one part the whole legend has to be disassembled. This disassembly is used as an opportunity to replace other parts. The parts of an overhaul have more or less similar lifetimes, or the parts have to be replaced as a result of maintenance on the other parts (auxiliary). An example of auxiliary parts are bolts; they can only be used once and have to be replaced after loosening to open a motor for instance. The lifetime of the parts within an overhaul influences the time limit set by the expert. The actual time intervals of the overhauls are set to at least meet the minimal time limit within each overhaul and allow the overhauls to be done in an integer multiple of each other.

Action upon failure

The Ratchet is planned to be replaced preventively every three years. When the Ratchet fails and causes 'the hammering', the Ratchet itself has to be replaced. Since the Ratchet is part of the PMS and does not lead to actual downtime, the Ratchet is replaced at the first planned overhaul (any overhaul kit). When the Curve height setting is the cause of 'the hammering', this again does not lead to actual downtime. The settings can be reset during the next break. The customer, as do other customers, has breaks within the shifts, which allow room for the Technical Department to, for instance, change the settings. Thus for both failure modes, there is some waiting time before it is solved, while in the meantime the lines are running and thus is 'the hammering' causing an increased wear on the affected parts.

Detection

Currently 'the hammering' has to be noticed by the customer based on the noise. However, this is entirely subjective and challenging as the rest of the production also makes noise. Also, there is nobody assigned to listen to 'the hammering' actively.

5.2 New situation

This section answers Research Sub-Question 2.2.

RQ2.2: "What can the CBM policy of the selected part be?"

Since the current detection is subjective, experts suggested improving this detection. The detection could be done directly and online by combining a camera and the Product Detection System (PDS). The PDS is MP's detection system, which detects products, that is used to control the operations. The camera would identify whether the Unit-Pushover hammers, and the PDS indicates whether the shackle was full. This would eliminate the time it takes to detect 'the hammering'.

The new detection strategy is shown in Figure 5.5. When 'the hammering' is detected, first the curve settings will be checked. When the curve settings are the cause, the settings are reset. When the curves were not the cause, the Ratchet is the cause and is therefore planned to be replaced.

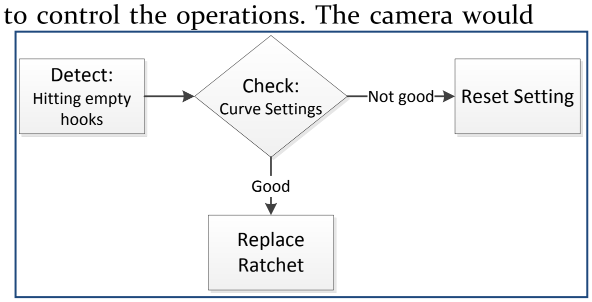

Figure 5.5: Detection strategy

Expected benefit

It is expected that the faster detection will reduce the time of 'the hammering', and thus reduce the increased wear on the affected parts. The decreased wear of these parts can lead to longer time limits due to increased lifetimes, which may result in a larger time interval of the PMS to meet the same customer's satisfaction. This larger time interval of the PMS will lead to a lower frequency, and thus the PM has to be done less often reducing the PM costs. The action upon detection is, as stated before, to wait for the next opportunity. Regardless of the failure mode, during this period the hammer hits the empty shackles. For the failure mode Ratchet, the action upon detection is to wait till the next upcoming overhaul. Often 'the hammering' starts and is detected before the next overhaul, see start 1 in Figure 5.6. The Ratchet is replaced at the next overhaul (the M at Quartile 2.2) and thus the time of 'the hammering' is the same regardless the detection time. However, sometimes 'the hammering' starts just before an overhaul, see start 2 in Figure 5.6. In the current situation (with detection time) the detection happens just after an overhaul and the replacement is delayed till the next overhaul (the S at Quartile 2.4). However, in the new situation, the start moment of 'the hammering' equals the moment of detection, and the action is done during the first upcoming overhaul (the M at Quartile 2.2). In this case, the detection time leads to a prolonged time of 'the hammering'.

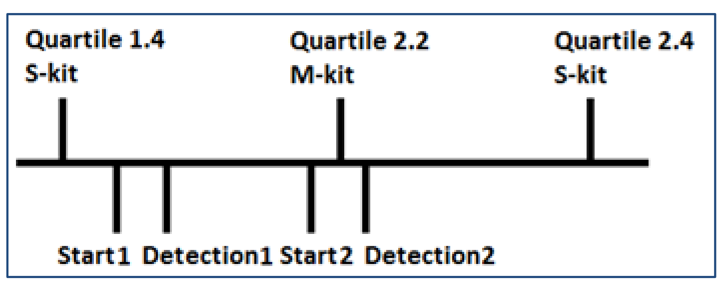

Figure 5.6: Timeline of example prolonged 'hammering'

Appendix 2 shows that on average the extra time of 'the hammering' due to delayed detection is equal to the delayed detection time.

5.3 Calculations

This section, together with Section 5.4 and Section 5.5, answer Research Sub-Question 2.3.

RQ2.3: "What are the expected costs savings of the CBM policy?"

To answer this question, the calculations needed that lead to the expected costs benefits are shown in Figure 5.7 (Appendix 3 contains Figure A3, which is an enlarged version of Figure 5.7). The steps in Figure 5.7 are explained one by one, and the numbers between the brackets are used in the text to refer to the blocks in the figure.

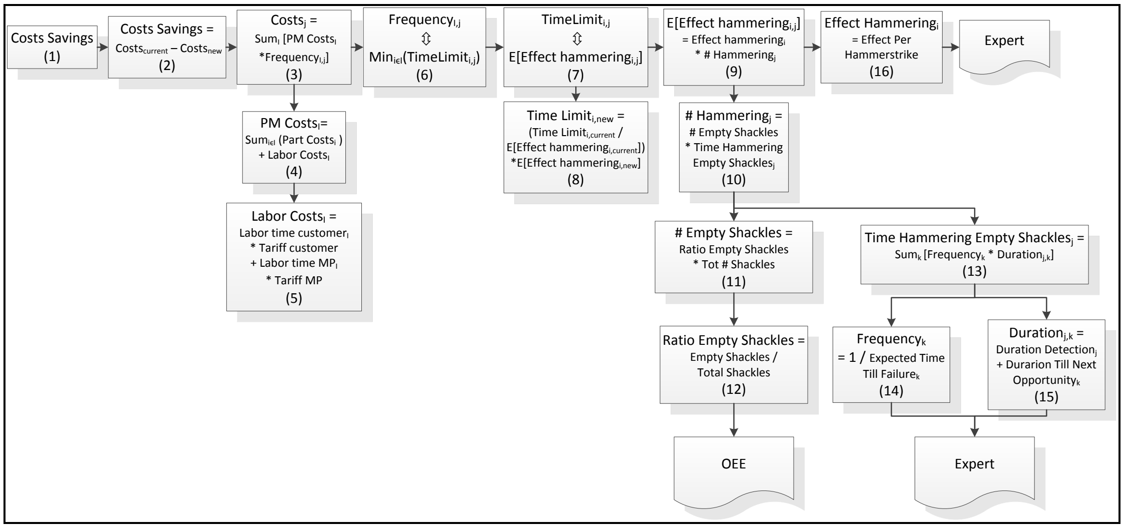

Figure 5.7: Steps to get to the costs savings

It should be noted that while the faster detection will reduce the time of hammering on empty shackles, only the actual hammer strikes on empty shackles are interesting. The lines are mostly full, but there are several reasons why there are also empty shackles. Shackles can be empty due to buffers without broilers between flocks, no broilers available because of no supply available (but the line still running), and loss of broilers because of rehanging error. The costs savings (1) are the current cost minus the new costs (2). The costs in either situation are the costs of the overhaul kit multiplied by the frequency of the overhaul kit summed for every overhaul kit (3). As mentioned before, only the preventive maintenance costs are considered. These costs consist of the part costs and the labor costs (4). The labor costs include the labor time of the customer's engineer multiplied by the tariff for the customer's engineer and the labor time of MP's engineer multiplied by the tariff of MP's engineer (5). The frequency of the costs of each overhaul kit is dependent on the minimal time limit of the parts within each overhaul kit (6). The time limits are a result of the lifetimes which are influenced by wear. This wear is affected by the hammering (7), and thus the change in hammering will influence the time limits. The current time limit, current effect of hammering and the new effect of hammering can be used to determine the new time limit (8). The effect of hammering is dependent on the effect per hammer strike multiplied by the amount of hammering (in hammer strikes) (9). The effect per hammer strike is a function based on the input of an expert (16). The amount of hammering (in hammer strikes) is dependent on the number of empty shackles and the time of hammering (10). The number of empty shackles is reliant on the ratio empty shackles and the total amount of shackles (11). The ratio is given by a measured average empty shackles divided by the total shackles (12), which comes from OEE (Overall Equipment Effectiveness). OEE is an industry standard method used by MP for measuring the utilization of a machine. The time of 'the hammering' is dependent on the frequency of the failure modes and the duration before it is solved (13). The frequency of the failure modes is dependent on the expected time till failure (14), and the duration is a summation of the duration to detect and the duration till next opportunity (15).

Formulas

This section translates the formerly mentioned steps into formulas.

Indices:

The parts are denoted with index i = 1,2,...,n;
The overhaul kits are denoted with index I = S, M, T. Where S represents Small overhaul kit, M represents Major overhaul kit, and T represents Total overhaul kit;
The situations are denoted with index j = current & new. Where current represents the current situation, and new represents the new situation with reduced 'hammering';
The failure modes are denoted with index k = Ratchet, Curve, where Ratchet represents the failure mode caused by the wear of the Ratchet, and Curve represents the failure mode caused by the height setting of the Curve.

We are interested in calculating the costs savings [€/year], which are the current costs [€/year] minus the new costs [€/year]. The costs [€/year] of situation j ($Costs_j$), calculated with Formula 5.3.1, is the summation of kits I of the preventive maintenance costs [€] of kit I ($PM\ Costs_I$) multiplied with the frequency [1/year] of kit i of situation j ($Frequency_{I,j}$).

$$Costs_j = \sum_I (PM\ Costs_I * Frequency_{I,j}) \qquad (5.3.1)$$

The preventive maintenance costs [€] of kit I ($PM\ Costs_I$) are calculated with Formula 5.3.2. The labor costs [€] of kit I ($Labor\ Costs_I$) is added to the summation per kit I of the part costs [€] of the parts in kit i ($\sum_{i \in I} Part\ Costs_i$).

$$PM\ Costs_I = Labor\ Costs_I + \sum_{i \in I} Part\ Costs_i \qquad (5.3.2)$$

The labor costs [€] of kit I ($Labor\ Costs_I$) are calculated with Formula 5.3.3. The labor time of the customer's engineer [hours] of kit I ($Labor\ time\ customer_I$) is multiplied by the tariff of the customer's engineer [€/hour] ($Tariff\ customer$), to get the labor costs for the customer engineers. The labor time in hours of MP's engineer [hours] kit I ($Labor\ time\ MP_I$) is multiplied by the tariff of MP's engineer [€/hour] ($Tariff\ MP$), to get MP's engineers' labor costs. These costs are added together.

$$Labor\ Costs_I = \\ Labor\ time\ customer_I * Tariff\ customer + Labor\ time\ MP_I * Tariff\ MP \qquad (5.3.3)$$

The frequency [1/year] of kit I in situation j ($Frequency_{I,j}$) is both dependent on the minimal time limit [years] of kit I in situation j ($Minimal\ Time\ Limit_{I,j}$) and the fact that kits have to be done in integer multiples of each other. The minimal time limit [years] if kit I in situation j is calculated with Formula 5.3.4. The frequencies will be determined manually.

$$Minimal\ Time\ Limit_{I,j} = \underset{i \in I}{Min}\ (Time\ Limit_{i,j}) \qquad (5.3.4)$$

The new time limit [years] for part i in situation j ($Time\ Limit_{i,new}$) is calculated with Formula 5.3.5. The observed current time limit [years] of part i ($Time\ Limit_{i,current}$) is divided by the current expected effect of hammering on part i ($E[Effect\ hammering_{i,current}]$) multiplied by the new expected effect of hammering on part i ($E[Effect\ hammering_{i,new}]$). The expected effect is between 0 and 1 (thus $E[Effect\ hammering_{i,ideal}] = 1$ as without hammering the time limit would be the largest).

$$Time\ Limit_{i,new} = \frac{Time\ Limit_{i,current}}{E[Effect\ hammering_{i,current}]} * E[Effect\ hammering_{i,new}] \qquad (5.3.5)$$

The expected effect hammering on part i in situation j ($E[Effect\ hammering_{i,j}]$) is calculated with Formula 5.3.6. The effect per hammer strike [$f(hammer\ strike)$] on part i ($Effect\ Hammering_i$) is multiplied by the amount of hammering [hammer strikes] in situation j ($\#\ Hammering_j$).

$$E[Effect\ hammering_{i,j}] = Effect\ Hammering_i * \#\ Hammering_j) \tag{5.3.6}$$

The effect per hammer strike [$f(hammer\ strike)$] on part i ($Effect\ Hammering_i$) will be a function based on the input of an expert. This function is discussed in Section 5.4. The amount of hammering [hammer strikes] in situation j ($\#\ Hammering_j$), calculated with Formula 5.3.7, is dependent on the number of empty shackles [shackles/year] ($\#\ Empty\ Shackles$) and the time of hammering [year] in situation j ($Time\ Hammering\ Empty\ Shackles_j$).

$$\#\ Hammering_j = \#\ Empty\ Shackles * Time\ Hammering\ Empty\ Shackles_j \tag{5.3.7}$$

The number of empty shackles [shackles/year] ($\#\ Empty\ Shackles$), calculated with Formula 5.3.8, is dependent on the ratio of empty shackles [empty shackles/total shackles] ($Ratio\ Empty\ Shackles$) and the total amount of shackles [shackles/year] ($Total\ \#Shackles$).

$$\#\ Empty\ Shackles = Ratio\ Empty\ Shackles * Total\ \#\ Shackles \tag{5.3.8}$$

The ratio of empty shackles [empty shackles/total shackles] ($Ratio\ Empty\ Shackles$) and the total amount of shackles [shackles/year] ($Total\ \#Shackles$) are based on input from the OEE system. The OEE system tracked the empty and total shackles for a time period which is expected to represent the average behavior.

The time of hammering [years] in situation j ($Time\ Hammering\ Empty\ Shackles_j$) is calculated with Formula 5.3.9. Per failure mode k the frequency [1/years] of failure mode k ($Frequency_k$) multiplied by the duration [years] of failure mode k in situation j ($Duration_{j,k}$) are summed. Note that the duration is the time 'the hammering' takes place, thus from start till it is solved, but in the meantime, the production can continue.

$$Time\ Hammering\ Empty\ Shackles_j = \sum_k \left(Frequency_k * Duration_{j,k}\right) \tag{5.3.9}$$

The frequency [1/years] of failure mode k ($Frequency_k$) is calculated with Formula 5.3.10. One is divided by the expected time till failure [years] of failure mode k ($Expected\ Time\ Till\ Failure_k$). The expected time till failure of the failure modes will be based on expert input.

$$Frequency_k = \frac{1}{Expected\ Time\ Till\ Failure_k} \tag{5.3.10}$$

The duration [years] of 'the hammering' due to failure mode k in situation j ($Duration_{j,k}$) is calculated with Formula 5.3.11. The duration till detection [years] in situation j ($Duration\ Detection_j$) is the time from the start of 'the hammering' until the detection. The duration till next opportunity [years] for failure mode k ($Duration\ Till\ Next\ Opportunity_k$) is the time form the detection until it is solved (at next opportunity). The duration till detection in situation j and the duration till next opportunity for failure mode k are summed. Both input values are based on expert input.

$$Duration_{j,k} = Duration\ Detection_j + Duration\ Till\ Next\ Opportunity_k \tag{5.3.11}$$

5.4 Input values

In this section, the input values needed for the formulas above are discussed.

Duration

$$Duration\ Till\ Next\ Opportunity_{Ratchet} = 0.25\ years \quad (5.4.1)$$

$$Duration\ Till\ Next\ Opportunity_{Curve} = 8.01 * 10^{-4}\ years\ (4\ hours) \quad (5.4.2)$$

The input values for the duration till next opportunity [year] for failure mode k follow from the expert input. The duration till next opportunity [years] for the Ratchet ($Duration\ Till\ Next\ Opportunity_{Ratchet}$) is expected to last a quarter year. Every half a year an opportunity arises, but the failure distribution is not known, and therefore an assumption has to be made about the average duration. It is assumed that on average the duration is half the time interval between opportunities as it is expected that the chance of happening is quite symmetric during the time interval. The duration till next opportunity [years] for the Curve ($Duration\ Till\ Next\ Opportunity_{Curve}$) is expected to be after 4 hours on average. During a break, the failure mode can be solved by resetting the height.

$$Duration\ Detection_{current} = 1.60 * 10^{-2}\ years\ (5\ days) \quad (5.4.3)$$

$$Duration\ Detection_{new} = 0 \quad (5.4.4)$$

The expert stated that the duration till detection [years] in the current situation ($Duration\ Detection_{current}$) is expected to take five days. The goal is to reduce the duration to detect to zero, which makes the duration till detection [years] in the new situation ($Duration\ Detection_{new}$) zero.

Frequency failure mode

$$Expected\ Time\ Till\ Failure_{Ratchet} = 3\ years \quad (5.4.5)$$

$$Expected\ Time\ Till\ Failure_{Curve} = 0.33\ years\ (4\ months) \quad (5.4.6)$$

The expected time till failure [years] of the Ratchet ($Expected\ Time\ Till\ Failure_{Ratchet}$) is expected to be three years. The expected time till failure [years] of the Curve ($Expected\ Time\ Till\ Failure_{Curve}$) is expected to be four months, which is 1/3th of a year. The durations and the expected time till failure of the failure modes input values are also shown in Table 5.2.

Shackles

The OEE system is used for the total amount of shackles [shackles/year] ($Total\ \#Shackles$). During a period of 0.20 years, the total amount of shackles was 13536820 of which 488019 empty.

$$Ratio\ Empty\ Shackles = \frac{Empty\ Shackles}{Total\ Shackles} = \frac{488019}{13536820} = 0.0359 \quad (5.4.7)$$

The ratio of empty shackles [empty shackles/total shackles] ($Ratio\ Empty\ Shackles$) is based on the OEE-system. The system registers the production time lost because of empty shackles between flocks as buffer, no broilers available because of no supply available (but the line still running), and loss of broilers because of rehanging error. The number of empty shackles divided by the total amount of shackles gives the ratio during this period. These values are also shown in Table 5.3.

Effect hammering

Which parts are affected is indicated by an expert, and can be found highlighted in Table 5.6. The effect on a part when it is affected is indicated by an expert. This effect is a function per hammer strike. This function had to be derived from the expert's input. The expert stated that time limit would be reduced by two months if the hammering would take on for five days. However, the relation is not linear as the effect flattens. A minimal time limit is reached regardless of the amount of hammering. The input from the experts is used to derive the effect function. The actual function derivation can be found in Appendix 4. Formula 5.4.8 is the effect function for Part L and Part M. Figure 5.8 is a plot of the function for Part L and Part M. Formula 5.4.9 is the effect function for Part N.

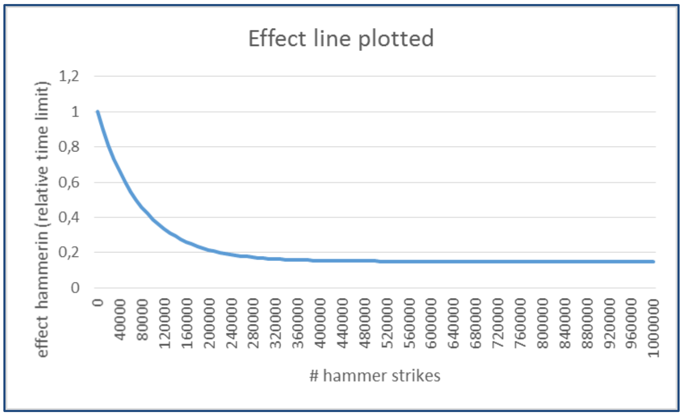

Figure 5.8: Effect line plotted

$$Effect\ Hammering_L = Effect\ Hammering_M = 0.85e^{-1.27*10^{-5}x} + 0.15 \qquad (5.4.8)$$

$$Effect\ Hammering_N = 0.194e^{-8.56*10^{-6}x} + 0.816 \qquad (5.4.9)$$

Where, x is the number of hammer strikes, the effect (y) is the relative time limit reduction between zero and one $(0 < Effect\ Hammering_i > 1\ and\ Effect\ Hammering_i = 1\ as\ x = 0)$.

Costs

$$PM\ Costs_I = Labor\ Costs_I + \sum_{i \in I} Part\ Costs_i \qquad (5.4.10)$$

The part costs are retrieved from SAP and are shown in Table 5.6. The costs of the labor are only known per kit and are shown in Table 5.5.

Overview input values

Table 5.2: Input values duration and MTTF for each failure mode

Duration				
	Current	New		
Failure mode	Duration Detection [years]	Duration Detection [years]	Duration Till Next Opportunity [years]	Expected Time Till Failure [years]
Ratchet	1.60*10⁻² (5 days)	0	0.25	3
Curve	1.60*10⁻² (5 days)	0	8.01*10⁻⁴ (4 hours)	0.33

Table 5.3: Input values for shackles

Empty Shackles	4.88*10⁵	[Shackles/Period]
Total Shackles	1.35*10⁷	[Shackles/Period]
Ratio Empty Shackles	0.0359	

Table 5.4: Input values AE-codes

Code	**Parts** [i]
C	L, 10, 12, 13, 19, M
D	5, 6, 18, 20, 21, 22, 24, 25
E	N, 2, 3, 4, 7, 9, 11, 14, 15, 16, 17

Table 5.5: Input values Kits

Overhaul kit	**Labor Costs** [€/I]	**Part Costs** [€/I]
Small	848	763.28
Major	1668	1375.4
Total	1668	9391.4

Table 5.6: Input values for each part (affected are highlighted)

Part	**Part costs** [€]	**Time Limit Current** [years]	**Code**	**Affected?**
N	**736**	**3**	**E**	**Yes**
Ratchet	3968	3	E	No
3	432	3	E	No
4	183	3	E	No
5	119	1.75	D	No
6	291	1.75	D	No
7	1936	3	E	No
L	**44.8**	**0.5**	**C**	**Yes**
9	416	3	E	No
10	480	0.75	C	No
11	183	3	E	No
12	158	0.75	C	No
13	40.8	0.75	C	No
14	150	3	E	No
15	8.32	3	E	No
16	2.88	3	E	No
17	0.8	3	E	No
18	26.6	1.75	D	No
19	1.28	0.75	C	No
20	8.64	1.75	D	No
21	4.8	1.75	D	No
22	141	1.75	D	No
M	**38.4**	**0.5**	**C**	**Yes**
24	18.2	1.75	D	No
25	2.88	1.75	D	No

5.5 Results

This section will show all the calculations. First the calculations regarding the hammering are shown, followed by the effect of hammering, the costs per kit, the new frequencies, and finally the costs savings. An Excel tool is created to do the calculations using the formulas mentioned above.

Hammering

$$Total\ \#\ Shackles = 1.35 * 10^7/0.2083 = 6.50 * 10^7\ Shackles/year \tag{5.5.1}$$

$$Frequency_{Ratchet} = \frac{1}{3} = 0.33\ /year \tag{5.5.2}$$

$$Frequency_{Curve} = \frac{1}{0.33} = 3\ /year \tag{5.5.3}$$

$$Duration_{current,Ratchet} = 1.60 * 10^{-2} + 0.25 = 2.66 * 10^{-1}\ years \tag{5.5.4}$$

$$Duration_{current,Curve} = 1.60 * 10^{-2} + 8.01 * 10^{-4} = 1.68 * 10^{-2}\ years \tag{5.5.5}$$

$$Duration_{new,Ratchet} = 2.50 * 10^{-1}\ year \tag{5.5.6}$$

$$Duration_{new,current} = 8.01 * 10^{-4}\ year \tag{5.5.7}$$

$$\#\ Empty\ Shackles = 3.59 * 10^{-2} * 6.50 * 10^7 = 2.34 * 10^6\ Shackles/year \tag{5.5.8}$$

$$Time\ Hammering\ Empty\ Shackles_{current} = (0.33 * 2.66 * 10^{-1}) + (3 * 1.68 * 10^{-2})$$
$$= 8.87 * 10^{-2} + 5.05 * 10^{-2} = 1.39 * 10^{-1}\ year \tag{5.5.9}$$

$$Time\ Hammering\ Empty\ Shackles_{new} = (0.33 * 2.50 * 10^{-1}) + (3 * 8.01 * 10^{-4})$$
$$= 8.33 * 10^{-2} + 2.40 * 10^{-3} = 8.57 * 10^{-2}\ year \tag{5.5.10}$$

$$\#\ Hammering_{current} = 2.34 * 10^6 * 1.39 * 10^{-1} = 3.25 * 10^5\ Shackles/year \tag{5.5.11}$$

$$\#\ Hammering_{new} = 2.34 * 10^6 * 8.57 * 10^{-2} = 2.00 * 10^5\ Shackles/year \tag{5.5.12}$$

Effect hammering

The parts that are affected and interesting are Part L and Part M. These are interesting as their Time Limit current limits the Time Limit of the kits. The Time limit current is 0.5 years. Thus the amount of hammering in that half year needs to be calculated, which is done with 5.5.13 and 5.5.14.

$$\#\,Hammering_{current} = 3.25 * 10^5 * 0.5 = 1.62 * 10^5\ Shackles \tag{5.5.13}$$

$$\#\,Hammering_{new} = 2.00 * 10^5 * 0.5 = 1.00 * 10^5\ Shackles \tag{5.5.14}$$

The expected effect of hammering in both situations uses the Formula 5.4.8 and the amount of hammering from Formula 5.5.13 and Formula 5.5.14 for the current and new situation, respectively.

$$E[Effect\ hammering_{L\ and\ M,current}] = 0.85e^{-1.27*10^{-5}*1.62*10^5} + 0.15 = 0.248 \tag{5.5.15}$$

$$E[Effect\ hammering_{L\ and\ M,new}] = 0.85e^{-1.27*10^{-5}*1.00*10^5} + 0.15 = 0.374 \tag{5.5.16}$$

The expected effect of hammering in both situations are used to calculate the new time limit [years] as is calculated in Formula 5.5.17.

$$Time\ Limit_{L\ and\ M,new} = \left(\frac{Time\ Limit_{L\ and\ M,current}}{E[Effect\ hammering_{L\ and\ M,current}]}\right) * E[Effect\ hammering_{L\ and\ M,new}]$$
$$= \left(\frac{0.5}{0.248}\right) * 0.374 = 0.755\ years = Time\ Limit_{L\ and\ M,new} \tag{5.5.17}$$

The new time limit as a result of the reduced hammering has now increased till over 0.75 years. Thus Part L and Part M are not limiting the frequencies of the S-kit anymore. The minimal time limit of the S-kit has now become 0.75 years.

Costs per kit

The preventive maintenance costs [€] per kit (C, D, and E) are the summation of the part costs and the labor costs of each kit, which are calculated with Formulas 5.5.18 through Formula 5.5.21.

$$PM\ Costs_I = Labor\ Costs_I + \textstyle\sum_{i\in I} Part\ Costs_i \tag{5.5.18}$$
$$PM\ Costs_S = 763.28 + 848 = €1611.28 \tag{5.5.19}$$
$$PM\ Costs_M = 1375.4 + 1668 = €3043.4 \tag{5.5.20}$$
$$PM\ Costs_T = 9391.4 + 1668 = €11059.4 \tag{5.5.21}$$

New Frequencies

The new time limits will change the frequencies of the kits. First, it is checked if the new minimal frequency of the C-parts can be used to determine the new frequencies of the D- and E-parts. The new frequencies are based on the new minimal C, D and E time limits, while taking into account that they have to be done as an integer multiple of each other. Table 5.7, first gives the minimal time limit and frequency per kit and then when the overhaul kits are clustered as an integer multiple of each other. The clustered frequencies are the new frequencies of the kits.

Table 5.7: New frequencies

Codes	Time Limit [year]	Frequency Parts [/year]	Kit	Frequency Kits [/year]
C	0.75	1.33	**S**	0.67
D	1.75	0.57	**M**	0.33
E	3	0.33	**T**	0.33

These new frequencies would result in the developed new PMS shown in Table 5.8. The Small kits (green S) are done twice every three years, the Major kits (red M) are done once every three years, and the Total kits (blue T) are also done once every three years.

Table 5.8: New PMS Unit-Pushover

					Year :	1				2				3			
	TRDE				Quarter :	1	2	3	4	1	2	3	4	1	2	3	4
Level	Pos	Item Type	Quant	Part Name	PMP :	1,1	1,2	1,3	1,4	2,1	2,2	2,3	2,4	3,1	3,2	3,3	3,4
.1	22	L	16	UNIT PUSHOVER-				S			M			S			T

Costs Savings

The new frequencies [/year] will lead to the new costs [€/year] calculated with Formula 5.5.22. The current frequencies led to the current costs calculated with Formula 5.5.23. The costs savings [€/year] follow from 5.5.24, and the relative costs savings from 5.5.25.

$$Costs_{new} = 1611.28 * \frac{2}{3} + 3043.4 * \frac{1}{3} + 11059.4 * \frac{1}{3} = 5775.12\ €/year \quad (5.5.22)$$

$$Costs_{current} = 1611.28 * \frac{4}{3} + 3043.4 * \frac{1}{3} + 11059.4 * \frac{1}{3} = 6849.31\ €/year \quad (5.5.23)$$

$$Costs\ Savings = 6849.31 - 5775.12 = 1074.19\ €/year \quad (5.5.24)$$

$$\%\ Savings = \frac{Costs\ Savings}{Costs_{current}} * 100\% = \frac{1074.19}{6849.31} * 100\% = 15.68\% \quad (5.5.25)$$

The costs savings are €1074.19/year for the Unit-Pushovers. The relative cost savings for the PM costs of the Unit-Pushovers are 15.68%. These costs savings still represent 6.57% yearly costs savings for the whole TRDE.

5.6 Sensitivity analysis

The sections above show that the improved lifetimes lead to yearly costs savings of 15.68%. However, this is the case for the particular assumed (best guessed) situation. Since the values could turn out to be different upon closer investigation, a small sensitivity analysis is done. The sensitivity analysis focuses on how changes in the input will change the outcome.

Varying input values

The input values are varied one-at-a-time to isolate the effect of that input value. The remaining input values remain the same unless explicitly explained otherwise.

Time limit for each part

Currently, it is assumed that the non-limiting (and non-affected) C-parts in the S-kit (part 10, 12, 13 and 19) can last 0.75 years. If this is not the case and these parts cannot last that long, the S-kits cannot be delayed leading to zero costs savings.

Currently, it is assumed that the D-parts in the M-kit (part 5, 6, 18, 20, 21, 22, 24 and 25) are (non-affected and) not limiting the frequency of the M-kit. However, the frequency of the M-kit is chosen based on an integer multiple of the S-kit. Changing the input values of the time limits of these parts would only change the new situation if they exceed two years, but that would also change the current situation, and thus unlikely this is the case.

Following the M-kit, the E-parts in the T-kit (part N, 2, 3, 4, 7, 9, 11, 14, 15, 16 and 17) are also chosen based on an integer multiple, but in this case of the M-kit. Since the frequency of the M-kit will not change, the T-kit will also not change.

Parts affected

Currently, it is assumed that the D-parts in the M-kit are not affected. If it turns out that these would be affected the effect has to be large enough for them to reach a time limit of two years to change anything. Although 2 is not a multiple of 0.75, it still could turn out to be cheaper to replace the C-parts every 0.5 years to replace the D-parts only every two years. In this case, the S-kits would remain their frequency of twice a year, and the M-kit will get a frequency of every two years, such that the kits are done in an integer multiple of each other. Moreover, the E-parts in the T-kit would also have to be able to last four years. The costs savings would then be 13.24%, as calculated with Formulas 5.6.1 through 5.6.3. This would mean that increasing the frequency of the S-kits to allow a reduction in the frequency of the M-kits is leads to fewer costs savings than reducing the frequency of the S-kits (and increasing the frequency of the M-kits).

$$Costs\ new = 1611.28 * \frac{6}{4} + 3043.4 * \frac{1}{4} + 11059.4 * \frac{1}{4} = 5942.62 \quad (5.6.1)$$

$$Costs\ savings = 6849.31 - 5942.62 = 906.69 \quad (5.6.2)$$

$$\%\ Savings = \frac{Costs\ Savings}{Costs\ Old} * 100\% = \frac{906.69}{6849.31} * 100\% = 13.24\% \quad (5.6.3)$$

Expected time till failure of the failure modes causing 'the hammering'

Currently, it is assumed that the Ratchet fails every three year and the Curve settings every four months. The impact of the frequency of the Ratchet failing is checked. It turns out that if the Ratchet fails more than every 2.9 years (increased frequency), the time limit of the limiting C-parts will drop below the 0.75 years. Meaning the S-kit cannot be delayed and no costs savings are reached. With a decreasing frequency of the Ratchet failing, the new time limits for the affected C-parts increases. However, even with the Ratchet never failing the time limits do not exceed 0.9 years. Moreover, a new time limit of at least one year is needed to improve the new situation further.

However, for the Curve settings, a reduction in the frequency does lead to too little advantage in the new situation with the improved detection. Since, again, the time limits of the limiting C-parts will drop below 0.75 years when the Curve settings have to be reset every 4.1 months. An increase in the frequency of the Curve settings will only lead to change if it increases to at least every 1.6 months. If that is the case, the new time limit of the limiting C-parts will become one year. This would, however, mean that the non-limiting C-parts would also have to last one year, the D-parts would have to last two years, and the E-parts would have to last four years. If all these parts last that long, the costs savings would then be 36.76%, as calculated with Formulas 5.6.4 through 5.6.6.

$$Costs\ new = 1611.28 * \frac{2}{4} + 3043.4 * \frac{1}{4} + 11059.4 * \frac{1}{4} = €4331.34 \quad (5.6.4)$$

$$Costs\ savings = 6849.31 - 4331.34 = 2517.97 \quad (5.6.5)$$

$$\%\ Savings = \frac{Costs\ Savings}{Costs\ Old} * 100\% = \frac{2517.97}{6849.31} * 100\% = 36.76\% \quad (5.6.6)$$

Current and new duration to detect

If the current detection is faster than four days and 14 hours than again the effect will not be enough and the time limits of the limiting C-parts will drop below 0.75 years, leading to no costs savings.

If the current detection is longer than ten days and 13 hours, the effect is enough for the limiting C-parts to reach the one year. Then again the D-parts have to last two years and the E-parts 4 years and the costs savings above (36.76%) can be reached.

If the new duration to detect is not zero but takes more than one hour, and seven minutes the improved situation would not be enough and the time limits of the limiting C-parts will drop below 0.75 years, leading to no costs savings.

Duration to solve

If the duration before solving the Ratchet on average goes below 77 days, again the effect will not be enough and the time limits of the limiting C-parts will drop below 0.75 years, leading to no costs savings. If the duration before solving the Ratchet on average goes above 136 days, the effect is enough for the limiting C-parts to reach the one year. Moreover, if the remaining parts have their increased time limits, the cost savings of above (36.76%) could be reached. If the duration before solving the Curve settings on average goes below 2 hours, again the effect will not be enough and the time limits of the limiting C-parts will drop below 0.75 years, leading to no costs savings. If the duration before solving the Curve settings on average goes above six days and 12 hours, the effect is enough for the limiting C-parts to reach the one year. Moreover, if the remaining parts have their increased time limits, the cost savings above (36.76%) could be reached.

Effect hammering

If the effect per hammer strike change, the effect might not be enough and the time limits of the limiting C-parts will drop below 0.75 years, leading to no costs savings. Whether the effect line becomes steeper or less steep, this change will in both cases lead to the effect not being enough and the time limits of the limiting C-parts will drop below 0.75 years, leading to no costs savings. If the remaining minimal lifetime increases too much the effect will not be enough and the time limits of the limiting C-parts will drop below 0.75 years, leading to no costs savings. If there is no remaining minimal lifetime, the effect will not be enough for the limiting C-parts to reach the one year, leading to no costs savings.

Conclusions

From the sensitivity analysis above, which varied the input values, can be concluded which input values are critical for the outcome. The Limit of the C-parts outside of Part L and Part M, the expected time till failure of the Ratchet, the expected time till failure of the Curve, the current detection time, the new detection time, the duration to solve the Ratchet, the duration to solve the Curve, and the effect, are all critical input values. Small changes in these critical input values eliminate the costs savings. Although the CBM policy can lead to relative costs savings, there is also quite some uncertainty whether this will hold in practice. There are however some extra improvement options that are explained shortly.

Other costs savings

The estimated costs savings focused on the preventive part and labor cost, however, currently also inspection costs are made. When visiting the customer, the Field Service Engineer (FSE) checks the Ratchet manually. While this is only a small aspect of the whole visit, the new detection strategy would make checking the Ratchet unnecessary. The new detection could immediately send a push message to MP. The Ratchet is now self-announcing, which reduces the visit time of the FSE. This can lead to additional costs savings but is not elaborated upon in this Thesis.

Modification

Upon discussion, a modification was identified. The only reason to replace the Ratchet is the Sharp Edge on the Ratchet. This is only a small part of the Ratchet, and the whole Ratchet is relatively expensive. The idea of the modification is instead of replacing the whole Ratchet, to have an exchangeable Sharp Edge in the Ratchet. This would make the Ratchet itself an un-coded, non-wearing part and only the Sharp Edge has to be replaced. In the new situation, the Ratchet itself is only needed once. This is only beneficial if the costs of the new Ratchet plus the PM costs multiplied by the replacement frequency of the Sharp Edge are less than the PM costs of the current Ratchet. The new PM costs are dependent on the lifetime of the Sharp Edge and the part and labor costs.

6. Conclusions and recommendations

This chapter concludes the thesis by answering the main research question.

"Can MP apply CBM policy to improve its current maintenance concept?"

Deliverable 1 – the selection method

Before MP can apply CBM, effort and investments are needed. It makes sense to only make an effort and investments for the parts most interesting for CBM. The first step at MP is selecting the parts most interesting for CBM. Currently, MP does not have a standardized way to identify parts interesting for CBM. Maintenance policies are assigned to parts via the AE-coding, but this does not yet include CBM policies. Selecting the part most interesting for CBM in a standardized way can be done by using the selection method developed (Chapter 3). This method starts with identifying the most interesting machines, followed by identifying the most interesting parts in these machines, and finally, the part most interesting for CBM is selected. In order to identify which parts are interesting, the yearly impact of failures expressed in costs is taken into account rather than the number of failures or downtime upon a single failure. Also, the yearly Preventive Maintenance (PM) costs, which could be reduced with a CBM policy, are taken into account. The selection method aims to do the selection in a data-driven manner and to need expert input only when really necessary. Although the selection method selects the most interesting parts as a starting point, it also identifies the next interesting parts, allowing a continuous improvement process. These features differentiate our selection method with the currently available selection methods. The selection method is expected to be generic as the steps likely apply to most OEMs (Original Equipment Manufacturers) providing maintenance, that want to apply CBM.

Deliverable 2 – the selected part

The developed selection method is applied to a customer of MP (Chapter 4). Applying the selection method to MP resulted in selecting the part Ratchet within the legend Unit-Pushover of the machine TRDE as the part most interesting for CBM. Applying the selection method resulted in identifying the data that are currently missing at MP, as well as the impact on the selection.

Deliverable 3 – the CBM policy for the selected part

A CBM policy for the Ratchet has been developed (Chapter 5), which improves detection. This policy showed yearly costs savings of €1074 for the Unit-Pushovers for one customer (16% of the PM costs of the Unit-Pushovers and 7% for the whole machine TRDE). These costs savings might apply to more customers. However, these costs savings are dependent on the input values. Sensitivity analysis showed that the input values are very critical; small changes in the critical input values eliminate the costs savings. Given the small costs savings and the level of detail needed for the input values to be sure these costs savings hold, it is recommended not to pursue the CBM policy developed for the Ratchet further. However, a modification of the Ratchet, for instance, the Sharp Edge identified at the end of Section 5.6, can turn out to be interesting dependent on its technical feasibility.

Main conclusion

When developing the three deliverables mentioned above, we identified gaps at MP to apply CBM policies to improve its current maintenance concept. We concluded that, at the moment, applying the selection method at MP is possible, but improvements are desirable as data is missing. The developed CBM policy was also constrained by missing data. Getting the data that is currently missing will improve the application of the selection method and smoothen the development of future CBM policies of parts selected. Therefore, the main steps recommended to MP regard getting the critical data (Chapter 6). The overall answer to the main research question is that MP should first put its effort in deriving the input values to allow proper implementation of the selection method. Such that a better selection can be made, for which CBM policies can then be developed, that might turn out to be promising.

Recommendations

First the main recommendation for the selection method that should allow correct application of the selection method is given. Executing the main recommendation should also smooth the transition from selecting the part and developing a CBM policy. Next, the main recommendation for developing a CBM policy is given. This is followed by several other recommendations that would further improve the application of the selection method.

Main recommendation selection method

The most critical limitation in the current application of the selection method is the inability to assign downtime to parts due to the data that lacks. We tried to solve this by combining the repair list and the downtime list. However, this proved difficult to do as the data is not registered on the same time interval making it difficult to assign parts to downtimes. It was also unclear which of the parts registered in the repair list are the actual cause of the failure (and downtime) or registered for another reason. Parts can be registered in the repair list when they are repaired as a consequence of other failing parts, replaced opportunistically as the machine is down and the legend is disassembled anyway, or replaced auxiliary (for example bolts). We recommend combining the data in a 'combined data list', see Table 6.7. This 'combined data list' also provides other data that lacks. For instance, the failure data includes a unique number for the parts that would allow identifying the actual lifetime (and failure times) of the parts that are multiple times in the same machine. This could be used for failure behavior analysis. While the process and condition data are not necessarily needed for the selection method itself, they should be added after a part is selected to allow analysis for the CBM policy. Also including the process and condition data in the 'combined data list' smooths the transition from selecting the part and developing the CBM policy. We will now elaborate for each data file on what data is exactly needed and how this should be registered. While the goal is to combine the data, it is likely more convenient to register each kind of data on its own. However, to allow combining the data into the 'combined data list' each data file should include the same generic data. This generic data should include where and when the entries took place. The required generic data is shown in Table 6.1.

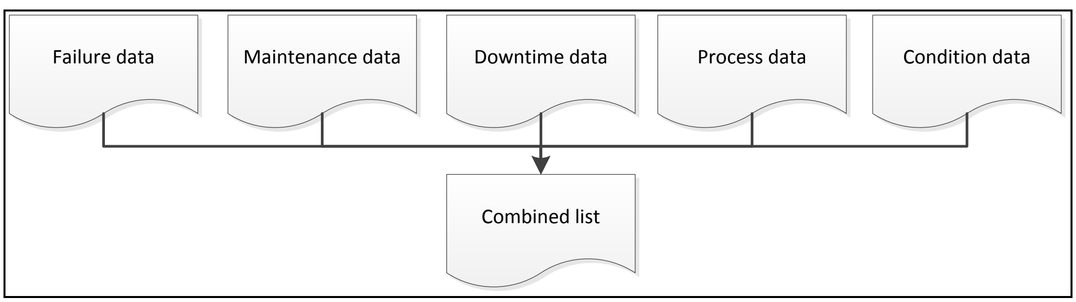

Figure 6.1: Combined data list

Table 6.1: Generic data

Generic data		
Where	Customer	[Customer]
	Location	[Location]
	Department	[Department]
	Line	[Line]
	Machine	[Machine]
	Legend	[Legend]
When	Year	[Year]
	Month	[Month]
	Week	[Week]
	Day	[Day]
	Time	[Seconds]

Table 6.2: Failure data specific

Failure data		
How long	Duration	[Seconds]
What	Parts	[Unique number]
	Failure mode of each part	[Failure mode]
	Parts causing failure	[Unique number]
	Parts causing downtime	[Unique number]
	Parts as consequential damage	[Unique number]
	Parts replaced opportunistic	[Unique number]
	Parts replaced auxiliary	[Unique number]

The specific failure data needed is shown in Table 6.2. The failure data should indicate which parts failed and their failure modes. It should also be indicated, which of these parts were the cause of failure and possible downtime, which parts failed as consequential damage, and which parts are replaced opportunistic or auxiliary. Besides the actual moment of failure, it would be useful to know how long the failure lasted. Each part that is registered should be registered with a unique number. Meaning that if there are multiple identical parts within a machine (or legend), it should be clear which specific part failed when.

The specific maintenance data is shown in Table 6.3. The maintenance data should indicate which parts are replaced. It is also useful what triggered the maintenance moment; either preventive of corrective. When the maintenance was preventive, none of the parts has failed, but some of the parts might fail as a result of the maintenance (auxiliary). When the maintenance was corrective, it should be indicated which parts failed, which parts are replaced opportunistic, and which part failed as a result of the maintenance (auxiliary). Again the parts should have a unique number so that it can be identified which specific part was maintained.

Table 6.3: Maintenance data specific

Maintenance data		
How long	Duration	[Seconds]
Why	Trigger	[Preventive/Corrective]
What	Parts	[Unique number]
	Parts corrective (failed)	[Unique number]
	Parts preventive (opportunistic)	[Unique number]
	Parts auxiliary	[Unique number]

The specific downtime data is shown in Table 6.4. The downtime data should 'only' indicate a few things as the generic data already contains plenty of the relevant data. Still interesting to register for the downtime specific are the duration of the downtime and the root cause(s) (which parts) of the downtime. Again the parts should have a unique number so that it can be identified the specific part.

Table 6.4: Downtime data specific

Downtime data		
How long	Duration	[Seconds]
Why	Parts causing downtime	[Unique number]

Combining the failure data, maintenance data, and downtime data would be enough for the selection method. However, when a part is selected, and CBM is of interest, the condition data and process data are also interesting to be added to this combined data. Again, this data should contain the same generic data to be able to combine and its own specific data. The specific process data is shown in Table 6.5. The process data should indicate for a specific location the number of products coming in and coming out, the line speed, the quality of the products, and the losses. This can be used to indicate how good the lines are operating. The specific condition data is shown in Table 6.6. The condition data should 'only' indicate the condition measurements as the generic data indicates the rest. The condition data is only identified after discussing the part resulting from the selection method.

Table 6.5: Process data specific

Process data		
What	In	[#]
	Out	[#]
	Speed	[sph]
	Quality	[#A & #B]
	Losses	[%]

Table 6.6: Condition data specific

Condition data		
What	Condition 1	[Condition 1]
	Condition ...	[Condition ...]
	Condition n	[Condition n]

When all data files are registered separately but all include the same generic data, the data can be combined easily into the 'combined data list', resulting in Table 6.7.

Main recommendation CBM policy

The developed CBM policy is not deemed beneficial enough to pursue further. This is partial because the application of the selection method at MP currently falls short by focusing primarily on the PM costs and not the downtime costs (which are most critical at MP). However, also, because basic input for the CBM policy is not known at MP. A CBM policy, as any maintenance policy, decides upon the optimal replacement moment. This is a trade-off, at any moment, between the costs of replacing at that moment and the costs of delaying replacement. For this, the costs of replacing and the cost of delaying the replacement need to be known. The costs of delaying are the increased risk of failure multiplied by the cost of failure. The probabilities of failure for a CBM policy are based on the condition measurement(s), thus it makes sense these are not yet known. However, the probability of failure based on time or usage could be known and used as input for the PMS (Preventive Maintenance Schedule). Besides these failure probabilities, the costs are also not known. This is partial because currently the downtimes cannot be assigned to parts. However, this could be solved with the ′combined data list′. Moreover, the other costs of failure (like emergency order costs) are also not known. Therefore it is recommended to MP to determine the failure distributions of the parts using the failure data provided by the ‘combined data list’ and to determine the costs of replacing preventively and replacing correctively.

Other recommendations

The remainder recommendations are given in order of importance.

1. Downtime costs machines

The downtime costs are critical for the selection method. However, at MP, the downtime costs are not precisely known. MP uses €300/minute as a ball-park figure as this is indicated by the customer with whom MP cooperates with the most. However, no differentiation is made between the machines, lines, and customers. Further investigation in the downtime costs per customer per machine is recommended.

2. Costs amongst multiple customers

The CBM policy developed for the Ratchet only leads to small costs savings, but these could be increased if applied to multiple customers. The costs of only one customer were considered. Ideally, the selection method would combine the costs of customers to identify the parts most interesting for MP as a whole. Therefore it is recommended to combine the costs data, for both the machines and the parts, for multiple customers. This would, of course, require registering the costs of more customers (which is currently not done).

3. Intermediate result of the selection method

The intermediate result of the selection method identifies costly machines that do not allow data handling, which are the Vakuumtrichter, JLR, and Tipping-Section. It would be interesting to look into the possibilities of projects resulting in the capacity to handle the data for those machines. All three machines would have been considered before the TRDE if they had the data handling capacity.

4. Further research in in-depth failure analysis

Detailed consideration of the in-depth failure analysis is out of scope for this thesis. However, the ‘combined data list’ provides the data needed for the analysis. Therefore, further research on in-depth failure analysis using the data obtained by the ‘combined data list’ is recommended, which should focus on the relevant characteristics of the failure modes. The failure modes should have an increasing failure rate as well as variation in time till failure such that a CBM policy can provide benefits over the current (time- or count-based) PM policy.

5. Costs data

The most critical costs at MP are the downtime costs. However, to make the best selection, all relevant costs should be taken into account. It is currently problematic to take all costs for all machines into account in a data-driven manner. It is recommended to get the labor time data for all machines, get the corrective maintenance (CM) costs data, and automate the calculations of the costs for all machines.

6. Long troubleshooting time

Another option for condition monitoring to reduce downtime would be not to focus on preventing the failure but decrease the troubleshooting time. The current selection method focusses on wear parts. Therefore the B-coded parts are not considered as they fail randomly. However, some subassemblies it is not clear which of the B-coded parts failed, and troubleshooting time is needed, while in the meantime there is downtime. Condition monitoring could be used to shorten the troubleshooting time and reduce the downtime. This would be interesting for parts with a lot of yearly downtime due to troubleshooting time. It is recommended to look into this option after the main costly wear parts have been considered.

7. Soft failures

The current selection method focusses on hard failures. This is done as hard failures lead to downtime, which is critical. After the main hard failures and a lot of the downtime are tackled, the next step would be to focus on the soft failures. These soft failures reduce the performance that leads to costs as well. Especially the Process data is handy for this. The reduced performance can be used to determine a cost rate. This costs rate could be compared to the costs of replacing to reset the performance to decide upon the replacement moment. Replacement should be done when the break-even point (between the increased revenue from the performance improvement and the replacement costs) is surpassed.

8. Validate AE-coding

Currently, AE-coding is used to indicate the higher level failure behavior. This is assumed to give an accurate representation of the failure behavior as it is based on mechanical knowledge and validated at the customer. However, this could still use validation from the data to be sure. We recommend validating the failure behavior of parts using the data obtained with the 'combined data list'. Extra interesting to validate are the B-coded parts. It is assumed that these fail random and do not wear, and thus have a constant failure rate. It could, however, turn out that the parts do wear but that the variation in time till failure is such that it is perceived random by MP. These parts would be interesting for CBM as this would allow predicting the failures, which is currently perceived impossible.

9. Modification data-driven or expert input?

For the modifications, expert input is assumed always to be needed, and therefore this is taken into account (late) in the selection method. This can lead to iterative steps, as shown in Chapter 4. It is deemed not possible to register the modifications such that a purely data-driven approach is possible. For this, it should be registered exactly what the impact (which problems are solved and for how much) of the modifications are, including all the dependencies of the production line. However, we recommend checking if this is really impossible, otherwise, the modifications should be taken into account in a data-driven manner when assigning costs to both the machines and the parts.

Table 6.7: Combined data list

Combined data list			
Generic	Where	Customer	[Customer]
		Location	[Location]
		Department	[Department]
		Line	[Line]
		Machine	[Machine]
		Legend	[Legend]
	When	Year	[Year]
		Month	[Month]
		Week	[Week]
		Day	[Day]
		Time	[Seconds]
Failure data	How long	Duration	[Seconds]
	What	Parts	[Unique number]
		Failure mode of each part	[Failure mode]
		Parts causing failure	[Unique number]
		Parts causing downtime	[Unique number]
		Parts as consequential damage	[Unique number]
		Parts replaced opportunistic	[Unique number]
		Parts replaced auxiliary	[Unique number]
Maintenance data	How long	Duration	[Seconds]
	Why	Trigger	[Preventive/Corrective]
	What	Parts	[Unique number]
		Parts corrective (failed)	[Unique number]
		Parts preventive (opportunistic)	[Unique number]
		Parts auxiliary	[Unique number]
Downtime data	How long	Duration	[Seconds]
	Why	Parts causing downtime	[Unique number]
Process data	What	In	[#]
		Out	[#]
		Speed	[sph]
		Quality	[#A & #B]
		Losses	[%]
Condition data	What	Condition 1	[Condition 1]
		Condition ...	[Condition ...]
		Condition n	[Condition n]

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Appendix 1 –Exploded view Unit-Pushover

The exploded view (Figure A1) of the Unit-Pushover shows the Ratchet, Part L, Part M, and Part N.

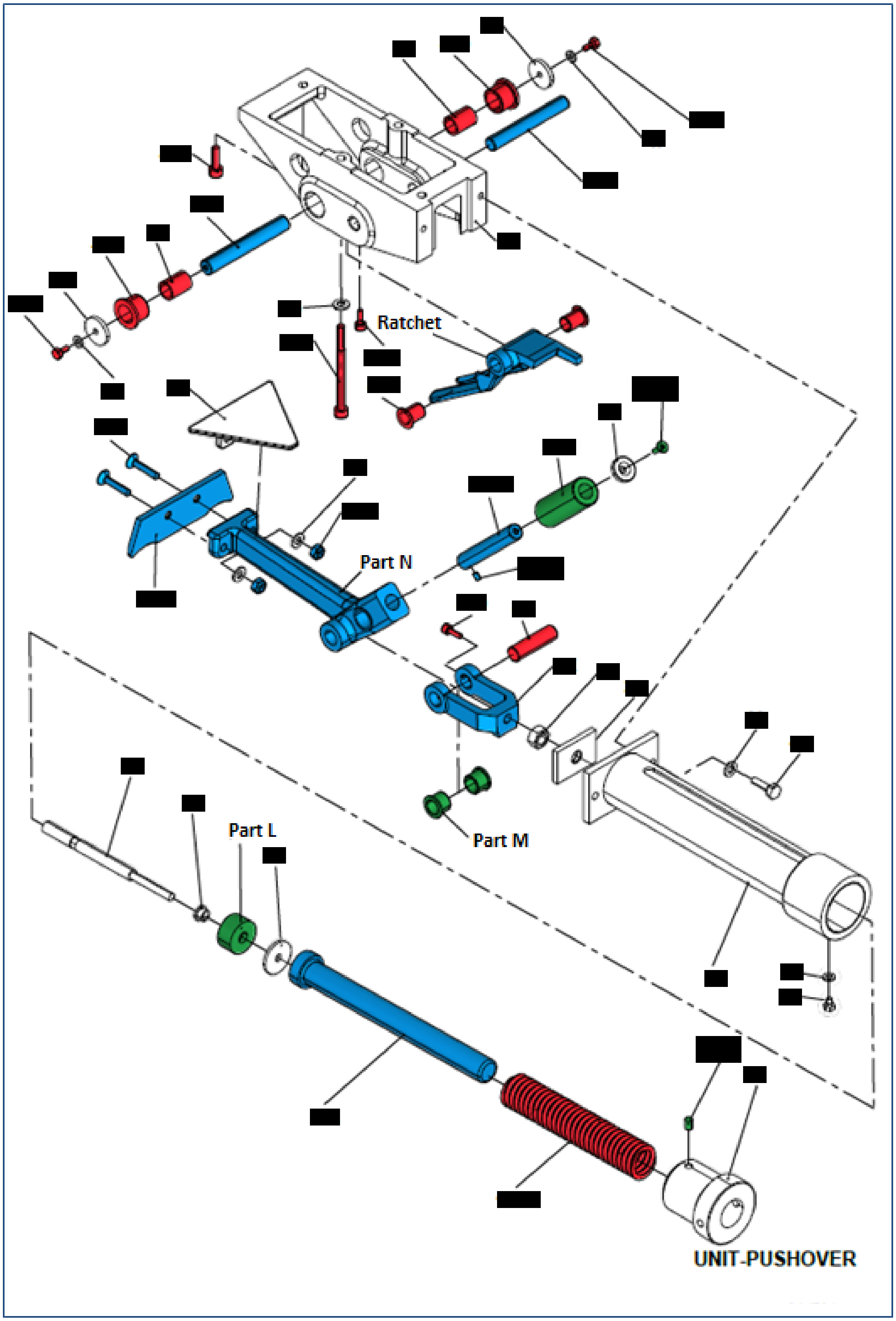

Figure A1: Exploded view Unit-Pushover

Appendix 2 – Detection time equal to the extra hammering time

This appendix shows how the detection time results in extra hammering time. The detection time in the current situation is five days according to expert input, see Section 5.4. There will be no detection time in the new situation according to expert input. This appendix will show that the reduction of the detection time of five days will also result in five days less hammer time on average.

New situation

As stated in Section 5.1 under Action upon failure, the duration of hammering is the time from the start of 'the hammering' due to a failure mode until the next opportunity to solve. For the failure mode Ratchet, the next opportunity to solve is at the next planned overhaul. Since there is an overhaul every half year, and a year has 312 operation days, half a year has 156 days. The time between overhaul kits is the time interval denoted with *T*. When the hammering starts at moment *x*, the duration will be till the next overhaul, and thus *T-x* (*156-x*). The probability of the hammering happening at time x since the last replacement is denoted with *f(x)*. The expected duration can be calculated with Formula A2.1.

$$Expected\ duration = \int_0^T (T - x) f(x) dx \qquad (A2.1)$$

When *T = 156* days and *f(x) = 1/T,* the expected duration is 78 days as calculated with Formula A2.2. This is also exactly half *T (156/2=78).*

$$\int_0^{156} \frac{156-x}{156} dx = \int_0^{156} 1 - \frac{x}{156} dx = \left[x - \frac{x^2}{2*156}\right] \begin{matrix}156\\0\end{matrix} = 156 - 78 = 78 \qquad (A2.2)$$

Current situation

The new situation is easier to calculate, as the duration will be the same during the whole *T*. The current situation with detection time (*Dt*) of 5 days is a bit harder. The duration to solve is equal to the remaining time till next overhaul (*T-x*) as in the new situation, expect for the 5 days just before the planned overhaul (*T-Dt*), since it is only detected after that overhaul. This will then take 156 days longer than the new situation (*T-x+T*). Duration to solve when detected too late is the remaining time till the overhaul plus another *T*, which is shown with Formula A2.3.

$$Duration\ to\ solve = T - x + T = 2 * 156 - x \qquad (A2.3)$$

The duration when the hammering starts between *x = 0* and *x = T-Dt* is equal to *T-x*. Moreover, the duration when the hammering starts between *x = T-Dt* till *x = T* is equal to *2T-x*. The expected duration of the current situation can be calculated with Formula A2.4.

$$Expected\ duration = \int_0^{T-Dt} (T - x) f(x) dx + \int_{T-Dt}^{T} (2 * T - x) f(x) dx \qquad (A2.4)$$

When the detection time is 5 days (*Dt = 5*), *T* is 156 days (*T=156*), and *f(x) = 1/T*, the expected duration of the current situation is 83 days, as calculated with A2.5.

$$\begin{aligned}
&= \int_0^{156-5} \frac{(156-x)}{156} dx + \int_{156-5}^{156} \frac{2*156-x}{156} dx = \\
&= \int_0^{151} 1 - \frac{x}{156} dx + \int_{151}^{156} 2 - \frac{x}{156} dx = \\
&= \left[x - \frac{x^2}{2*156}\right] \begin{matrix}151\\0\end{matrix} + \left[2x - \frac{x^2}{2*156}\right] \begin{matrix}156\\151\end{matrix} = \\
&= 151 - \frac{22801}{312} + \left(312 - \frac{24336}{312}\right) - \left(302 - \frac{22801}{312}\right) = \\
&= 151 - 73.08 + (312 - 78) - (302 - 73.08) = 83 \qquad (A2.5)
\end{aligned}$$

Difference

The old situation took 83 days and new situation 78 days, the difference is 5 days which is equal to the extra detection time (*Dt*). For the failure distribution, *f(x)*, a constant failure rate is assumed during the time interval. As previously mentioned, the failure distribution is not known. If the failure distribution is such that the failure modes happen more often just before *T*, the detection will happen just after the overhaul more often. This will lead to more extra hammering time. However, if the failure distribution is such that the failure modes happen more often just after *T*, the detection will happen on time more often. This will lead to less extra hammering time.

Appendix 3 – Enlarged Figure 5.7 of the calculations steps in Section 5.3

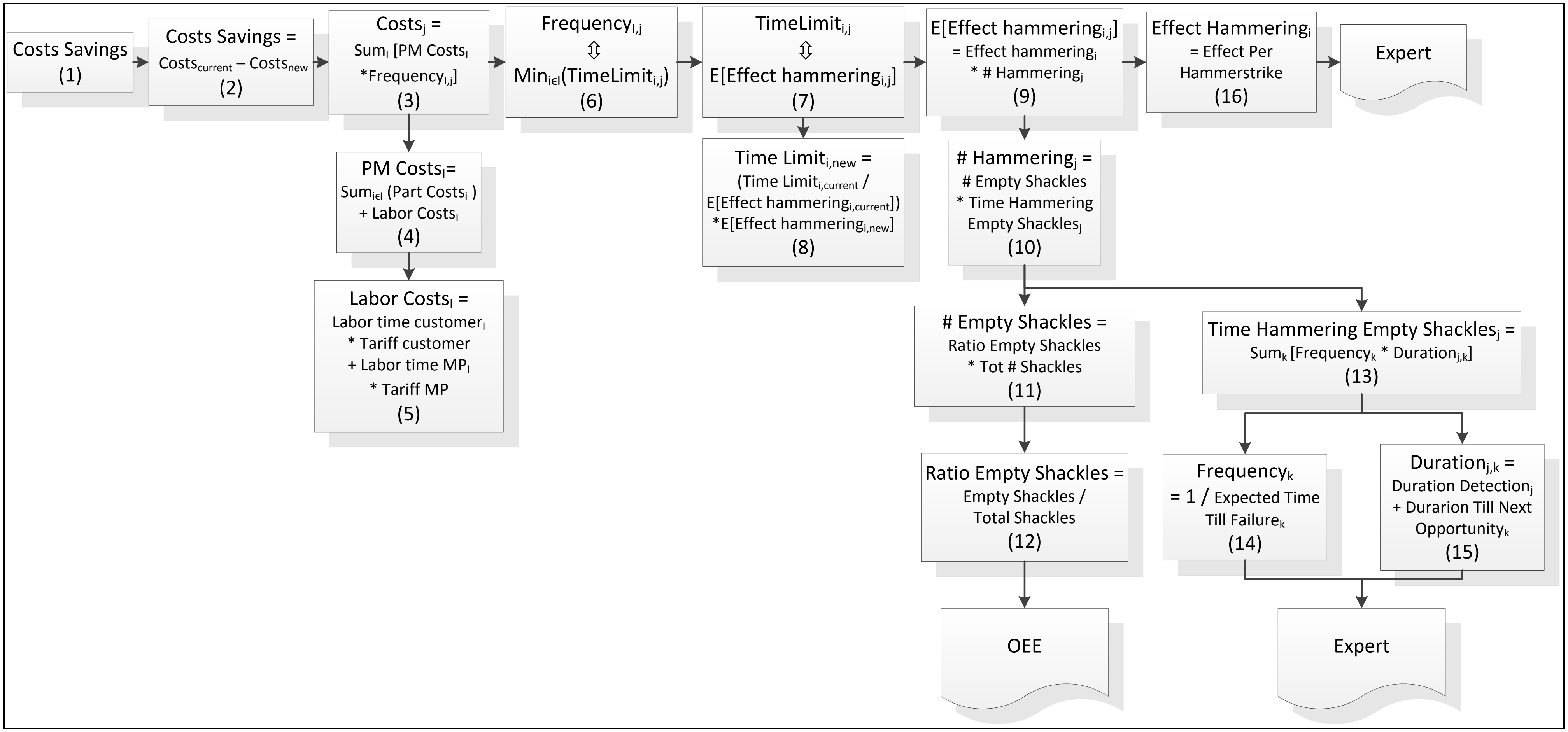

Figure A3: Enlarged Figure 5.7: Steps to get to the costs savings

Appendix 4 – Function of effect hammering

This appendix shows how the input from the experts is translated into a function for the effect of hammering. We aim to derive the effect per hammer strike on the relative Time Limit. Without hammering the relative Time Limit is one and every hammer strike will lower this relative Time Limit. The effect per hammer strike is expected to be an exponential function as the effect per hammer strike is also expected to diminish. The given expert input: Five days hammering equals a reduction of the Time Limit of two months, from six months to four months. However, there is a minimal Time Limit regardless the hammering. Five days of hammering is equal to 40252 hammer strikes (follows from the total shackles and the ratio of empty shackles, see Section 1.4). The relative Time Limit is 0.67 (=4/6) after the 40252 hammer strikes. The Minimal Time Limit is stated to be 0.15 by the experts. The relation between the effect on the time limit (y) and hammer strikes (x) is expected to be an exponential function of the form as shown in Formula A4.1.

$$Effect(Hammer\ strikes) = ae^{b*Hammer\ strikes} + Minimal\ remaining\ Time\ Limit \qquad (A4.1)$$

The expert input can be used to derive known points of the function. Table A4 shows the known points that are used to derive the values for a and b to get the effect function.

First, a is determined with the point of a relative Time Limit of one due to zero hammer strikes, which is point $(0{,}1)$. This results in $a = 0.85$, as shown in Formula A4.2.

$$Point\ (0{,}1) => 1 = ae^{b*0} + 0.15 => a = 1 - 0.15 = 0.85 \qquad (A4.2)$$

Second, b is determined with the point of a relative Time Limit of 0.67 due to 40252 hammer strikes (five days of hammering), which is point $(40252; 0.67)$. This results in $b = -1.27 * 10^{-5}$, as shown in Formula A4.3.

$$(40252; 0.67) =>$$
$$0.67 = 0.85e^{b*40252} + 0.15 => b = -1.27 * 10^{-5} \left(b = \frac{ln\left(\frac{0.67-0.15}{0.85}\right)}{Hammer\ strikes}\right) \qquad (A4.3)$$

With the values of a and b known, the effect function is Formula A4.4. This function is plotted in Figure A4.

$$Effect(Hammer\ strikes) = 0.85e^{-1.27*10^{-5}*Hammer\ strikes} + 0.15 \qquad (A4.4)$$

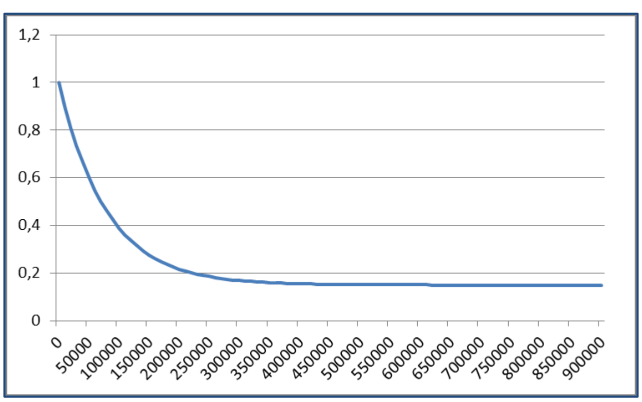

Figure A4: Effect line of hammering

Table A4: Points known

X	Y
0	1
40252	0.67
∞	0.15