MASTER

Improving spare part inventory levels recommended by Marel Poultry to its customers

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Improving spare part inventory
levels recommended by Marel
Poultry to its customers

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“Make a customer, not a sale.”

Katherine Barchetti
Abstract

Original equipment manufacturers are trying to improve their maintenance function in general, and their spare parts supply in particular. This research focuses on improving the concepts used to determine spare parts levels at Marel Poultry. We test the potential of using a system approach. A system target is set in the system approach, where one sets a target per item in the item approach. We further extend a simple multi-item (using a system approach) single location model with batching and item criticality. The multi-item models have been tested in four case studies. We find that the investment costs for spare parts can be halved while achieving the same system service levels.

Furthermore, we develop a model in which we include the line replaceable unit (LRU) definition problem. The LRU definition problem is the problem of deciding on which item to replace upon each type of failure. We show that Marel Poultry should recommend spare parts on different indenture levels in the product structure, so that failed parts can be replaced by replacing an assembly containing that part. This results in lower operational downtimes for the customer.
Management summary

This report contains the study about spare part supply, conducted at Marel Poultry (MP). The main activity of MP is the design and production of poultry processing lines. Furthermore, MP tries to create additional value to its traditional products by offering valuable services to customers. An important part of the after sales service is the strategy regarding spare parts supply. Whenever MP sells new production lines, it recommends its customers to buy a certain spare part package along with the processing line to anticipate on unpredictable failures that are critical. This package is called the critical parts package. Parts that are coded with a B (B-parts) are included in that package. MP argues the B-parts to be the parts that have a constant failure rate over time and that are critical for the customers. The amount in which they are in the package is set manually by product experts.

Problem statement
MP encounters some difficulties that come along with the current way of generating critical parts packages. Nowadays, the critical parts packages are generated decentrally. Every service location generates critical parts packages individually. The goal for the future is to generate the packages centrally in a consistent way. However, the service employees will become responsible for a much broader product portfolio as compared to the current portfolio. Since the procedure of generating the packages is done manually, service engineers need to have knowledge of the total product portfolio. Service engineers of MP do not always have the knowledge of all equipment in all industries, making it very hard to offer the right spare part package. Generating the package will become more and more time consuming. Secondly, MP does not know what service level it offers on average when selling such a package. Thirdly, when customers decide not to buy the complete extensive spare part package because of the high costs, it is their own responsibility to select the parts they do not want to have on stock. MP is not able to state the exact consequences of the deviation from the recommended package, let alone giving customers the trade-off between service level and costs.

Research goal
MP would like to have a more objective way of recommending spare part packages, based on part characteristics that give customers the opportunity to make the trade-off between service levels and purchasing costs that can be used by all industries within Marel. The process of deciding on the stock levels needs to be transparent, explainable and reproducible. The main research question that summarizes the main purpose of this research is:

How should MP determine spare part inventory levels recommended to its customers?

Methodology
A multi-item single location spare part model (see e.g. Van Houtum & Kranenburg (2015)) has been applied to several cases within Marel. We assumed Poisson distributed demand, unfulfilled demands to be backordered and the stock level to be continuously reviewed. Furthermore, the model is set up with different service level measures, namely aggregate fill rate, expected number
of backorders and the supply availability. The basic models have also been extended with batching and criticality to better fit the needs for MP.

**Multi-item model**

We test the different alternative models that are proposed by applying them to four case studies within Marel Meat, Marel Further Processing and Marel Cross Industry. We try to identify similarities between the different case studies. The case study from MP is shown in the following Table.

<table>
<thead>
<tr>
<th></th>
<th>As-Is Situation</th>
<th>System Approach with a Supply Availability constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Costs</strong></td>
<td>€ 19,887.34</td>
<td>€ 9,571.98</td>
</tr>
<tr>
<td><strong>Aggregate Fillrate</strong></td>
<td>97.98%</td>
<td>98.24%</td>
</tr>
<tr>
<td><strong>Expected number of backorder</strong></td>
<td>0.0235</td>
<td>0.0209</td>
</tr>
<tr>
<td><strong>Supply availability</strong></td>
<td>97.67%</td>
<td>97.93%</td>
</tr>
</tbody>
</table>

*Table: Potential improvement Marel Poultry*

The models based on the system perspective give better packages than the current logic. To show the difference, the total critical parts costs using the current decision-making logic and using the multi-item models have been investigated. To compare the logics, the service levels that are being achieved with the current practice were set as a constraint, such that the performance of the new models were at least as good as using the current decision-making logic.

In the MP case, the investment in a critical parts package would amount to €19,887.34 using the current practice, whereas using the new models the investment costs would be €9,571.98 while achieving the same supply availability of 97.67%. This means a theoretical saving of €10,315.36 (52%) can be achieved. In the other case studies, it has been shown that similar improvements can be achieved.

**Line replaceable unit problem**

In addition to the B-parts, some customers are also interested in stocking higher indenture level parts for faster or easier replacements. Although we exclude these parts in the spare part modelling of this research, it would be interesting to investigate whether it would be beneficial to include higher indenture levels as well in the critical parts package. We consider introducing an extra category next to the B category, which consists of all parts that may be kept on stock because of the faster or easier replacement. These parts could be denoted as R-parts.

We develop a model in which we include the line replaceable unit (LRU) definition problem. The LRU definition problem is the problem of deciding on which item to replace upon each type of failure. We show that Marel Poultry should also recommend spare parts on higher indenture levels.
**Main conclusion**
The main conclusion for MP is to implement the spare part model that we propose in this report. The system approach turned out to be much better than the current way of working. During the design and implementation phase we also conclude that the model optimizing with supply availability, fits the situation at MP best. The batching extension does make the model way more complex, and since there are only a few (very cheap) parts that are deliver in batch sizes the model with the one-for-one replenishment assumption is satisfactory. Furthermore, the model should consider part criticality in some way. We test some ways to determine part criticality and attach weighs to the criticality level. It is however very hard to categorize the parts and set the right weights. We do not find a satisfactory solution to include item criticality yet.

**Further steps**
In line with the main conclusion, the main recommendation for MP is to implement that model. However, we also find that there are some steps to take. We formulate the following three recommendations for further research or steps.

**Failure rate data**
An important recommendation is to gather data about failure rate of B-parts. MP has to estimate the failure rates of all B-parts initially. In the long run, it should determine failure rates with customer data. A maintenance management system that maintains a database of information about an organization’s maintenance operations can help. It can make it easier for MP’s customers to store data, and for MP to convert this data into useful information.

**Part criticality level**
MP should develop one consistent way of determining criticality levels per part. We already identify three important factors that should definitely be taken into consideration. First, whether the B-parts result in a breakdown of the line or affects the safety for the workers, or not. Secondly, one should think about supply availability. If one cannot fulfill a demand at the customer location, sometimes it can easily be bought locally. Thirdly, MP should distinguish between parts that can be fixed for a short moment to overcome the replenishment lead time by the customer itself, and parts that cannot.

We also recommend to test a different procedure, with which it is not needed to attach weights to criticality levels. Instead of considering all B-part simultaneously, MP should first consider high critical parts, and only include those in the model. Set a target service level for those and optimize. Next, include all the parts in the model and optimize to a target service level again.

**Line replaceable unit optimization**
We show that it would make sense to include higher indenture level parts in the packages as well. This research however does not propose a methodology to determine stock levels for parts on different indenture levels in the product structure. Separately optimization of different indentures does not lead to optimal solutions. Researchers can proceed in the direction of combining the LRU definitions problem and spare part stocking. This joint maintenance and logistics decision would be useful for MP.
Preface

This report is the result of my master thesis project, which I conducted at Marel in Boxmeer. The project is the final stage of my Master in Operations Management and Logistics at the University of Technology in Eindhoven. I would like to thank a number of people for their role during my study.

First of all, I would like to thank Rob Basten. Your support, suggestions and constructive feedback guided my through the project. Furthermore, you learned my how to structure the research and the reports. I also really appreciated the quite responds that you always gave when I had a question. Secondly, I would like to thank Engin Topan for being my second supervisor during the project, and for his valuable feedback: Teşekkür ederim.

I would also like to express my gratitude to everyone from Marel that was involved in the project. You gave me a great atmosphere to perform my thesis project in. Especially the guys from the SG-CTS department deserve a special word of thanks. It has been great working with you.

Many thanks go to my supervisor from Marel in particular, Robert Lemmens. Your great interest in the project has been a true inspiration for me along the way. You were always there whenever I needed help, but gave me the full responsibility to structure my project at the same time. Your critical questions pushed me to rethink every aspect of this project. I think we performed a great project and I am glad we eventually managed to convince a lot of people that our idea is the way to go. I am furthermore very happy that we can further implement the project in the Marel organization in the future.

Moreover, I would also like to thank all my friends from Eindhoven and Rijkevoort, and two in particular. Tom Derks, for the great times that we had in Istanbul, and also for always being there for me whenever I needed a drive to the university because I was not able to travel by public transport myself. I think I would not manage to graduate this soon without your helps. Additionally, I would give a special word of thanks to Jaap Arts, for reading my reports and giving me some valuable inputs.

I also want to thank my family and my parents in particular for the support that they gave me during my entire study and life. Mum, I am glad that “Hotel Mama” is always open. And dad, keep being the best entrepreneur I have ever seen. Your passion for what you do always inspires me.

Finally, I want to thank Loïs. You always support me during difficult times, but you are also the first one to buy me a huge bottle of champagne to celebrate good ones. Thank you for just being you!

With the delivery of this master thesis, my life as being a student comes to an end. It has been an amazing journey in which I learned a lot about myself, about business, about the academic world and about life in general. It concludes a great period and marks the beginning of a new one. I am curious what the future will bring. Enjoy reading!

Roel Bongers
October 12, 2016
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Chapter 1

Introduction

This report contains our study about spare part supply, conducted at Marel Poultry (MP). The main activity of MP is the design and production of poultry processing lines. In addition, it is nowadays working on Servitization. Vandermerwe and Rada (1988) were the first to use the term and they described it as the process of creating value by adding services to products. MP tries to create additional value to its traditional products by offering valuable services to customers. According to Oliva & Kallenberg (2003), this transformation from product manufacturer into service provider occurs gradually along a continuum, the product-service continuum. This continuum consists of two extremes: product manufacturing firms who regard services merely as an add-on to the product, and pure service providers who regard products merely as an add-on to the service.

An important way of moving from product manufacturer into service provider for MP is to develop after-sales services. Since the poultry processing lines that MP is selling are used in the main processes of the customer, it is a crucial task to keep the systems up in the field. Due to the technical complexity of the machines, customers are nowadays increasingly asking for after-sales service from the original equipment manufacturers (OEM) (Marel Stork Service Engineers, 2016). Therefore, MP provides services for the maintenance of these industrial systems. An important part of being able to deliver the after-sales service is the strategy regarding spare parts supply. Large amounts of money are typically invested in spare parts inventory.

The topic of maintenance and spare parts inventory management receives quite some attention of researchers and practitioners nowadays. Companies are trying to improve their maintenance function as a whole, and spare part supply is an important part of that (Kranenburg, 2006). This thesis project focuses on improving the concepts used to determine spare part levels. MP would like to have a more objective way of recommending packages that gives customers the opportunity to make the trade-off between service levels and purchasing costs. The project extends the existing models in literature, and applies them to the situation at MP. In that manner, MP can move more in the direction of being a service provider in the continuum of Oliva and Kallenberg (2003).
The remainder of this chapter is organized as follows: Section 1.1 gives a company description, and Section 1.2 elaborates on the specific department where the project is executed. Section 1.3 describes the problem context. Section 1.4 elaborates on the spare part packages MP sells, which is provided to the customer whenever they buy a new processing line. Section 1.5 gives the thesis outline.

1.1 Company description

Marel is the leading global provider of advanced processing systems and services to the Poultry, Meat and Fish industries. Marel employs approximately 4,600 employees worldwide. Their business units are located in the Netherlands, Denmark, the United States, Iceland, Slovakia, United Kingdom, France, Norway, and Singapore. Furthermore, it has offices and subsidiaries in 30 countries across six continents, and a network of more than 100 agents and distributors (Figure 2).

The company was established in Reykjavik, in 1983 and still has its headquarters there. It is listed on Nasdaq. Since the company’s establishment, a number of brands have come together to make Marel the company it is today. In 2008, Marel acquired Stork Food Systems owned by Stork.

Marel is divided into three different key industries: Marel Poultry, Marel Meat and Marel Fish. Each industry has unique technical expertise and decades of experience, allowing Marel to offer a comprehensive portfolio of equipment and solutions (Marel, 2016).

Marel’s products are designed to meet their customers’ every need: from harvesting raw materials to packaging the final product, and from standardized stand-alone units to all-inclusive integrated turnkey systems. Marel’s mission is to be the customers’ choice in supplying integrated systems, products and services to the poultry, fish, meat and further processing industries. Appendix A shows a poultry processing line which includes all the possible phases.

1.2 Marel Poultry

This research project is mainly executed within Marel Poultry (MP). That industry was owned by Stork Poultry before the merger. MP is currently the backbone of total Marel’s revenue base since it accounts for 53.2% of Marel’s revenue in the first quarter of 2016 (see Figure 1). Maximizing yield and uptime are key for MP. To back this up, specialized engineers operate from sales and service centers located across the globe. Additionally, several service contracts including different maintenance programs are offered to customers.
1.3 Research context

This section elaborates on the most important business research context, which is necessary knowledge to understand the remainder of this report. Section 1.3.1 presents the product structure of the equipment MP is selling. Section 1.3.2 then elaborates on the line replaceable unit definition. Section 1.3.3 presents the service part classification used within MP and Section 1.3.4 the spare part supply network.

1.3.1 Product structure

MP decomposes a customer’s plant hierarchically; an example of a resulting hierarchical structure is shown in Figure 3. A poultry plant is first decomposed into different production lines. A production line is composed of different machines that perform a functional activity (killing, plucking, cooling etc.) on all kind of poultries. Customers sometimes buy complete processing lines, whereas other customers only buy one machine.

A machine itself consists of individual articles and several assemblies that are denoted as legends within MP. The legends may consist of several smaller legends and further individual articles. Each machine consists, in that manner, of several legends and articles at different levels. So, everything between the highest level (machine) and the lowest level (article) is denoted as a legend in the product structure.

![Product structure diagram](Marel Stork Service Engineers, 2016)

When a machine develops a malfunction, the reason needs to be identified. Structural dependence (see, e.g. Nicolai & Dekker, 2008) applies for the production lines. The malfunction might be due to a legend within a certain legend. Subsequently, the reason for the legend to be malfunctioning needs to be identified. Again, that might be due to a legend or article. Demand on a high indenture level eventually causes lower indenture level demand for one or more legends or articles of that machine and so forth. We deal with a so-called multi-indenture product structure.

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1 The poultry that is being processed is denoted as product in the remainder of this report.
In order to get the machine up and running again, either the malfunctioning part or a legend containing that part needs to be replaced by a functioning one. To this end, each legend or article might be kept on stock as service part.

1.3.2 Line replaceable units
The item that is replaced is called the Line Replaceable Unit (LRU). The so-called LRU definition problem is in literature (Parada Puig & Basten, 2015) described as the problem of deciding on which item to replace upon each type of failure: when a replacement action is required in the field, service engineers can either replace the failed item itself or replace a parent assembly that holds the failure item. I.e. service engineers need to decide on whether a high or lower level legend or article should be replaced. The one option may be fast but expensive, while the other may take longer but against lower costs. MP currently does not have a consistent method of recommending its customers which items to replace upon failure.

1.3.3 Service parts classification
We first focus on the characteristics of the spare parts that are typical for the production lines MP is selling. Preventive maintenance programs are used to maintain the production lines. Still, some corrective maintenance is also required. This results in both planned as well as unplanned demands for spare parts. For planned maintenance activities, spare parts can be supplied at the moment that they are needed. It is not needed to keep safety stock for those demands. However, for unplanned demands resulting from corrective maintenance activities, one should hold inventory. Unplanned, random demands are often modelled as a Poisson process (Basten & Van Houtum, 2014).

MP uses service parts coding. The term part refers to both an article and a legend within MP. A code can be attached to each one of the parts in the product structure. Each coding corresponds to a certain prescribed operational and preventive maintenance strategy in order to keep the machine in a good mechanical condition so it is able to perform its intended function. The following coding description is based on the coding guideline document used within MP (2015). We assume that the definition of the parts is valid. We do not validate the demand characteristics, because it is outside the scope of this project.

**A-coded parts** are consumables. These are parts that often make direct contact with the product that is being processed and have an immediate effect on the technological performance of the machine. A-parts must be replaced frequently on judgment of and by the operator and therefore need to be easily accessible and changeable.

**B-coded parts** are parts or assemblies of parts that, when they become defective, make the production difficult (performance reduction) or impossible to continue (down time). B-coded parts fail suddenly. The failure of a B-coded part is unpredictable in time.

**C, D and E coded parts** are parts that are subject to gradual and predictable wear and tear and are replaced on a preventive base to safeguard the correct operation of the machine. The difference between the C, D and E coded parts is that C degrades faster over time than D, and D faster than E.
Next to the five main service codes, A through E, there are another three service codes used. These three combination codes always start with a B code followed by a C, D or E, and they are also critical. They wear out over time, just like the C, D and E parts. However, where C, D and E parts have a negligible probability of failure before they are preventively replaced, BC, BD and BE parts do have a reasonable probability of failure before they are preventively replaced. Although the coding is compounded, it needs to be emphasized that the BC, BD and BE parts have only one failure mode. The failure rate distributions of the different coded parts are graphically shown in Figure 4.

![Figure 4: Failure rate distributions (Adapted from (Marel, 2015))](image)

The demands for the A, C, D and E coded service parts are planned, because it is assumed that these parts do not fail before they are preventively replaced. One does not keep inventory to deal with uncertainties. At the moment that a customer performs a maintenance activity, the spare parts are supplied by MP. In order to be able to quickly respond to unplanned demands of the B, BC, BD and BE parts, customers keep inventory themselves. Whenever a B-parts breaks down, they are able to replace the part so that they do not face high and expensive down times.

In order to get a better understanding of the current practice of spare parts, and the B category in particular, we analyze the current classification. Ideally, one would validate the assumption regarding constant failure rates over time with a goodness-of-fit test with demand data for spare parts. However, as we discuss in more detail later in Section 6.1.2, we are not able to get the right data to perform these analyses. Therefore, semi-structured interviews are performed with several service managers and service coordinators within MP to discuss the current spare part coding structure, and the B code in particular.

It turns out that the current coding is not as it is stated in the coding structure guideline (Marel, 2015) in practice. Only B-coded parts are recommended to keep on stock to customers, i.e. according to the definition of B-parts: only parts with constant failure rate are recommended to keep on stock. However, some B-parts are that hard or time consuming to replace, so that a lot of customers want to have a whole legend (including that B-part) on stock. This saves the customer considerable time required for the replacement action. In order to include those legends in the critical parts package, MP has to code the part with a B as well. Actually, these parts do not have a constant failure rate and therefore they do not meet the requirements to be a B-part as stated. The

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2 This assumption is not validated during this research project.
3 The questionnaire of the interviews can be found in Appendix B.
set of all B-parts turns out to be the sum of parts which are kept on stock because of their constant failure rate, and legends that are kept on stock because they are easier and faster to replace then the B-parts it contains.

In other words, the spare part coding is meant to indicate the right inventory strategy. We, however, find that it is sometimes the other way around: the inventory strategy is indicating the spare part coding. Further analyses of the current practice shows that MP is only able to include parts attached with a B in the spare part package, due to the software system it is using. The total set of B-parts is generally quite extensive because of that. This extensive set of B-parts causes the recommended B-part package to be quite extensive as well, and therefore expensive. When customers decide not to buy the complete extensive spare part package because of the high costs, it is their own responsibility to select the parts they do not want to have on stock. While making that decision, the customer may not know whether a B-part is recommended because of its failure behavior, or because of its ease of replacement. As it turns out, they are not able to make an adequate decision that fulfills their needs regarding the desired service levels.

Note that there is no criticality differentiation between service parts. We however find that B-parts are in real life not equally critical. The criticality of a part is related to the consequences for the system and system output if that part is not replaced immediately. Some B-parts result in a complete machine to be down where others only affect the performance of a machine.

In the remainder of this report, we refer to this coding structure as AE coding. Articles or legends that are not attached with any code are parts that have a negligible probability of failure and do not wear-out. Therefore, they are not likely to become defective in case of normal use.

1.3.4 Spare parts supply network

The spare part supply network is shown in Figure 5. MP has service parts on stock. Whenever a customer orders a service part, it is fulfilled from MP’s stock. This can be both from a Sales and Service Unit (SSU) location as well as from a manufacturing center. Manufacturing centers are replenished from their supplier, or they produce spare parts themselves. SSU are replenished from manufacturing centers. Even though it is not desirable, customers sometimes buy directly from other suppliers as well.

![Figure 5: Spare part supply network](image_url)
1.4 Critical parts packages
Whenever MP sells new production lines, it recommends customers to buy a certain spare part package along with the processing line to anticipate on unpredictable failures that are critical. We further refer to the package as the critical parts packages in this report. Whenever a part breaks down, it can be replaced by a new part that the customer has on stock. The goal of the spare part package is to make sure that the customer has the right parts on stock to anticipate on foreseen but unpredictable breakdowns which are critical for the customer. The spare parts stock is continuously reviewed. Unfulfilled demands are backordered. We further elaborate on the operational inventory control strategy in Section 4.1.1.

Basically, MP consults its clients what to keep on stock and in what amount. It should, however, be emphasized that MP is not responsible for the inventory control, nor for service levels that are being achieved. The holding costs for the parts are payed by the customer and MP is not financially penalized for low service performance.

The critical parts package is made by experts that know the characteristics of the machine. They check the Bills of Materials (BOM) of the production lines, and recommend a base stock level for every B-coded part, based on their experience and certain rules of thumb. The process is executed manually, and takes approximately four hours per order (Marel Stork Technical Maintenance Coordinators, 2016). The spare part packages mainly consist of articles, but there are also legends included.

The current procedure for determining the spare part package is in principle as follows: Whenever a part is coded as B, BC, BD or BE, MP recommends the customer to have one item on stock. If a part occurs more than once in the Bill of Material of an order, 20% of the total number of occurrence is recommended. MP expects their service levels to be quite high.

1.5 Thesis outline
Chapter 2 presents the research design. In Chapter 3, we address a number of relevant issues in spare part management for our research, and provide insights in the existing literature. Chapter 4 to 7 contain the design phase of the research regarding spare parts supply. In Chapter 4, the commonly used model described by Van Houtum and Kranenburg (2015) is presented. In Chapter 5, we adapt the basic model to better fit the situation at MP. In Chapter 6, we test the models for a business case within MP and Chapter 7 gives the results of studies within other industries of Marel. In Chapter 8, we explain how to implement the designed models into the MP organization. In Chapter 9, we design a quantitative model to analyze the line replaceable unit problem. In Chapter 10 we provide our main conclusion and insights by answering the research questions and further discuss the main recommendation for MP.
Chapter 2

Research design

In this chapter, we describe the research design. Section 2.1 describes the problem definition for our research. Section 2.2 then gives the research goal in order to overcome the problem. Section 2.3 presents the scoping decisions that we make. Section 2.4 presents the research questions. Section 2.5 gives the main research deliverables and Section 2.6 finally describes the methodology of the research.

2.1 Problem definition

Buyers and users of capital goods demand ever increasing service levels due to the high downtime costs that they face. However, buyers and users do not want their maintenance costs and spare part inventory levels to grow too high. They look at the total costs they face when purchasing the machines. Original equipment manufacturers are trying to improve their maintenance function as a whole, and spare part supply in particular. The topic of maintenance and spare part inventory management therefore has much attention of researchers and practitioners.

In line with this trend, MP's customers want to minimize maintenance costs, while achieving high service levels at the same time. The service that MP is offering in order for its customers to maintain this is the critical parts package, as described in Section 1.4.

However, MP encounters some difficulties that come along with the current way of working.

Firstly, the product portfolio that service employees need to generate critical parts packages for is more extensive due to the merger of Marel and Stork Poultry. Nowadays, the critical parts packages are generated decentrally. Every service location generates critical parts packages individually. The goal for the future is to generate the packages centrally in a consistent way. However, the service employees will become responsible for a much broader portfolio as compared to the current portfolio. Since the procedure of generating the packages is performed manually, service engineers need to have knowledge of the total product portfolio. Service engineers of MP do not always have the knowledge of all equipment in all industries, making it very hard to offer the right spare part package. Generating the package will become more and more time consuming.
Secondly, MP does not know what service level it offers on average when selling such a package. It has always been quite hard for sales people to convince customer about the importance of the critical parts package, and one cannot quantify the advantage of the packages that is offered.

Thirdly, when customers decide not to buy the complete extensive spare part package because of the high costs, it is their own responsibility to select the parts they do not want to have on stock. MP is not able to state the exact consequences of the deviation from the recommended package, let alone giving customers the trade-off between service level and costs.

MP wants to fulfill the demand of customers to achieve high service levels with low spare part investments. It is currently not able to, because of the aforementioned reasons. In striving of being a better service provider, MP wants to examine their current way of working and seek for improvements. It might also be perfectly possible that MP will be responsible for spare part management and service levels at the customer side in the future. The spare part concepts used should then be thought about, because MP will be punished in monetary terms as well.

2.2 Research goal

MP would like to have a more objective way of recommending spare part packages, based on part characteristics that gives customers the opportunity to make the trade-off between service levels and purchasing costs. The process of deciding on the stock levels needs to be transparent, explainable and reproducible. The main research question that summarizes the main purpose of this research is:

How should MP determine spare part inventory levels recommended to its customers?

MP only recommends B-parts to stock. During the analyses as described in Section 1.3.3, we found that the set of B-parts turned out to be the sum of parts which are kept on stock because of their constant failure rate, and legends that are kept on stock because they are easier and faster to replace than the B-parts it contains. For now, we only consider articles that are coded as B-part. If we refer to B-parts in the remainder of this report, we only consider articles with constant failure rates, not legends. This results in a single-indenture problem situation.

MP needs to implement an adequate model to determine the best critical parts packages according to certain objectives, constraints, and assumptions. In exploring the best model to determine spare part packages it needs to decide on several fundamental modelling parameters.

During this research, we propose several existing models using different service level measures, and further extend them in two ways to better fit the situation at MP. Firstly, MP argues a lot of articles are only delivered in certain batch sizes. The existing models are extended to deal with batching. Secondly, B-parts are not always equality critical. Whenever one optimizes the spare part package, and considers what parts to in- or exclude, one prefers to include parts with a high criticality. This is now a manual decision that is made by product experts every time they generate a package. We have to design a model to include the criticality of an article in the decision what to stock. We therefore adapt existing models to include a criticality parameter of articles.
The different alternative models are applied at several Marel industries. Furthermore, the models are implemented in a decision support tool. By the hand of this tool, MP should be able to look into the different models and strategies. In that manner, this thesis project provides decision support in deciding which model to implement. The main added value of this research then for MP is the implementation of several models and strategies, and the possibility to investigate the advantages, disadvantages and differences of the alternatives proposed. The different models and the application of the models at several case studies should provide a good base to decide what strategy to implement in the MP organization.

In addition to the B-parts, some customers are also interested in stocking legends for faster or easier replacements. Although we exclude these legends in the spare part models in this research, it would be interesting to investigate whether it would be beneficial to include legends as well in the critical parts package. We consider introducing an extra category next to the B category, which consists of all parts that may be kept on stock because of the faster or easier replacement. These parts could be denoted as R-parts. Although these parts are not included in the models and the decision support tool, an additional goal of this project is to investigate whether the introduction of the R-parts would be beneficial. If that turns out to be the case, MP could invest in more research for a better understanding on how to determine the right R-parts stock levels.

2.3 Scope

Given the research problem and research goal, we define the following main scoping decisions for the project:

B-coded parts
As aforementioned in Section 1.3.3, the demand for A, C, D and E-parts is planned. Therefore customers do not keep inventory for those parts. However, the B, BC, BD and BE parts have unplanned demands occurring. These parts will be taken into consideration. The whole set of B, BC, BD and BE parts are denoted as B-parts in the remainder of this report, because this is consistent with the jargon used within MP.

Single location
We only consider the inventory at the customer location in this research. The actual network as shown in Figure 5 is simplified into the network in Figure 6.

MP equipment is in normal phase
We assume that the MP machinery and equipment is used for quite some years. Therefore the machine is in, so-called, normal phase. There are no failures that typically occur during infant mortality. Furthermore, MP has reliable supplier such that there is relatively low supply uncertainty.
2.4 Research questions

This section presents the research questions that are answered in order to answer the main research question. Research Questions 1 and 2 are part of the design phase, and refer to the spare part supply policies used.

1. **What mathematical models to determine spare part inventory levels fit the situation at MP?**

2. **How do the models perform when implemented at MP?**

   2a. *What is the benefit of the proposed models as compared to the current practice in terms of purchasing costs and service levels?*

   2b. *What is the advantage of the item approach as compared to the system approach?*

   2c. *What is the advantage of criticality extension?*

   2d. *What is the advantage of the batching extension?*

   2e. *What service level measure is the best for MP?*

We develop several models to determine spare part stock levels, all including different features. Further, we investigate the benefit of the models as compared to the current way of working and what model performs best. We elaborate on the differences between the system and item approach and the different extension in Chapter 4 and 5.

We further continue to the implementation phase with Research Question 3:

3. **What does a useful tool for MP to determine critical parts packages look like?**

The models that are being developed and tested are implemented in a prototype decision support tool.

Moreover, we investigate the potential benefit of a topic for further research in Research Question 4:

4. **Would it also be beneficial for customers to stock spare parts on a higher indenture levels in the product structure?**

Some customers that strive for maximal operational availability want to include higher indenture levels in the spare part packages for faster replacements.

The framework that presents the research questions at one glance is given in Figure 7 in Section 2.6. We also indicate to what phase of the regulative cycle the research question belongs.
2.5 Research deliverables
When the research questions are answered, this results in the following main research deliverables for MP.

- Different spare part inventory models to determine spare part packages;
- Validation of benefits of the models by the means of the case studies;
- A decision support tool with a few case studies implemented. With this tool, MP can experiment with the different spare part models that we propose;
- Recommendations regarding the line replaceable unit problem, supported by mathematical analyses.

2.6 Methodology
Structured organizational problem solving processes are often performed following the regulative cycle (Van Strien, 1997). The cycle is shown in Figure 7. The iterative search process generally continues until a satisfactory solution is found. The phases do not always follow one another in a set order. Some phases may be expanded during the research, while others may be combined or skipped. The output of the regulative cycle entails a theory that is applicable for an individual case study. In the scientific process of reflecting, researchers try to derive more generalizable design rules by systematically reflecting on a number of cases. This is generally performed following the reflective cycle (Van Aken, 2004). Our research is aimed at developing prescriptive solution concepts for a particular case. We, therefore, structure our research and this report according to the regulative cycle. We already performed some analyses in which we formulate the problem statement and problem goal. After the literature study described in the next chapter we continue to the design phase. Research Question 1 and 2 form the design phase of the regulative cycle. We design spare part models for MP. Research Question 3 forms the implementation step. Next, Research Question 4 forms an extra step in the regulative cycle. During this step, we investigate the potential of extra research in the line replaceable unit problem. Answering this research question might trigger a new regulative cycle to start. The evaluation step is shortly addressed in the concluding words of this report.

![Figure 7: Adapted regulative cycle (Van Strien, 1997)]
Chapter 3

Literature review

In this chapter, the parts from the literature review of Bongers (2016) that are most relevant for this thesis are discussed. Section 3.1 to 3.3 shortly elaborates on literature regarding spare parts classification, spare part inventory models and the line replaceable unit problem, respectively.

3.1 Spare parts classification

An important operational issue involved in the management of spare parts is that of categorizing the relevant items in order to facilitate decision-making, i.e. selecting appropriate forecasting and stock control methods and setting appropriate targets (Bacchetti, Plabani, Saccani, & Syntetos, 2012).

Differences between individual items with regard to, for example, demand and price are very large. For many practical cases, the number of items is too large to apply item-specific inventory control methods (Buxey, 2008). It is a reasonable solution to classify items in different categories. Classification is widely adopted by organizations, but the criteria and methods of classification vary widely. Bacchetti and Saccani (2012) summarize the literature on classification methods for spare parts. During this thesis project, we try to derive criticality levels and weights of inventory items. Liu et al. (2015) mention that the most important problem is the subjectivity of the decision maker involved. We face the same problems in this project.

3.2 Spare part inventory models

Sherbrooke (1968) developed the first widespread spare part inventory control modelling, called the METRIC method. METRIC is a mathematical model capable of determining base and depot stock levels for a group of recoverable items. It tries to optimize system performance for specified levels of system investment, and is designed for application at the weapon-system level. It is assumed that demand occurs according to a compound Poisson process at the local warehouses, and stock in all warehouses is controlled by base stock policies. The author also assumes ample repair capacities at the local warehouses and the central warehouse. A heuristic is proposed to find base stock levels for all items at all warehouses that either minimize the sum of expected backorder at all local
warehouses subject to an inventory investment constraint or minimize the inventory investment subject to a constraint to the sum of expected backorders. Similar approaches have been examined extensively since the METRIC method was developed. Section 3.2.1 and 3.2.2 shortly elaborate on the two issues regarding multi-indenture structures and batching, respectively.

3.2.1 Multi-indenture systems
Muckstadt (1979) included multi-indenture structures in the model. Multi-indenture structures are adding the feature of a spare part consisting of underlying subassemblies. Slay (1984) then develops VARI-METRIC, a two-echelon model with a more accurate approximate evaluation than in METRIC. Sherbrooke (1986) then extends VARI-METRIC to a version for two-indenture two-echelon systems.

3.2.2 Batching
In most of the spare part models, a one-for-one replenishment policy (base-stock policy) is assumed. Applying the logic of the EOQ rule, the base-stock policy generally makes sense for more expensive spare parts. However, there are some relatively inexpensive parts present in MP’s spare part assortment that are only delivered in batches, thus rendering the base stock policy assumption unjustified. Customers use an \((s,Q)\)-policy for those parts.

Axsäter (2006) derives some important results for such an \((s,Q)\)-policy, and explains how to determine the inventory level distribution relatively easy. The author states that the inventory level at time \(t\) plus lead time \(L\) is given by the inventory position at time point \(t\) minus the demand during the lead time:

\[
IL_i(t + L_i) = IP_i(t) - X_i
\]

Where \(IL_i(t)\) is the inventory level of item \(i\) at time \(t\), \(IP_i(t)\) the inventory position of item \(i\) at time \(t\), \(L_i\) the lead time of item \(i\) and \(X_i\) the demand for item \(i\) during the lead time. The two expression on the right hand side are independent, since demand after \(t\) is independent of the inventory position at time \(t\) when assuming Poisson distributed demand. Since \(t\) is an arbitrary moment in time, so is \(t + L_i\). By Equation (3.1), we can obtain steady-state probabilities.

3.3 Line replaceable unit problem
We find that the LRU decision (as described in Section 1.3.2) is implicit in existing models for maintenance planning, and thus has not received much attention. Most maintenance optimization literature defines the best policy for when to replace an item. However, due to the structural dependence in the production lines that MP is selling, it is also important to define what to replace. Jensen (1975) brings up the importance of optimally determining line replaceable units.

To the best of our knowledge, Parada Puig & Basten (2015) are the only ones that pay attention to the line replaceable unit problem. They show that the LRU definition problem is NP-hard. They also show that significant cost reduction can be achieved when compared to two heuristics commonly used in practice. The authors argue that their paper might provoke further research about the ways to improve LRU decision in practice. However, to our knowledge, there is still is a gap in literature regarding the LRU decision.
Chapter 4

Basic model

We first consider a basic multi-item single location inventory model for spare parts in this chapter. The model fits in case one considers only one location where spare parts are stocked. As the modeling is done stage wise, the chapter takes a step-by-step approach in defining the basic model and describing the model solving approach. It is organized as follows: Section 4.1 describes the main multi-item single location model. Sections 4.2 and 4.3 then elaborate on the evaluation and optimization of the model, respectively.

4.1 Model

Consider a customer of MP, which has a slaughtering house equipped with several processing lines of MP. The lines consist of several machines. Each machine consists of multiple components, some of which are B-parts (articles) and some of which are legends. The set of articles is $I$, and the number of articles is $|I|$. For notational convenience, the articles are numbered $i = 1, 2, ..., |I|$. Commonality exists in the production lines that MP is selling, so some articles are assembled in different legends. Let $P(i)$ be the set of all legends that are direct ascendant of article $i$ that is installed in the machine. To illustrate, let us consider the example in Figure 8: the set of articles $I = \{2, 3, 4\}$. Furthermore, $P(2) = P(3) = P(4) = \{1\}$.

![Figure 8: Example of product structure](image)
For each article $i \in I$ demand occurs according to a Poisson process with a constant rate $m_i = \sum_{j \in P(i)} m_i^j$, where $m_i^j$ is the demand rate of article $i$ in legend $j \in P(i)$. The total demand rate for all articles together is denoted by $M = \sum_{i \in I} m_i$.

Inventory control optimization models generally try to minimize costs subject to a constraint on a certain service measure. We look at the initial supply problem at the time MP sells a processing line. The objective is to minimize the total investment. Several different service level measures can be used for spare part inventory problems. Since the models should eventually serve the customer, it is important for them to understand the advice. MP argues that the aggregate fill rate is most understandable for customers. The aggregate fill rate is defined as the percentage of requested parts that can be delivered from stock immediately. We therefore initially deal with the fill rate as the service level. Chapter 5 also presents alternative models with different service level measure.

In mathematical terms, the optimization problem can be defined as follows:

$$(P_1) \quad \text{Minimize} \quad \sum_{i \in I} S_i c_i$$

Subject to: $\beta(S) \geq \beta^{obj}$

Where $S_i \in N_0$ is the recommended stock level for article $i$, $c_i > 0$ is the purchasing cost for article $i$ for the customer. $S$ is a vector containing the recommended stock levels for all articles, i.e., $S = (S_1, \ldots, S_{|I|})$. $\beta(S)$ is the aggregate fill rate with stock levels $S$ and $\beta^{obj}$ is the aggregate fill rate objective.

### 4.1.1 Assumptions
To be able to model the spare part supply system, some assumptions have to be made. This section summarizes and discusses the validity of the main assumptions.

**Poisson distributed demand**
Demand for spare B-part articles is modeled by a Poisson distribution. The assumption of Poisson processes is justified when lifetimes of components are exponential (Van Houtum & Kranenburg, 2015). The exponential distribution is the probability distribution that describes the time between events in a Poisson process. It is a process in which events occur continuously and independently at a constant average rate. It has the key property of being memoryless. With $T$ being the waiting time, $P(T > s + t | T > s) = P(T > t)$, $\forall s, t \geq 0$. The probability for an event to occur now equals the probability for an event to occur an hour from now. The exponential distribution is the only continuous probability distribution that has a constant failure rate.

MP argues the B-parts to fail suddenly as illustrated in Figure 4 (Marel, 2015). We discuss in Section 1.3.3 that this is not true for all parts coded with a B. We conclude that the B-parts could be B-coded either because it fails suddenly, or because of other reasons. As stated earlier, we only consider the B-coded articles. The legends that are being stocked are not taken into account. So by definition, the time between failures of articles that we consider is approximately exponential, and assuming Poisson distributed demand for the B-coded articles seem to be reasonable because of that.
Next to the B-parts, MP also distinguishes BC, BD and BE parts. Their failure rate distribution is increasing over time, but they are preventively replaced after a certain time. MP argues that the failure rate is approximately constant till the replacement (Marel Stork Service Engineers, 2016). This is also illustrated in Figure 4.

**A one-for-one replenishment strategy is assumed**
This is justified as long as there are no fixed ordering costs or fixed ordering costs are small relative to the prices of the articles. This is true for a lot of B-parts. For some very cheap parts, MP uses fixed order quantities. This extension is described in Chapter 5.

**Demand that cannot be fulfilled immediately from the stock at the customer is backordered**
This assumption is justified when one does not use emergency or lateral transshipments. Emergency transshipments are used every now and then in reality for customers located close to a MP production location.

With this in mind, we decide to assume demand that cannot be fulfilled immediately from the stock at the customer is backordered. We want our model to calculate the base stock levels without the option of emergency transshipments, because they are undesired.

**All B-parts are assumed to be LRU and customers replace only the B-part that is broken**
There is no unambiguous LRU definition. Some customers replace high indenture assemblies because of the shorter replacement time. For now, we assume all the B-parts articles are LRU. We further elaborate on the LRU definition in Chapter 9.

**Minimum quantities**
One final assumption has to be made regarding the demand distribution. MP is about to improve its maintenance consults to its customers. Whenever certain B-parts break down in a machine, that particular B-part is replaced. However, in order to execute a proper replacement and to bring the machine back to an approximately new one, the customer needs to replace other identical B-parts simultaneously. This implies that demand always arrives in multiples of the minimum quantities of that part. Note that in the demand quantity does not always have to be equal to one in order to perform the evaluation analyses as explained in this section. If parts are always used in other quantities, this quantity can simply be analyzed as unit demand. It is however important to multiply by the used quantity when determining the stock levels.

Moreover, it might be the case that part \(i\) is used in a quantity of three in one legend, and in quantity of five in another. Although MP is not sure whether this situation occurs in real life, this occasion should actually be modelled with a compound Poisson distributed demand process. Compound Poisson demand means that not only the demand arrival, but also the size of a demand is a stochastic variable that is independent of other customer demands and of the distribution of the customer arrivals. The distribution of the demand size is denoted as the compounding distribution. Modelling with compound Poisson distributed demand is not taken into consideration within this research project for two reasons. First, because MP is not sure whether demand really occurs according to a compound Poisson process. Second, because the complexity would increase
significantly, which makes the model hard to understand for both the service employees within MP as well as the customers.

If it eventually turns out that parts are indeed used in different quantities, for now, we use the highest quantity to calculate base stock levels, knowing that we do not reach the optimal solution. However, the parts for which this might occur are expected to be relatively cheap. The increase in purchasing cost is therefore not very high for the customer and this way of working is, therefore, acceptable. Note that the fill rate computed by the model is always as least as high as the true fill rate. If we want to compute the difference in fill rate, Appendix C elaborates on the evaluation procedure when modeling with a compound Poisson demand process.

4.2 Evaluation

This section evaluates the steady-state behavior and the aggregate fill rate for a given base stock policy. Because articles do not have interaction, the steady state behavior is first evaluated per article, and later aggregated. The evaluation is based on Chapter 2 of Van Houtum & Kranenburg (2015).

The aggregate fill rate ($\beta(S)$) is defined as the probability that an arbitrary demand for the total group of articles is fulfilled immediately from stock. This can only happen if there is on hand stock available. Since we have assumed that demands for the B-parts arrive according to a Poisson process, an arbitrary arriving demand observes the system in steady state according to PASTA (Poisson Arrivals See Time Averages). Hence, with probability $P\{OH_i(S_i) > 0\} = P\{X_i < S_i\}$, a positive stock on hand is observed and the demand can be fulfilled immediately, with $OH_i$ is the stock on hand and $X_i$ is the demand during lead time. This brings us to the equation to calculate the item fill rate:

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

Where $\beta_i(S_i)$ is the item fill rate with an base stock level of $S_i$. The aggregate fill rate can then be calculated as follows:

$$\beta(S) = \sum_{i \in I} \frac{m_i}{M} \beta_i(S_i)$$

Where $\beta(S)$ is the aggregate fill rate.

So, in order to calculate the fill rate, the distribution of the demand during lead time, also called the pipeline stock should be calculated. In our model, articles fail according to a Poisson process, and therefore failed articles enter the resupply pipeline according to a Poisson process as well. Each failed article stays on average time $t_i$ in the repair pipeline. The resupply pipeline may be seen as a queueing system with infinitely many servers and service time $t_i$. So the resupply pipeline is an $M|G|\infty$ system and thus we may apply Palm’s theorem.

**Palm’s theorem:** If jobs arrive according to a Poisson process with rate $\lambda$ at a service system and if the times that the jobs remain in the service system are independent and identically distributed according to a given general distribution with mean $EW$, then the steady-state distribution for the total number of jobs in the service system is Poisson with mean $\lambda EW$. 
When we apply this theorem to the resupply pipeline, we can say that it is Poisson distributed with mean \( m_i t_i \), and:

\[
P(X_i = x) = \frac{(m_i t_i)^x}{x!} e^{-m_i t_i}, \quad x \in \mathbb{N}_0
\]

For the sake of efficiency, we also use the following recursion to calculate the resupply pipeline stock:

\[
P(X_i = 0) = e^{-m_i t_i}
\]

\[
P(X_i = x + 1) = \frac{m_i t_i}{x+1} P(X_i = x) \text{ for } x \in \mathbb{N}_0
\]  

\[4.1\]

### 4.3 Optimization

Problem \( P_1 \) is item separable and the function \( \beta_i \) is increasing and concave for \( S_i \geq m_i t_i - 1 \) (see e.g. Van Houtum & Kranenburg, 2015). Hence, a set of efficient solution can be generated by a greedy algorithm. By using the greedy algorithm, we compute the increase in \( \beta_i \) relative to the increase in costs \( C(S) \) for each item. \( C(S) \) is equal to \( S_i \cdot c_i \). The item with the biggest bang for the buck is selected and the corresponding base stock level is increased by one unit. This is continued until a given stopping criteria in terms of aggregate fill rate is reached. The formal procedure is described in Algorithm 4.1.

**Algorithm 4.1 (Greedy Algorithm)**

\[\begin{align*}
\text{Step 1:} & \quad S_i := \max\{m_i t_i, 0\} \text{ for all } i \in I; \\
& \quad C(S) := \sum_{i \in I} S_i \cdot c_i \text{ and } \beta(S) := \sum_{i \in I} \frac{m_i}{M} (\sum_{x=0}^{S_i-1} P(X_i = x)). \\
\text{Step 2:} & \quad I_i := (m_i P(X_i = S_i))/(M c_i) \text{ for all } i \in I; \\
& \quad k := \arg\max\{I_i: i \in I\}; \\
& \quad S_k := S_k + 1 \\
\text{Step 3:} & \quad C(S) := C(S) + c_k \text{ and } (S) := \beta(S) + (m_k P(X_k = S_k))/M; \\
& \quad \text{If } \beta(S) \geq \beta_{obj}, \text{ then stop, else go to Step 2.}
\end{align*}\]
Chapter 5

Alternative models

In this section we present slightly different and extended models. All the different models that we set up are applied on the situation at MP. It is then eventually able to choose the model that fits its needs. Section 5.1 presents the item approach. Section 5.2 and 5.3 present the model with different service level measures, aggregate mean number of backorder and supply availability respectively. Section 5.4 presents the model with the criticality extension, and Section 5.5 finally elaborates on the batching extension.

5.1 Item Approach

In Chapter 4, we treat all service parts in one model. We follow the so-called system approach. In the system approach, a system target is set and the goal is to find a combination of stock levels that minimize costs subject to a system target constraint. In the item approach, targets are set per item and stock levels are calculated per item separately. One then gets a simple decision problem per part. Sherbrooke (1968, p. 123) mentions that the system approach “focuses management attention on the entire system so that an appropriate combination of system effectiveness and system cost can be selected”. Thonemann, Brown & Hausman (2002, p. 1224) argue that the benefits of using a system approach instead of an item approach depends mainly on the unit costs: “Inventory system with high unit cost skewness benefit significantly from the system approach while systems with low unit cost skewness benefit little”.

The parts cost price of the B-parts at MP range from €0.01 to €9,490.00. Table 1 gives a broad overview of the differentiation of the price of B-parts. Figure 9 shows the unit cost skewness graphically. All B-parts are rounded up the nearest multiple of €10. Then all parts within a group are summed and plotted for each multiple of €10. As can be seen, the figure shows a positive skew, meaning that it is probably beneficial to use a system approach.

However, Thonemann et al. (2002) mention that the system approach is much more complex and requires more time, money and skill to implement as compared to the item approach. Due to this downside, we explicitly check for the relative benefit in our research.
Table 1: Differentiation of Price B-parts

<table>
<thead>
<tr>
<th>Range</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price ≤ €1</td>
<td>4%</td>
</tr>
<tr>
<td>€1 &lt; Price ≤ €100</td>
<td>40%</td>
</tr>
<tr>
<td>€100 &lt; Price ≤ €500</td>
<td>24%</td>
</tr>
<tr>
<td>€500 &lt; Price ≤ €1000</td>
<td>10%</td>
</tr>
<tr>
<td>€1000 &lt; Price ≤ €3000</td>
<td>16%</td>
</tr>
<tr>
<td>€1000 &lt; Price ≤ €5000</td>
<td>4%</td>
</tr>
<tr>
<td>€5000 &lt; Price</td>
<td>2%</td>
</tr>
</tbody>
</table>

**Price differentiation of B-parts**

![Price differentiation graph](image)

Figure 9: Differentiation of Price B-parts

Mathematically, model $P_1$ is adapted into model $P_2$ where the constraint for the aggregate fill rate is decomposed into constraints per item:

$$(P_2) \quad \text{Minimize} \quad \sum_{i \in I} S_i c_i$$

Subject to: $\beta_i(S) \geq \beta^{\text{obj}}$ for $i \in I$

The evaluation phase goes just as in the system approach explained in Section 5.2. The optimization phase is however much easier, since one gets a simple decision problem per item. The greedy algorithm for the item approach is as follows:

**Algorithm 5.1**

Step 1: $S_i := 0$, $C_i(S_i)$ := 0 and $\beta_i(S_i)$ := 0 for all $i \in I$, $i := 0$;

Step 2: $i := i + 1$

Step 3: $S_i := S_i + 1$

Step 4: $C_i(S_i) := C_i(S_i) + c_i$ and $\beta_i(S_i) := \beta_i(S_i) + P[X_i = S_i]$;

If $\beta_i(S_i) < \beta^{\text{obj}}$, then go to step 3, else if $i = |I|$ then stop, else go to Step 2.

Step 5: $C(S) := \sum_{i \in I} C(S_i)$ and $\beta(S) := \sum_{i \in I} \frac{m_i}{M} \beta_i(S_i)$

This simplified approach is suboptimal. However, it is easier to calculate and to understand for practitioners.
5.2 Aggregate mean number of backorders

An alternative objective for MP to define the service level could be the expected number of backorders. The expected number of backorders does not only take the number of unfulfilled demand into account, but also the time it takes to full fill the demand. Under conditions of identical average repair or resupply times for each item, a model with aggregate expected number of backorder results in the same optimal stock levels as a model with aggregate fill rate. However, this is not true for MP.

The backorder criteria is preferred in most literature regarding spare part modeling. Experimentations seem to indicate that a policy that minimizes the expected number of backorder provides good results with respect to fill rate, but the converse is not necessarily true (Sherbrooke, 1968).

MP argues the aggregate fill rate to be the most understandable and explainable service level measure. It is however interesting to investigate the difference in the optimal spare part package when modeling with aggregate fill rate and modeling with aggregate expected number of backorders. It is, fortunately, possible to adjust the model and the greedy algorithm to deal with different service level measures.

The mathematical formulation of the spare part model when minimizing purchasing costs subject to a constraint based on aggregate mean number of back orders is formulated as follows:

\[
\text{(P}_3\text{)} \quad \text{Minimize} \quad \sum_{i \in I} S_i c_i \\
\text{Subject to:} \quad \text{EBO}(S) \geq \text{EBO}^{\text{obj}}
\]

Where \(\text{EBO}(S)\) is the expected number of backorder with recommended stock levels \(S\), \(\text{EBO}^{\text{obj}}\) the objective number of backorders.

We now need to evaluate the steady-state behavior and the expected number of backorders for a given base stock policy. Because articles do not have interaction, the steady state behavior is first evaluated per article, and later aggregated. The evaluation is again based on Chapter 2 of Van Houtum & Kranenburg (2015).

Consider an arbitrary article \(i\), and assume that the basestock level \(S_i\) is given. Whenever article \(i\) fails, it goes into repair or it is discarded and a new one is ordered. The average repair or resupply time takes on average \(t_i\) time units. The state of the spare part system of article \(i\) at time instant \(t\) can be described by \(X_i(t)\), \(OH_i(t)\) and \(BO_i(t)\), where \(X_i(t)\) denotes the number of articles in repair or resupply at time \(t\), \(OH_i(t)\) denotes the stock on hand at time \(t\) and \(BO_i(t)\) the number of backorders at time \(t\). The amount \(X_i(t)\) is also called the pipeline stock. Sherbrooke (2004) shows the relation between \(X_i(t)\), \(OH_i(t)\) and \(BO_i(t)\) by the stock balance equation.

\[
OH_i(t) - BO_i(t) = S_i - X_i(t)
\]  

(5.1)
The distribution of the number of backordered demands \( BO_i \) is given by:

\[
P(BO_i = x) = \begin{cases} 
\sum_{y=0}^{S_i} P(X_i = y) & \text{if } x = 0; \\
P(X_i = x + S_i) & \text{if } x \in \mathbb{N}.
\end{cases}
\]

Further, we can obtain the mean backorder position:

\[
EBO_i(S_i) = \sum_{x=S_i}^{\infty} P(X_i = x) 
\]

Additionally, one can derive an easier expression for \( EBO_i(S_i) \) for computational purposes from the stock balance Equation (5.1) as it avoids sums with infinitely many terms.

\[
EBO_i(S_i) = m_i t_i - S_i + \sum_{x=0}^{S_i} (S_i - x) P(X_i = x) 
\]

The aggregate mean number of backorders then is, in steady state:

\[
EBO(S) = \sum_{i \in I} EBO_i(S_i) 
\]

The greedy algorithm to get to the optimal solution is described in Algorithm 5.2.

**Algorithm 5.2** (Greedy Algorithm)

1. \( S_i := 0 \) for all \( i \in I \);
   \( C(S) := 0 \) and \( EBO(S) := \sum_{i \in I} m_i t_i \)
2. \( \Gamma_i := (1 - \sum_{x=0}^{S_i} P(X_i = x))/c_i \) for all \( i \in I \);
   \( k := \arg \max \{\Gamma_i; i \in I\} \);
   \( S_k := S_k + 1 \)
3. \( C(S) := C(S) + c_k \) and \( EBO(S) := EBO(S) - (1 - \sum_{x=0}^{S_k} P(X_k = x)) \);
   If \( EBO(S) \leq EBO^{obj} \), then stop, else go to Step 2.

### 5.3 Average supply availability

The constraint on the aggregate number of backorders is closely related to a supply availability constraint. The average supply availability is the fraction of time that all the B-parts that are needed are available. The following approximation for the supply availability can be obtained for a certain machine:

\[
A(S) \approx \prod_{i \in I} \left(1 - \frac{EBO_i(S_i)}{N_i}\right)^{N_i}
\]

Where \( N_i \) is the total number of articles \( i \) that are installed on the machine.

For a sufficiently high target availability \( A^{obj} \), a heuristic solution for the problem with a target average availability can be obtained for the problem with target \( EBO^{obj} = (1 - A^{obj}) \) for the aggregate mean number of backorders. We refer to Van Houtum & Kranenburg (2015, p.32) for a more detailed description of the problem with supply availability as target service measure.
5.4 Criticality extension

All B-parts are assumed to be equally critical until now. However, as mentioned in Section 1.3.3, it turns out that this assumption is not justified. Whenever we optimize our spare part package, and consider what parts to in- or exclude, we prefer to include cheap articles, with high failure rates. In addition, the articles should have a high criticality. MP needs to store data about criticality as well, in order to be able to take criticality into consideration as well. The model can be adapted to be able to take criticality of articles into consideration as well:

\[
\begin{align*}
\text{(P4)} & \quad \text{Minimize} \quad \sum_{i \in I} S_i \frac{c_i}{w_i} \\
\text{Subject to:} & \quad \beta(S) \geq \beta^{obj}
\end{align*}
\]

Where \(w_i\) is a criticality measure for article \(i\). We describe different ways of determining the criticality level in Chapter 6.

The greedy heuristic is adapted to Algorithm 5.3. Due to the inclusion of \(w_i\) parts with a high criticality factor are selected earlier.

\textbf{Algorithm 5.3 (Greedy Algorithm).}

\begin{itemize}
\item \textbf{Step 1:} \(S_i := \max\{m_i t_i, 0\}\) for all \(i \in I\); \\
Compute \(C(S) := \sum_{i \in I} S_i \cdot c_i\) and \(\beta(S) := \frac{\sum_{i \in I} m_i \sum_{x=0}^{S_i-1} P(X_i = x)}{M c_i}\).
\item \textbf{Step 2:} \(I_i := w_i \cdot (m_i P(X_i = S_i)) / (M c_i)\) for all \(i \in I\); \\
\(k := \arg \max\{I_i: i \in I\}\); \\
\(S_k := S_k + 1\).
\item \textbf{Step 3:} Compute \(C(S) := C(S) + c_k\) and \(S) := \beta(S) + (m_k P(X_k = S_k)) / M\); \\
If \(\beta(S) \geq \beta^{obj}\), then stop, else go to Step 2.
\end{itemize}

5.5 Batching

We assumed that the customer uses a one-for-one replenishment policy for its B-parts thus far. However, some B-parts are only delivered in certain batches by MP. We adapt the model so that we can include batching and examine the impact of that inclusion, which results in an \((s, Q)\)-policy. When using the \((s, Q)\)-policy, a batch of size \(Q\) is ordered whenever the inventory position drops to or below the reorder point \(s\). Note that in the case when one-for-one replenishment is used, this can also be modeled with an \((s, Q)\)-policy with \(s = S - 1\) and \(Q = 1\). In order to evaluate the performance of an \((s, Q)\)-policy, we need to make some additional assumptions. We first assume that the replenishment lead times for articles are deterministic. We further assume that batch sizes are fixed. As stated before, it is assumed that a component is always demanded in the same quantity. That does not always have to be equal to one. Demand however is still one-for-one. Therefore a service part \(i\) is always ordered in the exact batch size \(Q_i\). \(Q\) is a vector containing the batch sizes for all articles, i.e. \(Q = (Q_0, \ldots, Q_{|I|})\).
The mathematical model does not change very much. Only the evaluation and optimization of the model becomes more complicated.

\[(P_5) \quad \text{Minimize} \quad \sum_{i \in I} s_i c_i \]

\[\text{Subject to:} \quad \beta(s, Q) \geq \beta^{ab}\]

In order to analyze the fill rate given certain stock levels when one uses the \((s, Q)\)-policy, we combine work from Axsäter (2006) and Van Houtum & Kranenburg (2015).

When \(t_i\) is deterministic and the demand during the lead time of article \(i\) is Poisson distributed with mean \(m_i t_i\), the inventory position at an arbitrary time point is uniformly distributed between \(s_i + 1, \ldots, s_i + Q_i\) (see Proposition 5.1 in Axsäter, 2006). Additionally, in Section 5.3.2 of Axsäter (2006) it can be seen that the inventory level at time point \(t\) plus lead time \(t_i\) is given by the inventory position at time point \(t\) minus the demand during the lead time:

\[IL_i(t + t_i) = IP_i(t) - X_i\]

Where \(IL_i(t)\) is the inventory level of article \(i\) at time \(t\) (equals \(OH_i(t) - BO_i(t)\)), \(IP_i(t)\) the inventory position of article \(i\) at time \(t\), \(t_i\) the lead time of article \(i\) and \(X_i\) the demand for article \(i\) during the lead time. The two expressions on the right hand side are independent, since demand after \(t\) is independent of the inventory position at time \(t\) when assuming Poisson distributed demand.

Now we can compute the fill rate of article \(i\). As aforementioned, the fill rate is the fraction of the demand that can be fulfilled immediately from stock. The expected fill rate of a single article with an \((s, Q)\)-policy can be computed as follows:

\[
\beta_i(s_i, Q_i) = P(IL_i(s_i, Q_i) > 0) = P(IP_i(t) = s_i + u \land X_i < s_i + u) = \frac{1}{Q_i} \sum_{u=1}^{Q_i} \sum_{x=0}^{s_i + u - 1} P\{X_i = x\} \quad (5.2)
\]

Van Houtum & Kranenburg (2015) prove that the aggregate fill rate is increasing in its whole domain and concave for \(S_i \geq \max\{[m_i t_i - 1], 0\}\) for a base stock replenishment policy. We state in Lemma 5.1 that the item fill rate, is also increasing on its whole domain and concave for \(S_i = \max\{[m_i t_i - 2], 0\}\) when an \((s, Q)\)-policy is used.

**Lemma 5.1** For each article \(i \in I\), the item fill rate \(\beta_i(S_i)\) is strictly increasing on its whole domain and concave for \(S_i \geq \max\{[m_i t_i - 2], 0\}\).

**Proof.** Let \(i \in I\). By Equation (5.2):

\[
\Delta \beta_i(s_i, Q_i) = \beta_i(s_i + 1, Q_i) - \beta_i(s_i, Q_i) = \frac{1}{Q_i} \sum_{u=1}^{Q_i} \sum_{x=0}^{s_i + u} P\{X_i = x\} - \frac{1}{Q_i} \sum_{u=1}^{Q_i} \sum_{x=0}^{s_i + u - 1} P\{X_i = x\}
\]
\[ P(s_i + u) = \frac{m_i t_i}{s_i + u + 1} P(s_i + u) \]

And by substitution of this recursive relation into Equation (6.10), we find:

\[ \Delta^2 \beta_i(s_i, Q_i) = \frac{1}{Q_i} \sum_{u=1}^{Q} P(s_i + u) \cdot \left( \frac{m_i t_i}{s_i + u + 1} - 1 \right) \]

From this, it follows that \( \Delta^2 \beta_i(s_i, Q_i) \leq 0 \) if \( \left( \frac{m_i t_i}{s_i + u + 1} \right) < 1 \) for all \( u \). In other words, \( \Delta^2 \beta_i(s_i, Q_i) \) is concave when \( s_i + u + 1 \geq m_i t_i \), so if \( s_i \geq m_i t_i - u - 1 \) for all \( u \). Since \( u \) is uniformly distributed between 1 and \( Q_i \), we can state that the item fill rate is definitely concave for \( s_i \geq m_i t_i - 2 \). Because of the integrality and non-negativity of \( s_i \), the condition \( s_i \geq m_i t_i - 2 \) is equivalent to \( s_i \geq \max\{m_i t_i - 2, 0\} \).

From Lemma 6.1., we can conclude that a greedy algorithm can be used to generate efficient solutions. The formal procedure is described in Algorithm 6.4.

**Algorithm 5.4 (Greedy Algorithm).**

**Step 1:**

\[ s_i := \max\{m_i t_i - 2, 0\} \text{ for all } i \in I; \]
\[ C(s, Q) := \sum_{i \in I} s_i \cdot c_i \text{ and } \beta(s, Q) := \sum_{u=1}^{Q} \frac{1}{Q_i} \cdot \sum_{x=0}^{s_i + u - 1} P(X_i = x) \]

**Step 2:**

\[ I_i := \frac{1}{c_i} \left( \frac{1}{Q_i} \sum_{u=1}^{Q} P(X_i = s + u) \right) \text{ for all } i \in I; \]
\[ k := \arg \max\{I_i; i \in I\}; \]
\[ s_k = s_k + 1 \]

**Step 3:**

\[ C(s, Q) = C(s, Q) + c_k \text{ and } \beta(s, Q) := \beta(s, Q) + \frac{1}{Q_k} \sum_{u=1}^{Q} P(X_k = s_k + u); \]

If \( \beta(S) \geq \beta^{*\text{obj}} \), then stop, else go to Step 2.
Chapter 6

Case study at Marel Poultry

To test the benefit of the spare part models as set up in Chapter 4 and 5, we perform a case study at MP. With this study, we can compare the outcomes of the different models proposed.

An existing order is taken, where an AMF-BX breast cap filleting system is sold to a customer in Slovakia. The system is made up of modules installed along a transport mechanism with turning product holders. Each module is responsible for one process step. Breast caps are loaded onto the holders. These convey them through the system’s modules and turn them into the correct position for each step. Modules can be switched on or off for different end product. Figure 10 shows an AMF-BX line. The system eventually produces a wide range of breast fillet products for retail and industrial customers and harvests by-products.

Figure 10: AMF-BX breast cap filleting system
The order contains 169 different B-parts. These articles occur in different legends, where they might have a different failure rate. This results in a total of 288 articles in legends for which we define the input parameters. This is done in Section 6.1. Section 6.2 analyzes the critical parts package generated with the current way of working as explained in Section 1.4. Section 6.3 discusses the spare part packages the models generate, distinguishing between different service level measures, criticality alternatives, and system- or item approach. In Section 6.4, we verify and validate the models. In Section 6.5, we perform a sensitivity analyses. Section 6.6 finally gives a conclusion.

### 6.1 Input parameters

This section describes how we collect the data for the input parameters. The input parameters are presented in Table 2 and we address them in the order of presentation. The values of the parameters can be found in Appendix D.

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead time</td>
<td>( t_i )</td>
</tr>
<tr>
<td>Failure rate</td>
<td>( m_{i}^{j} )</td>
</tr>
<tr>
<td>Purchasing costs</td>
<td>( c_i )</td>
</tr>
<tr>
<td>Minimum quantity</td>
<td>( MinQ_{i}^{j} )</td>
</tr>
<tr>
<td>Criticality</td>
<td>( w_i )</td>
</tr>
</tbody>
</table>

#### 6.1.1 Lead time

One of the necessary input parameters of the model is the lead time per part for the customer in calendar days. We only model a single location spare part model, meaning that we do not take the stock levels at MP into consideration. In the ERP system that MP uses, lead times \( LT_{i}^{marel} \) are stored for every part \( i \), where it is assumed that MP does not have any inventory at all. The ERP lead times that are stored are basically the supplier replenishment lead time plus the time needed for assembly or production. In reality, MP has quite some B-parts on stock.

Customers face the complete \( LT_{i}^{marel} \) if they order a B-part that is not hold on stock at a MP warehouse. For parts that are kept on stock at a MP warehouse, MP strives to achieve a fill rate of 95%. If the customer orders a B-part that is hold on stock at a MP warehouse, we take 5% of the ERP lead time as input.

Furthermore, we add 2 days for picking and packing of the material \( (LT_{pp}^{pp}) \), and shipment time \( (LT_{shipping}^{pp}) \) of 3 days to Slovakia. The composition of the lead time that the customer faces is graphically shown in Figure 11.

Concluding, we determine the lead time that the customer faces according to Equation (6.1). Recall that due to the single location assumption, this lead time is an input parameter, and no decision variable.

\[
t_i = \begin{cases} 
LT_{i}^{marel} + LT_{pp}^{pp} + LT_{shipping}^{pp}, & \text{if item } i \text{ is not hold on stock at a Marel warehouse} \\
(0.05 \cdot LT_{i}^{marel}) + LT_{pp}^{pp} + LT_{shipping}^{pp}, & \text{if item } i \text{ is hold on stock at a Marel warehouse}
\end{cases}
\] (6.1)
Another crucial input parameter for the model is the failure rate per B-part. MP stores historic sales data per B-parts. However, the historic sales data are not very useful for us because of four reasons.

Firstly, the data is not separated between new equipment sales and spare part sales.

Secondly, it is not possible to find out which parts are ordered for corrective or preventive maintenance. As we discussed earlier, compounded B-parts (BC, BD and BE) are replaced preventively, but have an additional probability of failure before replacement for which you want to store spares. We are only interested in the sales data resulting from corrective replacement.

Thirdly, the failure rate differs for the same part in different machines and applications. We cannot know what application failed and made the customer reorder a certain B-part.

Lastly, customers also buy common spare parts from local suppliers.

Because of all this, the data at hand cannot help us in determining failure rates. The best way of gathering failure rates per B-parts then is to talk with equipment experts that visit customers regularly. We divided the B-parts into mechanical or pneumatic parts, and electrical parts. The failure rates of the two different groups of B-parts are estimated by different experts from the service and electrical department, respectively. The failure rate should only estimate the probability of failure, assuming that the part is also preventively replaces according to the preventive maintenance schedules suggested by MP. The estimates eventually resulted in $m_i$.

We validate the average failure rate with data Section 6.4. During the sensitivity analyses in Section 6.5, we investigate the impact of differentiation from the estimated failure rate.
6.1.3 Purchasing costs
The fixed purchasing costs for customers are stored in the ERP system MP is using. This price is determined by a service pricing engineer, and is based on the purchasing costs that MP incurs plus a margin depending on several characteristics of the part. In Section 6.1, we presented the total differentiation in prices for B-parts. The prices for B-parts in this order range from €0.05 to €4403.73.

6.1.4 Minimum quantity
This parameter, as explained in Section 4.1.1 is not stored yet. We ask the equipment experts to determine the minimum quantity needed for proper replacement.

6.1.5 Part criticality
In Chapter 5, we propose a model that is able to include a parameter regarding article criticality ($w_i$). This criticality level per article $i$ is not determined yet within MP, and can be done in several ways. We test three alternatives to determine $w_i$.

**Alternative 1**
A first base alternative regarding criticality is to just assume all B parts to be equally critical. This is how it is currently assumed. Even though this assumption is not 100% true, one does not need to store more data. Moreover, determining criticality classes and attaching weights to those classes is a subjective task. By sticking to the assumption of equal criticality, there is no subjective judgement regarding criticality needed.

**Alternative 2**
Alternatively, there is this idea put forward by service engineers to distinguish two different classes of criticality. The one class represents all the parts that are critical in terms of down time for the machine and critical in terms of safety. The other class represents the remaining parts that are considered to be less critical. However, we noted during the interviews with the service managers that there is still quite some difference in criticality in the remaining parts. But it is quite an exhaustive task to define and maintain the criticality level more specifically for all B parts. When using this alternative, MP needs to define how much more critical class 1 is as compared to class 2.

**Alternative 3**
We propose a third alternative. We have to keep the goal of our classification in mind: when optimizing spare part packages, we need to include cheap parts with high failure rate and high criticality. Very cheap parts or parts that have very high failure rates are included obviously in the critical parts packages. Therefore, it does not make sense to determine criticality levels for those parts. The criticality level is particularly important for expensive parts with low failure rates. If a part is expensive and has a low failure, it would not be stocked. By including a certain criticality level, the part could still be chosen to stock. Therefore, MP might only introduce criticality levels for expensive parts with a low failure rate.

Let:

\[ c_i \quad = \quad \text{purchasing costs of article } i \text{ for customer} \]
\[ m_i \quad = \quad \text{Poisson failure rate of article } i \]
\[ v_i = \frac{c_i}{m_i} \]

\( V \) = threshold value

And, only for those parts for which \( v_i > V \), the criticality level is important. The other parts, where \( v_i \) does not exceed the threshold value, are always included in the package and the criticality is therefore not very interesting.

Whenever a part needs to be taken into consideration regarding its criticality level, the question is how to do that. What factors impact the criticality level, and how much more critical is one article as compared to the other? We propose the following matrix in order to determine criticality in this case study.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weight</th>
<th>0</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uptime</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hygiene</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The default value is 1, which indicates the maximum criticality. This is also the value that is attached to the articles for which \( v_i \) does not exceed \( V \). For articles where \( v_i \) does exceed the threshold, criticality level is determined by multiplying the factor with its weight plus 1. It needs to be emphasized that the matrix is an example about how to determine criticality level. Whenever this alternative is considered to be the most desirable one, the best matrix can be determined. The factors to determine the criticality of a certain article might also depend on the service level measure you are using. Assume we use the fill rate as service level for instance. The fill rate only considers the percentage of unfulfilled orders, and does not take the time it takes to fulfill the order into consideration, i.e. lead time. This could be taken into account when determining the criticality.

In addition, the question is what threshold value is desirable.

### 6.2. As-Is situation
We start with the As-Is situation. We explain in Section 1.4. how the critical parts packages are determined in the current situation. The spare part package that was recommended to the customer that bought this equipment is analyzed.

In order to analyze the service level of the packages recommended according to the current way of working, we determine the aggregate fill rate (\( \beta(S) \)), expected number of backorders (\( EBO(S) \)) and supply availability (\( A(S) \)). The results are shown in the second column of Table 4.

MP achieves decent service levels with the current way of working. The question is however if one is able to achieve the same levels with lower spare part inventory investment. We investigate that in the next paragraph. For now, we look into the service level of individual articles. Take the blade-holding with part ID 12345 (See Appendix D). It has a total failure rate of 80 per 10 years and a lead time for the customer of 9.3 days and it costs €21.12. MP recommends its customers to have 10
parts on stock, resulting in an article fill rate of approximately 100%. We manually decrease the stock level to 5 parts. When we reanalyze the article fill rate, we find out that it is still approximately 100%. With the extra 5 parts that the customer is keeping on stock, it does not achieve significant increased service levels.

Other parts only have an article fill rate lower than 90%. The bearing-ball groove, for example, has a total failure rate of 10 per 10 years, a lead time of 38 days and it costs € 8.79. Theoretically, the money spend for the blade-holding can be better spend in extra stock for bearing-ball grooves. We validate this statement with product experts. We discuss several comparable cases with the service employees that are currently making the spare part packages. The outcome of those meeting are discussed during both Section 6.3 and 6.4.

### 6.3 To-Be situation

This paragraph elaborates on the different models that we propose in Chapter 5 and 6. We first give a quick overview of the results in Table 4, and discuss the table. Furthermore, we discuss the models separately in Sections 6.3.1 to 6.3.5.

Table 4 is set up as follows: The first row indicates the approach that is used, the target service level measure that is used and the extensions that the models has. The next row gives the investment costs for a spare part package. The last 3 rows give the different service level measures.

The most important thing that should be noted is that huge improvements can be made when using the system approach. Comparable service levels are achieved by less than half of the costs of the price in the As-Is situation. In the remainder of this chapter, we validate whether the spare part packages and therefore the improvement that we see in Table 4 are realistic.

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</tr>
</thead>
<tbody>
<tr>
<td>agg. Fill rate</td>
<td>agg. Fill rate</td>
<td>agg. Fill rate</td>
<td>agg. Fill rate</td>
<td>agg. Fill rate</td>
<td>Criticality 2</td>
<td>Criticality 3</td>
<td>Batching</td>
<td></td>
</tr>
<tr>
<td>Total Costs</td>
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<td>€ 20,875.04</td>
<td>€ 19,998.78</td>
<td>€ 8,720.25</td>
<td>€ 8,713.09</td>
<td>€ 8,720.25</td>
<td>€ 8,720.20</td>
<td>€ 9,571.98</td>
</tr>
<tr>
<td>Aggregate Fill rate</td>
<td>97.98%</td>
<td>99.46%</td>
<td>98.10%</td>
<td>98.01%</td>
<td>98.00%</td>
<td>98.01%</td>
<td>98.01%</td>
<td>98.24%</td>
</tr>
<tr>
<td>Expected number of backorder</td>
<td>0.0235</td>
<td>0.0038</td>
<td>0.0124</td>
<td>0.0473</td>
<td>0.0473</td>
<td>0.0473</td>
<td>0.0473</td>
<td>0.0209</td>
</tr>
<tr>
<td>Supply availability</td>
<td>97.67%</td>
<td>99.92%</td>
<td>98.77%</td>
<td>96.71%</td>
<td>95.37%</td>
<td>95.37%</td>
<td>95.37%</td>
<td>97.93%</td>
</tr>
</tbody>
</table>

In the remainder of this section, we step by step elaborate on all the different models, and compare the models and strategies with the current practice. Section 6.3.1 elaborates on the item approach and Section 6.3.2 on the system approach. Section 6.3.3. elaborates on the model with criticality included. Section 6.3.4 elaborates on the model with batching included. Section 6.3.5 and 6.3.6
discuss the model with different service level measures, respectively expected number of backorders and supply availability.

### 6.3.1 Item approach

We start with the simplest alternative for determining the spare parts stock levels for the critical parts packages, which is the item approach. In the item approach, targets are set per article and stock levels are calculated per article separately. The target service level is set in terms of fill rate per article \( \beta_i^{obj} \) for every \( i \in I \). Since the aggregate fill rate in the As-Is situation is 97.98%, the target level per article is first set to the same level. The third column in Table 4 summarizes the results (Item Approach (I)).

Note that the aggregate fill rate ends up to be higher than the article target fill rate of 97.98%. One achieves an aggregate fill rate of 99.46% with an investment of €20,875.04 in spares. Both the expected number of backorders \( (EBO(S)) \) and the supply availability \( (A(S)) \) improve significantly.

For a fair comparison, we however need to achieve an aggregate fill rate that is closer to the 97.98% of the As-Is situation. If we set the article fill rate objective to 94%, we achieve an aggregate fill rate of 98.10%. This package can be better compared with the As-Is situation. This is shown in column 4 of Table 4. We can conclude that the item approach with the aggregate fill rate as the target service level measure results in a package with approximately the same costs. However, the expected number of backorders and supply availability are improved.

The improvements are achieved because the item approach lowers base stock levels that have 100% fill rate in the As-Is situation, while it increases stock levels that have a low article fill rate. In the As-Is situation, as aforementioned, experts recommend their customers to have 10 blade holdings and 10 spring pressures on stock, resulting in an article fill rate of approximately 100%. The item approach lowers the base stock levels for the blade holding and spring pressure to two and one, respectively. This results in article fill rates of 98%. This saves the customer approximately €200.-. With that savings, the item approach is able to increase the stock level of a switch pull that costs €120.-, resulting in an increase of the article fill rate from 93% to 99.8%.

Concluding, the item approach is already an improvement as compared to the As-Is situation.

### 6.3.2 System approach

The second alternative that we consider is the system approach. A system target is set and the goal is to find a combination of stock levels that minimize costs subject to a system target constraint. We use the aggregate fill rate \( (\beta(S)^{obj}) \) as target constraint. Since the aggregate fill rate in the As-Is situation is 97,98%, the target level per part is set to the same level. Column 5 of Table 4 summarizes the results.

As one can see, a high aggregate fill rate of 98.01% can be achieved with significant lower costs of €8,720.25, resulting in a cost savings of €11,167.09 as compared to the current situation. At first glance, this leads to very positive reactions by the service employees. However, a closer look into the results learns us that the EBO is doubled in this situation. This might indicate that the service
level constraint regarding the fill rate is not a very good one. We discuss that in more detail in section 6.3.5.

Moreover, we implicitly assume that all the B-parts are equally important is this model. As we already discussed that this assumption is not valid. We therefore extend the model with a criticality factor in the next section. We cannot yet state that we can achieve the same service level with half of the investment costs, because the assumption of articles being equally critical is not justified. However, we can see that there definitely is quite some improvement possible in theory.

Figure 12 graphically presents the approaches discussed so far. The current situation is near the optimal line when using the item approach. By definition, the system approach is more beneficial when prices from spare parts differ. For this case study, the system approach turns out to be very interesting to use for MP.

6.3.3 Criticality extension
As aforementioned in Section 1.3.3, B-parts are not always equally critical. Some parts only affect the performance of the equipment when they break down, whereas others lead to downtime of the whole machine. This is also why the costs savings that we see in Section 6.3.2 might be a bit less in reality.

We propose two different approaches to differentiate based on criticality as explained in Section 6.1.5. As it turns out, including these criticality extensions does only lead to minor differences in the packages and the associated costs. This is shown in column 6 and 7 of Table 4. This might indicate that the differences in weights that we attach to the different criticality categories are too low. For now, we conclude that this solution does not fit the needs for MP regarding criticality inclusions.

6.3.4 Batching
We would like to test what effect the inclusion of batching into the model has on the outcome. Unfortunately, this case study does not give the opportunity to test because it only contains one B-part for which MP only delivers in batches. We however expect that this feature does not ever affect
the outcome, since the prices of the items with a batch size are relatively cheap. Further analyses of the B-parts also show that only few very cheap parts are delivered in batch sizes. Due to the increase of complexity of the model, and the small amount of B-parts that are delivered in B-parts, we can already conclude that the batching extension is probably not very interesting for MP.

6.3.5 Expected number of backorder

We see that quite some improvements can be achieved when considering the aggregate fill rate as service level measure. However, we also know that the aggregate fill rate is not always the best service level measure, especially when the lead times differ significantly. We see in Table 4 that although the investment costs for spare are halves when optimizing with the aggregate fill rate as service level measure, the expected number of backorder is doubled. Therefore we investigate the alternative model with the expected number of backorder as service level measure.

Figure 13 shows the relationship between package costs and expected number of backorders, when optimizing with expected number of backorder as service level constraint. It shows that the current situation does not lay on the blue line, indicating that there is room for significant improvement in the spare part packages. This can also be seen in Table 4. MP is theoretically able to generate packages that achieve the same expected number of backorder with less than half of the packages costs.

If we take a closer look at the individual stock levels, we see that there are minor differences with the package that is generated when optimizing with aggregate fill rate as service level measure. The base stock level of the circuit break-mini for example (see Appendix D), that has a lead time of 32 days, changes. When optimizing with the aggregate fill rate as service level measure, the circuit break-mini is not recommended. In contrast, it is recommended to keep on stock when optimizing with the expected number of backorders.

Furthermore, we see that the cost saving is a bit less as compared to the situation with aggregate fill rate as service level measure.

Figure 13: Expected Number of Backorders Marel Poultry
6.3.6 Supply availability

As stated earlier, the constraint on the supply availability is closely related to the expected number of backorder constraint. Figure 14 shows the relationship between package costs and the supply availability of B-parts. It indicates that one is able to achieve a higher availability with the same package costs. The supply availability, in addition, is way more understandable for both the customer as well as MP service employees.

![Supply Availability B-parts](image)

**Figure 14: Supply Availability B-parts Marel Poultry**

6.4 Validation and verification

This section describes the verification and validation of the model in Section 6.4.1 and 6.4.2, respectively. Verification ensures the correctness of the model. Validation tests whether the model fits with real-life.

6.4.1 Verification

The model is verified in different ways during and after its development and programming. First, we used a very small test instance that is also considered in Kranenburg & Van Houtum (2015), p. 21 to illustrate different spare part optimization models. They considered a single warehouse that supports a reasonably large number of installed machines. All spare parts are fulfilled from that warehouse. They consider three different stock keeping units (SKU’s). The average failure rate per year ($m_1$) is 15 for SKU 1, 5 for SKU 2 ($m_2 = 5$) and 1 for SKU 3 ($m_3 = 1$). The average lead times are equal to 2 months for all SKU’s. The prices of SKU 1, 2 and 3 are 1,000, 3,000 and 20,000 euros respectively. They obtained an optimal solution of Problem $P_3$ with $EBO(S) \leq 0.1$. That leads to a solution $S = (6,2,1)$, with $EBO(S) = 0.098$ and $C(S) = 32,000$ euros. When analyzing the optimal solution, we come up with exactly the same results.

Next, we verify our model by logical reasoning. We adjust the input parameters and check whether the model leads to the change in solution that we expect. Finally, we further verify these model
adjustments by applying extreme parameter settings. The output of the model on these extreme parameter settings is also checked with logic reasoning. This all lead to logical results.

### 6.4.2 Validation

Gass (1983) describes several aspects of validation: Model validity, Data validity, logical validity and operational validity. Model validity and logical validity are tested comprehensively when setting up the case study. We elaborate on the data- and operational validity in this section.

Data validity ensures that the data necessary for the model experiments is accurate and correct (Sargent, 1996). To avoid incorrect and inadequate conclusions, we validate the estimates for the failures rates. One of MP's customers stores data about its replacements. This data gives us information about average failure rates of B-parts, and is used to see whether there are huge differences in the estimated failure rates and the data. This turned out not to be the case. However, the data from this customer cannot represent the average over all customers, because they do not always execute preventive replacements according to the schedules. This is affecting the number of corrective replacements needed. Moreover, expected failure rates depend highly on the way customers clean its machines. However, it is interesting to investigate the deviation from the failure rates as estimated by experts.

Models are unable to totally reproduce or predict the real environment. We check whether the model is realistic enough to generate realistic spare part packages with the operational validity step. The packages that are being generated by the models are discussed with the equipment experts. It turns out that the model generates reasonable packages. However, it also turns out that the model is not able to deal with some features of the packages. Certain drives, for example, should always be stocked with certain bolds. These bolds are used to install the drive.

Moreover, the package should contain more parts that are very crucial. The pairwise comparisons as we did with the bearing-ball groove and the blade-holding purely based on service level is not realistic, since criticality is often different. As discussed, we are able to include the criticality level in the model. MP should, however, reconsider the criticality determination and criticality level again. We address the criticality extensions in Chapter 10 again.

Additionally, customers want to stock higher indenture levels because of faster replacements. These higher indenture B-parts are excluded in the model for now. We elaborate on these higher indenture parts in Chapter 9.

### 6.5 Sensitivity analyses

This paragraph discusses the sensitivity analyses. We only analyze the failure rate ($m_i$). No analysis is performed on the other input parameters because there is little uncertainty.

We test the sensitivity of the failure rate per article in two ways. First, by taking different percentages of the failure rates that we take in the original case study, namely 50, 75, 100, 125 and 150. If we then run the greedy algorithm with the $\beta^{obj}(\mathcal{S}) \geq 97.98$, which is the aggregate fill rate that is achieved in the current situation, we find that the spare part levels do not change very much.
The costs of the package to achieve the same service level are higher, but the differences are small. This is illustrated in Table 5.

Table 5: Sensitivity Average Failure Rate

<table>
<thead>
<tr>
<th>Percentage of original failure rate</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
<th>125%</th>
<th>150%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package Costs</td>
<td>€ 8,343.57</td>
<td>€ 8,489.77</td>
<td>€ 8,720.25</td>
<td>€ 8,865.93</td>
<td>€ 9,247.93</td>
</tr>
</tbody>
</table>

Next, we vary each demand rate with a random number. We assign a random variation of -50% to +50% to each demand. The results are shown in Table 6. It shows that the package costs differ between € 8,341.04 and € 9,436.30. It is, however, interesting to see that the spare part packages that are generated do not differ very much from each other. Concluding, the model seems to be not very sensitive to changes in average failure rate. This is probably due to the fact that the average failure rate is that low in this case, and the lead times that short, that the demand during lead time is almost negligible and the greedy algorithm selects the part primarily on price.

On average, 0.53 articles are stocked for every article that is installed on the machine. Whenever we double the failure rate per article, only 0.54 articles are stocked. An 100% increase in failure rate does not hardly influence the stock that is kept for that article. This validates the above conclusion.

Table 6: Sensitivity Average Failure Rate

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
</table>

We obtain average failure rates for our model by asking experts for their best estimates. If MP wants to implement this spare part model to generate its packages, it has to estimate the failure rates of all B-parts. This is quite an exhaustive task. Therefore there is an idea put forward to only distinguish a certain amount of different failure rate categories. This would make the process of estimating the failure rates less time consuming. We investigate what different packages our model would generate if we only use 3 different categories for failure rate. The parts are categorized according to Table 7.

Table 7: Categorization failure rates

<table>
<thead>
<tr>
<th>Original $m_i$</th>
<th>Category $m_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_i &lt; 1$</td>
<td>0.5</td>
</tr>
<tr>
<td>$1 \leq m_i &lt; 3$</td>
<td>2</td>
</tr>
<tr>
<td>$3 \leq m_i$</td>
<td>4</td>
</tr>
</tbody>
</table>

It turns out that we achieve the same aggregate fill rate with an investment in spare parts of €9,296.46. Again, we see that the spare part package that is generated is quite the same as the package generated with the original average failure rate value. 87% of the stock levels are kept on the same level. The other are only increased or decreased by one unit. MP should make the tradeoff
between the time necessary for failure rate determinations and the quality of the spare part package.

6.6 Conclusions
We can conclude from this case study that there is quite some improvement possible for MP in generating spare part packages. In all the models that we analyzed, we see that, theoretically, the investment costs can be halved while achieving similar service levels. A big step forward can be made when using the system perspective instead of the item perspective. Experts at MP agree that they always used the item perspective to come up with stock levels per item (article) separately. There are quite some expensive spare part that only fail once in 20 years, and have a short replenishment lead time. The experts agree that these parts can be excluded to decrease the investment costs for clients. They trust the outcome of the models. Experts also agree that even the simplest model, the item approach, gives better packages than the current way of working. The example with the blade-holding and bearing-ball groove is discussed with experts. They agree that stock levels that they give are not optimal, considering the failure rates, lead times and prices of the parts.

We also note during the sessions with the experts that due to the differentiation among lead time for customers, the aggregate fill rate does not give the best spare part packages. The expected number of backorders might be a better measure. That service measure is however quite hard to understand for both customers and MP employees. The service level closely related to the expected number of backorder, the supply availability, seems to be most appropriate because of its understandability. It should however be emphasized that the availability service measure that we are working with only calculated the time that all the B-parts that are needed are available. It therefore differs from operational availability.

However, they also argue that there is still some improvement necessary. In particular, the criticality extension that we propose is not adequate. Service employees all propose different parameter about how to set the criticality level. We further come back on that in Chapter 10.

Concluding, the multi-item approach including the criticality extension, optimizing with the supply availability seems to be the best model. But, there is still a challenge to come up with a better way of including criticality in the model.
Chapter 7

Case study at other Marel industries

Although the project is initialized by Marel Poultry, other industries are also interested in the model. Moreover, Marel aims to be aligned in the service products they offer to its customers with all the Marel industries. Therefore, the global service department of Marel was involved in the project as well.

This gives us the opportunity to test the model also for business cases from Marel Meat, Marel Further Processing and Marel Cross Industry Equipment, and see whether we draw the same conclusion for the other industries as we do in Chapter 6. Section 7.1, Section 7.2 and Section 7.3 present the case from Marel Meat, Marel Further Processing and Marel Cross Industry, respectively. Since we discussed the different models for generating the spare parts packages extensively in Chapter 6, we only show the most important results per case study and identify similarities between the studies in Section 7.4. We only elaborate on the multi-item single location model optimizing with the supply availability constraint. This because the supply availability turned out to be the most appropriate service level measure in Chapter 6. The criticality extension is not taken into consideration here, since it turns out the proposed methods do not work in Chapter 6. Moreover, the case studies also do not contain B-parts that are delivered in batch sizes, so we again are not able to test the batching extension.

7.1 Marel Meat

Marel Meat (MM) is the leading global supplier of advanced stand-alone processing equipment and integrated systems to the red meat industry. It develops and supports equipment for all stages of the meat processing value chain, covering the stages from carcasses or product intake to dispatch. MM provided us with a case of four conveyorized skinners. It removes skin from a variety of flat beef and pork products.

Figure 15: Conveyorized skinners
MM also sets the spare part levels manually. This is done by experts that know the characteristics of the machine and its B-parts by hard. We analyze the package that is being sold along with the 4 conveyorized skinners. The results are summarized in Table 8.

Table 8 shows the different alternatives. It is set up just as Table 5 is for the Poultry case. In line with the Poultry case, we see that the current situation results in more or less the same results as the item perspective does. However, one can again obtain better spare part packages by using the system approach. The models with the criticality extension do not affect the packages. The batching extension also does not give a difference. Figure 16 graphically shows the room for improvement by using the system approach instead of the item approach.

Table 8: Different models implemented at Marel Meat

<table>
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<tr>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>99.61%</td>
<td>99.93%</td>
<td>99.61%</td>
<td>99.63%</td>
<td>99.63%</td>
<td>99.63%</td>
<td>99.57%</td>
<td>99.57%</td>
</tr>
<tr>
<td>Expected number of backorder</td>
<td>0.0026</td>
<td>0.00014</td>
<td>0.0011</td>
<td>0.0022</td>
<td>0.0023</td>
<td>0.0022</td>
<td>0.0022</td>
</tr>
<tr>
<td>Supply availability</td>
<td>99.74%</td>
<td>99.99%</td>
<td>99.89%</td>
<td>99.78%</td>
<td>99.77%</td>
<td>99.78%</td>
<td>99.78%</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Total Costs</th>
<th>€ 9,273.30</th>
<th>€11,021.80</th>
<th>€9,100.90</th>
<th>€6,570.28</th>
<th>€6,566.68</th>
<th>€6,570.28</th>
<th>€6,570.28</th>
<th>€6,433.85</th>
<th>€6,433.85</th>
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<tr>
<td>Aggregate Fill rate</td>
<td>99.61%</td>
<td>99.93%</td>
<td>99.61%</td>
<td>99.63%</td>
<td>99.63%</td>
<td>99.63%</td>
<td>99.57%</td>
<td>99.57%</td>
<td></td>
</tr>
<tr>
<td>Expected number of backorder</td>
<td>0.0026</td>
<td>0.00014</td>
<td>0.0011</td>
<td>0.0022</td>
<td>0.0023</td>
<td>0.0022</td>
<td>0.0022</td>
<td>0.0026</td>
<td>0.0026</td>
</tr>
<tr>
<td>Supply availability</td>
<td>99.74%</td>
<td>99.99%</td>
<td>99.89%</td>
<td>99.78%</td>
<td>99.77%</td>
<td>99.78%</td>
<td>99.78%</td>
<td>99.74%</td>
<td>99.74%</td>
</tr>
</tbody>
</table>

Figure 16: Situation at Marel Meat

We discuss the package that the model generates with product experts in order to see to what extent the theoretical costs increase that the model suggests is realistic. They argue that the
package that the model generates is better than the package generated with the current way of working. Nowadays for example, MM recommends keeping 2 roller-tooth with a sales price of €1,355.00 on stock (see Appendix F). The multi-item model only recommends 1, which saves the customer quite some money by achieving availability of over 95%. Moreover, the model decreases the stock level of a bearing ball groove from 20 to 3. The experts agree that 20 is way too many and 3 is enough. This already results in quite some costs savings for the customer. With that costs savings, it is able to stock 2 regulator-pressures instead of 1. This increases the service level significantly because the replenishment lead time for that part is almost a month. However, the experts argue that this part is less critical for the machine as compared to other parts, because it does not result in a complete break down when it fails. Concluding this case, we can state that the outcomes of this case study are in line with the MP cases: There are quite some improvements possible when using the system approach. We however need to think about better ways to take the article criticality into consideration.

7.2 Marel Further Processing

Marel Further Processing (MFP) concentrates on equipment for the further processing of white meat, red meat, fish, potatoes, vegetables as well as meat substitutes. MFP provides us with a case of the revoportioner. It portions products at low pressure, which retain the texture and structure of the raw material.

Marel Further Processing offers its customers 3 different packages, a small, medium and large one. The customer can decide what package it prefers. We analyze them all. The results can be seen in Table 9. Considering the current situation, the increase in service levels relative to the increase in spare part investment for the customer is high if one goes from a small package to a medium package. Next, the increase in service level relative to the extra investment of spares is lower if one buys the large package instead of the medium package. This seems reasonable.

It is interesting to note that we need to invest half of the prices in spares to achieve the same aggregate fill rate as the large package, but we only need to invest one fourth of the price in spares to achieve the same supply availability. This indicates that there is quite some difference when optimizing with different service levels. We also found in Chapter 6 that the aggregate fill rate is not the best service level, but the difference was not this big. The difference in outcomes when optimizing with aggregate fill rate or expected number of backorders is much bigger than in the other case studies. This is because many parts in the FP case study are not on stock at a Marel warehouse, and therefore the lead time differentiation in this case study is relatively high. This can also be seen in Appendix F.
Table 9: Different models implemented at Marel Further Processing

<table>
<thead>
<tr>
<th>Total Costs</th>
<th>€ 1,255.00</th>
<th>€ 5,471.14</th>
<th>€ 22,383.08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fill rate</td>
<td>34.20%</td>
<td>70.00%</td>
<td>98.77%</td>
</tr>
<tr>
<td>Expected</td>
<td>0.47</td>
<td>0.28</td>
<td>0.04</td>
</tr>
<tr>
<td>number of</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>backorder</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply</td>
<td>62.61%</td>
<td>75.57%</td>
<td>96.17%</td>
</tr>
<tr>
<td>availability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply</td>
<td>99.00%</td>
<td>99.00%</td>
<td>99.00%</td>
</tr>
<tr>
<td>Availability</td>
<td>93.13%</td>
<td>96.22%</td>
<td>96.33%</td>
</tr>
</tbody>
</table>

As we can see in Table 9, we are able to achieve the same supply availability as the large package with less than one-fourth of the price. This huge costs saving in achieved by not stocking the expensive parts. The machine contains 6 B-parts that costs more than €1,000. These are all stocked in the current situation. The model however does not choose to stock a single one of these parts. The model does choose to stock quite a lot of the cheap screws, pins and coupling-shafts. This results in the same supply availability. We discuss the package that the tool generates with product experts in order to see to what extend the theoretical costs decrease that the model suggests in realistic. They argue that the package the model generates is quite a good one. It should however definitely include the criticality extension. The expensive parts are in general way more critical than the screws, pins and coupling shafts.

7.3 Marel Cross Industry

In addition to all the industry specific equipment, there is equipment that is used for different industries. We also analyze a case for the I-cut machine. It is designed for cutting boneless, non-frozen products to fixed weight and/or uniform dimensions. Marel Cross Industry also offers its customers 3 different packages. We analyze them all in Table 10.
Table 10: Different models implemented at Marel Cross Industry

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Costs</td>
<td>€7,876.70</td>
<td>€12,094.90</td>
<td>€31,319.90</td>
<td>€36,714.45</td>
<td>€28,569.90</td>
<td>€36,724.45</td>
<td>€28,927.80</td>
<td>€29,238.80</td>
<td>€29,238.80</td>
<td>€29,238.80</td>
<td>€29,238.80</td>
</tr>
<tr>
<td>Expected number of backorders</td>
<td>0.027</td>
<td>0.0075</td>
<td>0.0024</td>
<td>0.00041</td>
<td>0.00025</td>
<td>0.000064</td>
<td>0.000064</td>
<td>0.000064</td>
<td>0.000091</td>
<td>0.000091</td>
<td></td>
</tr>
</tbody>
</table>

Figure 20 graphically presents the frontier of efficient packages in terms of package costs and supply availability. Theoretically, the same supply availability can be achieved with €2,500.00 less investment costs for the critical parts package. As can be seen in Appendix G, there is this drum motor installed that costs €2,750.00. The drum motor is recommended twice in the large package, which does not affect the supply availability very much. The model does only recommend this drum motor once, but increases the base stock level of other items instead. Product experts agree that recommending two drum motors does not make sense, and the model generates better packages.

Figure 20: Situation at Marel Cross Industry

7.4 Conclusions

All the cases that we analyzed in this chapter show that non-efficient packages are generated with the current way of working and better packages can be generated using the system approach. Note that the savings that can be achieved are very big for the Poultry case (52%), and less for the Meat (31%) and Cross Industry case (8%). The main reason behind that difference is the amount of unique B-parts in the orders. Poultry contain 142 B-parts, whereas Meat and Cross Industry only contain 47 and 28 respectively. The increase in the Further Processing case (78%) is even higher, due to the high differentiation in lead times. The real improvements are lower than the graphs and tables suggest in reality. This is again because the criticality level should be included in a good way. This would be the biggest step forward to eventually come up with a more realistic critical parts package. We further elaborate on that in Chapter 10.
Chapter 8

Implementation

This chapter describes the development of the decision support tool, which is part of the implementations step in the regulative cycle shown in Figure 7. We first explain the tool itself in Section 8.1. For a more extensive explanation of the tool, we refer to the tool manual in Appendix H. Next, in Section 9.2 we state which actions need to be performed to be able to fully implement the tool in the MP organization.

8.1 Decision support tool

The models and algorithms that we address in Chapter 4 and 5 are programmed in Microsoft Excel Visual Basic⁴. It can be used to generate spare part packages whenever new equipment is sold. Service engineers are able to generate the packages with the different alternative models in one mouse click. The main goal of this decision support tool is to further experiment with the different models and strategies.

The packages can be generated based on customer requirements regarding service levels. The tool contains four different case studies in the first four sheets. All the data needed to perform the analysis and optimizations are loaded already. Furthermore, the tool is able to analyze any case that one wants to analyze. However, service employees then need to gather and load the necessary input parameters manually. The Bill of Material can be loaded from the product lifecycle management system (PLM), and other input parameters can be loaded from the SAP ERP system.

Service engineers can experiment with the different models, service level measures and extensions to see what model generates the best packages in their opinion. One only has to fill in the picking and packing time and the shipment time needed for the order. One can also fill in the downtime costs for that customer to get an idea about costs incurred when not stocking certain parts.

By using the first green column(s) of the sheets, one is able to analyze the package that is generated using the current way of working by clicking the analyze button. When one clicks the “Determine

⁴ The decision support tool that is referred to this report is DecisionSupportTool.xlsm
Package” underneath one of the red columns, one is able to generate packages according to the different models that are proposed in Chapter 4 and 5. Figure 21 shows a screenshot of the tool.

![Figure 21: Screenshot of decision support tool](image)

### 8.2 Actions to be performed during implementation

The service leadership team decided that the critical parts packages should be determine according to one of the multi-item spare parts packages that we propose. However, before the models are fully implemented in the MP organization, there are quite some actions to be performed.

First, the new way of working should be proposed to all service employees on all levels in the organization. The main idea of the model should be explained. It has to be explained clearly that in the system approach the focus is on a service level for the system as a whole, rather than on a service level per item. Subsequently, the service engineers need to work with the decision support tool to experiment with the different models and to get trust in the outcome of the tool. The manual (see Appendix H) should be given to the users. Next, one should aim to improve the model, and to formulate next steps to generate better packages. The issues that we encountered in the case studies in Chapter 6 and 7 should be reconsidered. Subsequently, the service department has to plan sessions with the sales department to get a better understanding about what is discussed with customers, and what the customer should see. One should eventually come up with tool requirements. MP also has to think about the best ways to gather valid input data for the model. The failure rate should be estimated by service engineering initially. MP should however think about a system with which it is able to gather demand data for spare parts in a more consistent way. We come back on how to gather the right input data in Chapter 10. Lastly, the eventual tool has to be developed. This tool should make it possible for MP to tune critical parts packages upon the customer needs. Moreover, the tool should enables sales and service people to prove to the customer that the critical parts package provides added value to his operation.
Chapter 9

Line Replaceable Unit Problem

In addition to the parts that fail, some customers are also interested in stocking parts for faster or easier replacements. We consider introducing an extra category, which consists of all parts that may be kept on stock because of the faster or easier replacement. These parts could be denoted as R-parts. In this chapter, we investigate whether the introduction of the R-parts would be beneficial and whether MP should invest in more research for a better understanding on how to determine the right R-parts stock levels.

The need for R-parts is customer specific, depending on the need for fast and easy replacements. Literature refers to this problem as the Line Replaceable Unit (LRU) problem, see e.g. Parada Puig & Basten (2015). The authors consider the decision to be part of the strategic or tactical maintenance planning. “The exchange of LRUs produces downtime, and therefore the selection of items that should be defined as LRUs is a critical decision. Downtime can be compensated for with spare assets, and this means that the LRU decision should be considered from the outset of a capital asset acquisition program” (Parada Puig & Basten, p.2). We do not think this is true in general. Considering the situation at MP, customers determine their LRUs also depending on the budget for spare parts. The LRU decision is made with the spare part stock levels simultaneously, and is customer specific. In that sense, the LRU decision cannot be regarded as a strategic decision.

We have made an assumption about the LRU indenture level in Chapter 4. We have assumed all B-parts to be LRU. This assumption resulted in a single-indenture model. In reality, B-parts are not always the LRU. Failed B-parts are sometimes replaced by replacing a legend one indenture level higher. The reason to do this is because the legend has a shorter replacement time: Replacing a legend upon failure of one of its underlying articles results in higher operational availability for the customer.

MP’s machines usually contain several identical items that perform the same operation simultaneously. This can for example be seen in Figure 22, 23 and 24. There are several units
(Figure 23) installed on the machine in Figure 22. We investigate whether it makes sense to stock the units, i.e. code these units as R-parts. While we know that machines generally consist of more than two indenture levels, we only consider two indentures in this chapter, being the articles at the lowest indenture level and the legends one indenture level higher in this chapter. The legends are called units in the remainder of this chapter.

The decision on which indenture level to replace is taken implicitly in the existing models in literature. In this chapter, we investigate the LRU definition and include that into the model. We then have to come up with a multi-indenture model. Traditionally, non-economic criteria are used to define LRUs. Although the non-economic criteria are of key importance, inclusion of economic criteria can lead to a more cost-effective LRU definition. This is already shown by Parada Puig & Basten (2015). The aim of this chapter is to take a further step in that direction. Section 9.1 presents the model that enables us to analyze the LRU problem. In Section 9.2, we present the evaluation procedure. In Section 9.3, we present a method to investigate optimal LRU definitions. Section 9.4 describes a case study performed at MP, and Section 9.5 finally gives a conclusion.

### 9.1 Model

We use the same notations as we did in Chapter 4 and 5 and stick to the assumptions that we made earlier. We only consider the customer location in the model. We also only consider one machine at a customer location. We assume that the machine is only up and running whenever all items are installed and working properly. As aforementioned, we only consider a two-indenture model. However, in contrast to what we assume in Chapter 4, we now assume that there is no commonality.

System availability is widely used as a performance measure for capital equipment. Almost all inventory models assume that operational availability is equivalent to spare part availability. We now define operational availability as the percentage of time that the equipment is up and running when one wants it to be, mathematically presented as follows:

\[
A_i = \frac{MTBF_i}{MTBF_i + MTR_i} \tag{9.1}
\]
Where, in a repairable system, the uptime is defined by MTBF; (mean time between failures), and the downtime is defined by MTTR; (mean time to repair). Furthermore, the operational availability of item $i$ is defined by $A_i$. Note that we implicitly assume that there is no operational unavailability due to preventive maintenance.

A machine consists of multiple critical parts, which are subject to failures. When a machine fails, then this is first observed at the LRU level. Later on, when the LRU is repaired, one can identify which one of the legends was the cause of the failure. Where set $I$ only consisted of articles in Chapter 4 and 5, we now let $I$ be the total set of articles as well as the units (legends) they occur in. We refer to the total set of $I$ as items, and the number of items is $|I|$. For notational convenience, the items are numbered $i = 1, 2, ..., |I|$. Let $m_i$ be the individual failure rate of item $i \in I$. Let $C(i)$ be the subset of items that are direct descendants (one indenture level lower) of item $i \in I$ that is installed on the machine. Notice that $C(i) = \emptyset$ if item $i$ is an article.

We now describe the operational process, which involves the failures, replacements and repairs of parts. Whenever a failure of an article is noticed, the article itself or a unit that contains the article should be replaced. We assume that the replacement time for item $i$ is deterministic and given by $t_i^{rep}$. This is the total time from the moment an item fails until the moment that it is working properly again. Whenever an article is replaced, it is reordered at MP. The replenishment lead time of item $i$ is assumed to be deterministic and given by $t_i^{res}$. If a unit is replaced, it is repaired by replacing the failed underlying article. The repair lead times for those units may be stochastic, depending on the stock levels of its children. The operational process depends on the LRU definition. The process when the lowest indenture is defined as LRU is given in Figure 25, and the process when the higher indenture level is defined in Figure 26.

![Figure 25: Operational process LRU on low indenture level](image1)

![Figure 26: Operational process LRU on high indenture level](image2)
The mean time to repair plays an important role in determining the equipment availability. The equipment availability primarily depends on two factors: the repair time and the spare part stock level. As aforementioned, equipment availability is jointly determined by spare part inventory and the LRU definition. Besides the base stock level that we already had in Chapter 4 and 5, we need to introduce another decision variable for the LRU definition:

\[ R_i = \begin{cases} 1, & \text{if component } i \in I \text{ is defined as LRU} \\ 0, & \text{otherwise} \end{cases} \]

The subset of items that are defined as LRU, \( I^{LRU} = \{ i \in I | R_i = 1 \} \).

By assuming that not more than one LRU is broken simultaneously, the system availability can be determined as follows:

\[ A = \prod_{i \in I^{LRU}} A_i \]

The objective is to minimize the total investment in spares subject to an operational availability constraint. We can state the optimization model in mathematical terms as follows:

\[
(P_6) \quad \text{Minimize} \quad \sum_{i \in I} S_i c_i \\
\text{Subject to:} \quad A(S, R) \geq A^{obj}
\]

Where \( S_i \) is the base stock level of item \( i, c_i > 0 \) is the costs of item \( i, S \) is the vector containing the recommended stock levels for all items, i.e., \( S = (S_1, ..., S_{|I|}) \). \( R \) is a vector containing the decision whether an item is defined as LRU for all items, i.e., \( R = (R_1, ..., R_{|I|}) \). \( A^{obj} \) is the equipment availability objective.

### 9.2 Evaluation

In this section, we evaluate the steady-state behavior and the supply availability. Recall that \( m_i \) is the individual failure rate of item \( i \in I \). Let \( \lambda_i \) be the total failure rate of item \( i \in I \). \( \lambda_i \) is the sum of the total failure rates of those child items \( j \in C(i) \). \( \lambda_i \) can be calculated as follow, and can be used to calculate the total failure rate at every indenture level in the product structure:

\[ \lambda_i = m_i + \sum_{j \in C(i)} \lambda_j (1 - R_j) \]

The mean time between failure of item \( i \) (MTBF\(_i\)) is calculated using the total demand rate of item \( i \) (\( \lambda_i \)) in the following way:

\[ MTBF_i = \frac{1}{\lambda_i} \tag{9.2} \]

Note that this is an approximation of the MTBF, because we implicitly assume that there is no time to repair in this equation.
between two successive failures is a bit shorter than 0.5 years. The total time that item \( i \) is in repair is very small, and Equation (9.2) is therefore a good approximation.

We also need to address the determination of the mean time to repair of item \( i \) (\( MTTR_i \)). It depends on the repair time and the spare part stock level as follows:

\[
MTTR_i = t_i^{rep} + W_i
\]

(9.3)

Where \( t_i^{rep} \) is the parameter for the mean time to repair for item \( i \), and \( W_i \) the mean waiting time. This can be calculated from the expected number of backorder (\( E\{BO_i\} \)) and the total failure rate by Little’s Law:

\[
W_i = \frac{E\{BO_i\}}{\lambda_i}
\]

(9.4)

Further, we need to compute the pipeline and backorder distributions. We compute the distribution of the number of backorder \( BO_i \) of a part \( i \) by the following equation (see, e.g. Van Houtum & Kranenburg, 2015):

\[
P\{BO_i = x\} = \begin{cases} 
\sum_{y=0}^{S_i} P\{X_i = y\} & \text{if } x = 0 \\
\sum_{y=0}^{S_i} P\{X_i = y\} & \text{if } x > 0 
\end{cases}
\]

(9.5)

Next, we elaborate on the procedure to determine pipeline and backorder distributions. By Equation (9.5), we can compute the backorder distribution from the pipeline distribution of that part. However, the distribution of the pipeline stock of item \( i \) depends on the backorder distribution of item \( j \in C(i) \). Each failed part has a deterministic repair lead time \( t_i^{rep} \), but the start of this deterministic repair lead time may be delayed because an underlying part is required for the repair while that part is not immediately available. The total pipeline stock can be computed as follows:

\[
X_i(t) = \text{items in repair that arrived in the interval } (t - t_i^{rep}, t) \\
+ \sum_{j \in C(i)} [\text{items in repair that arrived prior to } (t - t_i^{rep}) \text{ and which are waiting for a backorder item of item } j \text{ at time } t - t_i^{rep}] 
\]

Now let random variable \( Y_0 \) be the number of items \( i \) sent into repair during the repair lead time. Let \( Y_j^i, j \in C(i) \), be the number of items that are waiting to be repaired because of a backorder of an underlying item \( j \) at an arbitrary time. \( Y_0 \) is a Poisson distributed random variable with parameter \( \lambda_i t_i^{res} \) and \( Y_j^i \) is a random variable with mean \( \lambda_j t_j^{res} \). \( Y_0 \) is independent of \( Y_j^i, j \in C(i) \), because of the non-overlapping time interval and the fact that Poisson processes have independent increments. Furthermore, note that \( Y_j, j \in C(i) \), are independent of each other. We can come up with the following steady state expression for the pipeline stock.

\[
X_i = Y_0 + \sum_{j \in C(i)} Y_j^i 
\]

(9.6)

For a more extensive Proof of Equation (9.6), we refer to Lemma 7.3. in the book of Van Houtum & Kranenburg (2015, p. 170).
9.3 Optimization

In finding the best LRU definition for this problem, we first fix the LRU decision by setting the $R_i$ values for all items. We then optimize the operational availability at different costs levels for spares. This optimization procedure differs depending on whether we set articles or the unit as LRU. Therefore, this section is split into two sections. Section 9.3.1 describes the procedure when the lowest indenture (article) is chosen as LRU level. Section 9.3.2 describes the procedure when the higher indenture (unit) is chosen as LRU level.

9.3.1 Lowest indenture LRU assumption

At first glance, we are not able to solve this LRU problem by the greedy algorithm, because Problem $P_6$ is not item separable. However, note that for sufficiently large objective values for operational availability, we can come up with quite a good approximation for the availability.

The equipment unavailability can be approximated by the sum of the unavailability of all of its LRU's, and so the equipment availability can be approximated as follows:

$$\prod_{i \in LRU} A_i \approx 1 - \sum_{i \in LRU} (1 - A_i) \quad (9.7)$$

When adapting Problem $P_6$ with Equation (9.7), the problem becomes item separable. Moreover, the problem needs to be increasing and concave. Recall from Chapter 5 that the expected number of backorder is proven to be decreasing and convex. By Equation (9.3) and (9.4), we can see that MTTR is also decreasing and convex. Since MTTR is deterministic, it can be easily shown from Equation (9.1) that the operational availability as we defined it is increasing and concave. Therefore, we can use the greedy procedure to solve the problem when assuming the lowest indenture level as LRU.

9.3.2 Highest indenture LRU assumption

Next, we investigate the operational availability curve if we use a level one indenture level higher as LRU. In order to do so, we use the following heuristic. We first fix the base stock level of the legend. We then use the greedy heuristic to achieve the lowest expected number of backorder for its children with the extra investment in spares\(^5\). Then we take the upper envelope of the resulting curves.

We can come up with an upper bound for the number of units to stock. If we assume that no child parts are stocked, the expected replenishment lead time of the unit is:

$$t_{\text{res}}^{\text{unit}} = t_i^{\text{rep}} + \sum_{j \in C(i)} m_j \frac{t_j^{\text{res}}}{M} \quad (9.8)$$

Since the operational availability function is increasing and concave, we can increase the unit stock level one by one and calculate the associated operational availability with the resupply lead time as given in Equation (9.8). The base stock level that achieves that objective is the upper bound for the number of units to stock, $S_i^{UB}$. We enumerate between $S_i = 0$ and $S_i^{UB}$.

\(^5\) It should be mentioned that Basten, van der Heijden & Schutten (2012) prove this approach does not always give efficient solutions. Total enumeration of all the items in a problem is required to find efficient solutions. This is a realistic approach for any but very small problems. Moreover, we think the heuristic we propose should give us close to efficient solutions, which is enough for the analysis of the problem and answering Research Question 4.
9.4 Case study at Marel Poultry

During the analysis phase of the research, we found that both articles as well as units are included in the critical parts packages. In general, articles are recommended because they fail randomly. Units are recommended because they are easier and faster to replace upon failure.

We continue with the case study in Chapter 6, so we consider the AMF-BX breast cap filleting system that was sold to a customer in Slovakia. Apart from all the B-parts on the lowest indenture (article) level, MP also recommends to keep units on stock. The order contains a breast loading module, in which products are fed in a constant flow and placed on infeed unit. The machine contains 13 of these infeed units. MP recommends its customer to keep one unit as a whole on stock as well as its individual underlying articles.

Table 11 gives all the necessary input parameters for this case study. The replacement time is the total time needed to replace a certain part that is installed on the machine. These replacement times are estimated by field service engineers. Since the machine needs to be working until the poultry is processed, the downtime that is faced is independent of the moment a part fails. In this study, we neglect the time necessary to identify the failed part. This assumption is considered to be valid by field service engineers. The other data in the table are already available from the case study performed in Chapter 6.

Table 11: Case study Line replaceable unit Marel Poultry

<table>
<thead>
<tr>
<th>i</th>
<th>Name</th>
<th>Indenture level</th>
<th>Qty</th>
<th>Price€</th>
<th>Replacement time $t_i^{rep}$ (min)</th>
<th>Repair time $t_i^{rep}$ (working days)</th>
<th>Failure rate $\lambda_i$ (in 10 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unit</td>
<td>2</td>
<td>13</td>
<td>€ 1,500.00</td>
<td>20</td>
<td>1/8</td>
<td>109</td>
</tr>
<tr>
<td>2</td>
<td>Block</td>
<td>1</td>
<td>13</td>
<td>€ 200.00</td>
<td>45</td>
<td>1.45</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Spring Pressure</td>
<td>1</td>
<td>13</td>
<td>€ 5.00</td>
<td>30</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Bearing-ball groove</td>
<td>1</td>
<td>13</td>
<td>€ 10.00</td>
<td>30</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Chain-SGL-Conn. Lnk</td>
<td>1</td>
<td>13</td>
<td>€ 5.00</td>
<td>30</td>
<td>1.6</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Spring Pressure</td>
<td>1</td>
<td>13</td>
<td>€ 7.00</td>
<td>10</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Spring Pressure</td>
<td>1</td>
<td>26</td>
<td>€ 3.00</td>
<td>10</td>
<td>0.9</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Presser</td>
<td>1</td>
<td>13</td>
<td>€ 20.00</td>
<td>10</td>
<td>0.9</td>
<td>65</td>
</tr>
<tr>
<td>9</td>
<td>Spring Pressure</td>
<td>1</td>
<td>13</td>
<td>€ 4.00</td>
<td>10</td>
<td>1.6</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>Guide</td>
<td>1</td>
<td>13</td>
<td>€ 190.00</td>
<td>15</td>
<td>2.15</td>
<td>10</td>
</tr>
</tbody>
</table>

As one can see in Table 11, there are 5 parts on the lowest indenture level that are replaced faster than the unit on the higher indenture level ($i = 6,7,8,9$). Whenever these parts break down, service employees do not replace the unit as a whole, but only the broken part. We exclude those parts

---

6 Due to confidentiality reasons, the prices in this version are not correct.
from the study, because it would not make sense at all to replace the unit upon failure of one of these articles. The other 4 parts \((i = 1,2,3,4)\) on the lowest indenture level do have a longer replacement time, so it could make sense to replace the unit upon failure of one of those parts.

First, we generate efficient solutions when assuming that we replace failed articles on indenture level 1 upon failure, i.e. \(R = (0,1,1,1)\). This results in the blue line. The line indicates that a maximum operational availability of 99.9553\% can be achieved when replacing on indenture level 1. This corresponds to a downtime of approximately 75 minutes per year, assuming that one produces 350 days a year and 8 hours a day.

Next, we assume to replace on indenture level 2, i.e. \(R = (1,0,0,0)\). The red line shows the operational availability that can be achieved whenever no units are stocked. The green line shows the operational availability if one unit is stocked. It indicates that a higher operational availability can be achieved whenever the customer is willing to invest more than €1,500.00 in spare parts. The maximal operational availability that can then be achieved is 99.9714\%, corresponding to a downtime of approximately 48 minutes per year. Stacking one more unit at a customer site does not give significant increase in operational availability.

Although this does not seem to result in high increase in operational availability, it might be very beneficial for a customer. The increase in operational availability results in approximately 30 minutes less downtime per year. MP’s customers incur approximately €300 downtime costs per minute, resulting in a reduction in downtime costs of €9,000.00 per year. For a customer with such a downtime cost rate, an investment in an extra unit on stock is very interesting.

![Operational availability vs Package costs](image)

**Figure 27: Operational availability optimization**

### 9.5 Conclusions

We can conclude that it is beneficial for MP to consider introducing an extra category which consists of units on higher indenture levels that are recommended to customers because of its ease of replacement. These parts may not be interesting for every customer, due to the high price of units. However, if customers have high downtime costs, they can benefit from stocking units. MP should therefore design a smart approach to set the requirement for R-parts and to set the stock levels for those R-parts.
Chapter 10

Conclusions and recommendations

In this chapter we first complete the regulative cycle of our research study by answering the research questions in Section 10.1. Furthermore, we identify the most important limitations of the project, and formulate further recommendations or steps based on the limitations. This is done in Section 10.2 and Section 10.3 respectively. We finally describe how other companies can benefit from our research project in Section 10.4.

10.1 Conclusions

The goal of this project is to come up with a method with which MP is able to generate its critical parts packages in a more objective way, based on part characteristics that give customers the opportunity to make the trade-off between service levels and purchasing costs. Several models are proposed during the design phase, each dealing with different service level measures and including different spare part features. The models are tested in different Marel industries. There has been quite some discussion with service employees in the different industries. We now draw the main conclusions per research question as given in Chapter 2.

1. What mathematical models to determine spare part inventory levels fit the situation at MP?

A multi-item, single location, single indenture spare part model has been applied to the situation at MP. This model has also been extended with batching and criticality to better fit the needs for MP. Furthermore, the model is set up with different service level measures, namely aggregate fill rate, expected number of backorders and the supply availability.

2. How do the models perform?

We test the different alternatives by applying them to four case studies within different Marel industries, and identify similarities in the results. We shortly discuss the results by answering Research Questions 2a to 2e:
2a. What is the benefit of the proposed models as compared to the current practice in terms of purchasing costs and service levels?

The models based on the system perspective give MP better packages than the current logic. To show the difference, the total critical parts costs using the current decision-making logic and using the multi-item models have been investigated in different case studies within 4 Marel industries. To compare the logics, the service levels that are being achieved with the current practice were set as a constraint, such that the performance of the new models were at least as good as using the current decision-making logic.

In the MP case study, it turns out that the current practice does not lead to optimal package. Using the current practice, the investment in a critical parts package would amount to €19,887.34, whereas using the new models the investment costs would be €9,571.98 while achieving the same supply availability of 97.67%. This means a theoretical saving of €10,315.36 (52%) can be achieved. We already discussed why the real saving would be a bit less due to part criticality, but it is easily seen in Chapter 6 that the new models generate better package in terms of costs and supply availability. In the other case studies in Chapter 7, it has been shown that similar improvements can be achieved.

We further elaborate on how the improvements have been achieved when answering the next research questions.

2b. What is the advantage of the item approach as compared to the system approach?

It turned out to be a big step forward when using the system perspective instead of the item perspective. There are quite some expensive spare part packages that only fail once in 20 years and have a very short replenishment lead time. In the current practice, these parts where always included in the critical parts package. By getting to know the system perspective logic, service employees agreed that is does not always make sense to stock such parts.

2c. What is the advantage of criticality extension?

It is not realistic to assume all B-parts to be equally critical. Some B-parts result in a complete machine to be down, where others only affect the performance. In order to be able to generate realistic package, we can conclude that one definitely needs an criticality extension. The model with its alternatives to determine criticality levels proposed is not satisfactory yet. We come back on that in Section 10.2 and 10.3.

2d. What is the advantage of the batching extension?

We can conclude that there is only little advantage of the batching extension. There are only few B-parts that are delivered in batch sizes. Additionally, those parts are relatively inexpensive. The increase of model complexity does not outweigh the increase in the solution because of the two aforementioned reasons.
2e. What service level measure is the best for MP?

Initially, we expected the aggregate fill rate to be the most appropriate service level measure. This because it was considered to be the most understandable one. However, due to the differentiation among lead times for customers, this did not turn out to be the case. The supply availability turned out to be a better measure.

3. What does a useful tool for MP to determine critical parts packages look like?

A decision support tool is developed with which MP can experiment and get to know the different models. The tool enables MP to apply the models that are described in this report on several Marel case studies. Service employees did understand the possibilities of the decision support tool and it provided a very good starting point for a discussion about what would be the way to go, and it also helped with the acceptance of the system perspective. The service employees also argue that such a tool can help sales people explain customers about the importance of the critical parts package.

4. Would it also be beneficial for customers to stock spare parts on a higher indenture levels in the product structure?

We can conclude that it is beneficial for MP to consider introducing an extra category which consists of units on higher indenture levels that are recommended to customers because of its ease of replacement. This might trigger a new research project, continuing the iterative search process in order to come up with even better solution.

10.1.1 Overall conclusion

Since we answered all the underlying research questions in order to answer the main research question, we are now able to draw the main conclusion of the research. The main research question that summarizes the main purpose of the research is:

How should MP determine spare part inventory levels recommended to its customer?

The main conclusion for MP is to implement a spare part model that we propose in this report. The system approach turned out to be much better than the current way of working. During the design and implementation phase we also conclude that the model optimizing with supply availability, fits the situation at MP best. The batching extension does make the model way more complex, and since there are only a few (very cheap) parts that are deliver in batch sizes the model with the one-for-one replenishment assumption is satisfactory. Furthermore, the model should consider part criticality in some way.

MP also needs to take certain steps in order to make the packages even better. We point out these steps in the next section where we formulate limitations of this research and recommendations. However, there are no big roadblocks or reasons to stop with the initiative according to the service engineers. Both from a strategic and operational level there is support to use the model in the generation of spare part packages.
10.2 Main limitation of research
We identify three main limitations of this research project:

Failure rate data
The case studies in this project are performed with estimated input data. Although we validated the data in Section 6.4.2, the results are only based on estimates.

Part criticality extension
We propose a model to include part criticality in Chapter 5. Additionally, we test three alternatives to determine that criticality level of every part in Chapter 6. As it turned out, the methods proposed are not satisfactory yet. It is very hard to attach weights to the different categories: i.e. set the $w_i$ value for a certain criticality level. We did not manage to set the right $w_i$ values. In that sense, the models that we propose are not able to generate completely realistic critical parts packages.

Line replaceable unit optimization
In Chapter 9, we show that it would make sense to include higher indenture level legends in the packages as well. This research however does not propose a methodology to determine stock levels for the legends together with stock levels for the articles. Separately optimization of articles and legend does not lead to optimal solutions.

10.3 Recommendations for further research or steps
When answering the main research question, we conclude the multi-item model with the supply availability constraint fits the situation at MP best. The main recommendation then is to implement that model in the MP organization. However, we also find that there are some limitations. Based on the three main limitations of the research project, we formulate the following three recommendations for further research or steps.

Failure rate data
An important recommendation in order to be able to implement the spare part model is to gather data about failure rate of B-parts. MP has to estimate the failure rates of all B-parts initially. This is quite an exhaustive task. We test a method to only distinguish three different failure rate categories in Section 6.5. This idea seems to work out. It should however be tested for smaller critical parts packages as well.

In the long run, it should determine failure rates with customer data. Some customers already gather data about its maintenance activities. It is however very hard for MP to convert all these different sources of data in different formats into useful information. In order to overcome that problem, MP currently discovers the possibilities that come with a maintenance management system. Such a system maintains a database of information about an organization's maintenance operations. It can help maintenance workers do their jobs more effectively and management to make informed decisions. This can help maintenance workers do their jobs more effectively. Additionally, it can make it easier for MP’s customers to store data, and for MP to convert this data into useful information.
Part criticality extension

MP should develop one consistent way of determining part criticality levels, taking into consideration the right parameters. Literature describes quite some approaches to deal with criticality. Bacchetti & Saccani (2012) wrote an extensive review paper.

During several discussions that we had with the service engineers, we already identify three important factors that should definitely be taken into consideration when determining the criticality level of a part. First, whether the B-parts results in a breakdown of the line or affects the safety for the workers. Secondly, one should think about supply availability. If one cannot fulfill a demand at the customer location, sometimes it can easily be bought locally. Thirdly, MP should distinguish between parts that can be fixed fast at the customer side to get the part working for another few days, and B-parts that are impossible to repair fast at the customer side. We further propose to set the criticality to 1 for all the parts that result in downtime of the line or affect the safety of the worker, that are not locally available and that are not easily fixed by the customer itself. The rest of the parts get criticality level 2. In this manner, the item criticality level determination is determined.

Furthermore, we noticed that it is very hard to attach weights to the different categories: i.e. set the $w_i$ for certain criticality level. We therefore recommend to test a different procedure, with which it is not needed to attach weights to criticality levels. Instead of considering all B-part simultaneously, MP should first consider the criticality 1 parts, and only include those in the model. Set a target service level for those and optimize. Next, include all the parts in the model and optimize to a target service level again.

Line replaceable unit optimization

One can proceed in the direction of combining the LRU definitions problem and spare part stocking. This joint maintenance and logistics decision would be beneficial for MP.

10.4 Generalizability

The improvements that we find by using the system approach may also be found at other companies. The benefit of the system approach depends mainly on unit costs, but better solutions in terms of service levels and investments costs are obtained by definition. However, there is also downside of the system approach. It is much more complex, requires more time and skills to be understood. This is also what we noted during this research. Service employees did not easily understand and accept the system perspective, due to its complexity. Our research can help other companies determine their potential benefit of using the system approach, but more importantly, help other companies to create acceptance regarding this perspective. By comparing the different models and strategies proposed, it can first investigate its best strategy regarding spare part supply. Furthermore, the decision support tool can be easily used to illustrate the potential benefit of the system approach in order to get a better understanding of how it works. It provides a valuable starting point for discussion about the system approach and improved spare part supply in general, and can eventually lead to acceptance of the perspective.
Bibliography


Appendix A: Poultry processing line
# Appendix B: Questionnaire interviews

## Interview Master Thesis Critical Parts Packages

### Introduction:
- Function interviewee
- Goal Thesis Project

### Classification:
Can you shortly explain the AE coding structure?

What do you think of the current AE coding structure?

Do you think Marel should differentiate more on service part than they currently do?

There is the idea for a differentiation in criticalness. What is your opinion about that?

### Service level measure:
What do you think of the current service level of spare parts?

Do you have data?

In building a model, which service level measure would you suggest? Fillrate, EBO, Availability?

### Discuss system approach:
Nowadays, all B-parts are always recommended to have on stock. When using the system approach, there is a possibility of achieving higher service levels by not stocking expensive items, and stocking more of cheap items.
Appendix C: Analyses compound poisson demand

Axsäter (2006) proves some important theorems on compound Poisson distributions, and explains how to compute the demand during the lead time when compound Poisson demand is assumed:

The number of customers during lead time $t_i$ has a Poisson distribution and the probability of seeing $k$ customer during the lead time is:

$$P(k) = \frac{(m_i t_i)^k}{k!} e^{-m_i t_i}, k = 0,1,2,...$$

When assuming Compound Poisson demand, the size of a demand is also a stochastic variable.

Let

$$f_j = \text{probability of demand size } j (j = 1,2,...)$$

$$f_j^k = \text{probability that k arrivals give the total demand } j$$

$$X_i = \text{demand during lead time of part } i$$

It is assumed that there is not possibility of demand size zero. The distribution of $X_i$ can be determined as follows. Note that $f_j^0 = 1$ and $f_j^1 = f_j$. Given $f_j^2$ we can obtain the $j$-fold convolution of $f_j, f_j^k$, recursively as

$$f_j^k = \sum_{i=k-1}^{j-1} f_i^{k-1} f_{j-i}, \; \; k = 2,3,4...$$

$f_{j-i}$ are input parameters. If the probabilities of $f_i^{k-1}$ are known for all $i$, we are able to calculate $f_j^k$ as well.

In the end, the distribution of the demand during lead time can be described as follows:

$$P(X_i = j) = \sum_{k=0}^{j} \frac{(m_i t_i)^k}{k!} e^{-m_i t_i} \cdot f_j^k$$

Which is the probability of having $k$ arrivals with a total demand size of $j$. 
Appendix D: Input data Poultry case

- Due to confidentiality reasons, this Appendix is not disclosed.
Appendix E: Input data Meat case

Due to confidentiality reasons, this Appendix is not disclosed.
Appendix F: Input data Further Processing case

- Due to confidentiality reasons, this Appendix is not disclosed.
Appendix G: Input data Cross Industry case

- Due to confidentiality reasons, this Appendix is not disclosed.
Appendix H: Manual decision support tool

Manual decision support tool

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21-7-2016

Attachment: DecisionSupportTool.xlsm
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1. Goal of the Tool

With this tool, we propose an objective, reproducible and explainable way of generating critical parts packages based on the crucial parameters of B-parts. It can be used globally by all Marel industries.

This is only a prototype decision support tool. Marel can experiment with the case studies that are implemented and generate the critical parts packages. This tool also forms a base for a discussion about how to deal with the B-parts in the future. Quite some different models are implemented in the tool, all of which give different packages. This tool gives insights in the difference between the models.

In this manual we explain the several models and a bit of the math behind it. Moreover, we explain how to use the tool.

We think this method fulfills all requirements for the critical parts packages procedure, and is therefore the way to go. If you have any questions, feel free to ask Robert Lemmens (Service Innovation Engineering, Poultry, Boxmeer) or Roel Bongers (Service Trainee, Poultry, Boxmeer).
2. Input Parameters

When one opens the tool, there is a blue table on the left-hand side of the sheet. This table contains all the necessary inputs for the models. In this section, all the parameters are discussed one by one. If you disagree the way that the parameters are set, you can adjust them as much as you want and check what different results you get.

2.1. Part ID
This column gives the part specific number.

2.2. Description
This column gives the description of the part.

2.3. Total Qty in order
This column gives the total quantity of a particular part in the total order you want to make the critical parts package for.

2.4. Total Failure Rate
This column gives the total number of failures of that particular part in the order. Basically, this is the number of times that the part needs to be replaced correctly.

2.5. Criticality 2
B-parts are not always equally critical. With this column, as well as with the following one, you are able to play around with different criticality levels.

2.6. Criticality 3
B-parts are not always equally critical. With this column, as well as with the previous one, you are able to play around with different criticality levels.

2.7. Lead Time
This column gives the time needed to have the B-part. Marel stores data about the maximum lead time whenever it has no inventory at all. However, Marel strives to have 95% of the B-parts on stock. So, in 95% of the cases when a customer orders a B-part, Marel has it on stock. In 5% of the cases, it has not. The lead time is therefore calculated as follows:

\[
\text{Lead time} = 0.05 \times \text{Maximum Lead time}
\]

2.8. Price
This column gives the purchasing price that the customer faces.

2.9. Minimum Quantity
Whenever certain B-parts break down in a machine, that particular B-part is replaced. However, in order to execute a proper replacement and to bring the machine back to an approximately new one, the customer needs to replace other identical B-parts simultaneously. This implies that demand always arrives in multiples of the minimum quantities of that part. That minimum quantity is used as input parameter.

2.10. Batch Size
For some B-parts, Marel only delivers in certain batch sizes. If that is the case, the batch size is an input parameter as well.

2.11. Picking and packaging time
This gives the time needed for picking and packaging a B-part. This is added to the Lead time that we discuss in Section 2.7.

2.12. Shipment time
This gives the average time needed for shipment to the customer. This is also added to the Lead time that we discuss in Section 2.7.

2.13. Downtime costs
This gives the downtime costs that a customer incurs when it does not have a B-part when it is needed.
3. Output Parameters

This section describes the output parameters of the models. They indicate the service level regarding spare part supply that Marel offers to its customers.

3.1. Aggregate fill rate

The aggregate fill rate is defined as the percentage of requested parts (failures of B-parts at the customer side) that can be delivered from the customers stock immediately. It is aggregated from the item fill rate. The item fill rate is the percentage of failures that can be replaced from stock of a particular part. This is equal to the probability of having stock of particular parts: \( P(\text{Stock on hand} > 0) \). This is equal to the probability of having a demand during lead time that is smaller than the stock level: \( P(X < S) \), where \( X \) is the demand during lead time and \( S \) the stock level. This can be quite easily be calculated with the Poisson distribution in Excel. For a more extensive explanation on how to calculate the demand during lead time, we refer to Appendix 2. If one has calculated the item fill rate, it can be aggregated to get the aggregate fill rate.

3.2. Expected number of backorders (EBO)

A customer has a backorder whenever it needs a part, but it is not on the shelf. Where the aggregate fill rate only counts the number of time a part is missing when it is needed, the expected number of backorders also takes the time until the part is available into consideration.

3.3. # unfilled demands

The number of unfilled demands simply multiplies the aggregate fill rate with the total number of failures during 10 years.

3.4. Availability lower bound

The availability gives the percentage of time that all the B-parts that are needed are working properly. With this lower bound, we simply multiply the number of unfilled demand with the lead times. In general, whenever a customer faces a backorder the part is already re-ordered. In that manner, it does not face the total lead time, but only a part of the total lead time. Therefore, this availability is only a rough lower bound, and it is way higher in reality.

3.5. Hypothetical availability

The hypothetical availability is much more reliable. This is a more sophisticated way of calculating the availability. The calculation is based on the expected number of backorders (EBO).

3.6. Downtime costs

The downtime costs are simply the hypothetical downtime (100%- hypothetical availability) multiplied by the total production time and the costs for downtime.
4. Assumptions
The following assumptions are made in the models:

- Demand for the different parts occurs according to independent Poisson Processes. A Poisson distribution is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time and/or space if these events occur with a known average rate and independently of the time since the last event. When we look at the failure rate distribution of all the different parts, we can see that the probability that a B-part fails is independent of its age. Therefore, it does not make sense to replace the part preventively. When we look at C, D and E parts, it does. These parts wear and the probability of failure therefore increases.

The assumption of Poisson failure process is justified when lifetimes of components are distributed as in Figure 1.

- For each part, the failure rate is constant over time.
- A one-for-one replenishment strategy is applied at the customer side.
5. Greedy Procedure

In this chapter, the basic idea behind the greedy procedure is presented. For a more exhaustive explanation of the math, we refer to Appendix 3 or the book of Van Houtum & Kranenburg (2015)\(^7\).

With the greedy procedure, one can generate efficient solutions. A solution is efficient whenever the best service level is reached for that particular investment costs. We start with all the stock levels set to 0. This solution is efficient because it has the lowest possible investment costs. Next, for each part, we compute the improvement of the service measure relative to the increase in investment costs when the stock level would be increased by one unit. The part with the “biggest bang for the buck” is selected, and the corresponding base stock level is increased by one unit. The generation of efficient solutions is continued until a given target service level or inventory investment has been reached.

To illustrate, let us consider three different parts with the following characteristics:

<table>
<thead>
<tr>
<th>Failure rate (per year)</th>
<th>Part 1</th>
<th>Part 2</th>
<th>Part 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>€ 100,-</td>
<td>€ 20,-</td>
<td>€ 5,-</td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We start with all the stock levels set to 0. We want to achieve an aggregate fill rate of 95%. With all stock levels set to 0, we achieve an aggregate of 0%. In order to achieve the target value, we perform a greedy procedure. We calculate the increase in aggregate fill rate relative to the increase in investment costs. Already looking at the characteristics of the parts, one can imagine that you always want to stock part 3 first. This is because it is quite a cheap part with a lot of failures per year. When stocking this part once, it increases the aggregate fill rate significantly while your investment is only 5 euros. Iteration 1 is finished now. Let us go to iteration 2.

We now have only one item on part 3 on stock, and we probably still do not achieve an aggregate fill rate of 95%. We need to invest more. We again calculate the improvement of the aggregate fill rate relative to the increase in investment costs when the stock level would be increased by one unit, and select the “biggest bang for the buck”. This will probably be again part 3, because it has such a high failure rate and low costs.

However, after you have stocked a certain amount of part 3, it would not make sense to store more of it. The improvement of aggregate fill rate relative to the increase in investment costs will be higher for Part 2.

In the end of your procedure, when you have stock enough of part 2 and 3, part 1 will give you the “biggest bang for the buck”.

6. Models

There are several ways of determining stock levels. In this chapter we present the different models, all of which are slightly different from each other. The solutions of all the models are obtained by performing a similar greedy procedure as explained in Chapter 5. The table in the beginning of each section indicates which input parameters are needed for that model.

### 6.1. Item Approach; Optimizing with item fill rate

<table>
<thead>
<tr>
<th>Total Qty in order</th>
<th>Total Failure rate</th>
<th>Criticality</th>
<th>Lead times</th>
<th>Price</th>
<th>Minimum Quantity</th>
<th>Batch Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
</tbody>
</table>

The item approach is the simplest model. This approach makes sure that the objective fill rate is achieved for every individual part in the order. This can be verified in the second column of this model.

### 6.2. System Approach; Optimizing with aggregate fill rate

<table>
<thead>
<tr>
<th>Total Qty in order</th>
<th>Total Failure rate</th>
<th>Criticality</th>
<th>Lead times</th>
<th>Price</th>
<th>Minimum Quantity</th>
<th>Batch Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

In the previous section, we set an objective value for every item individually. When using the so-called system approach, a system target is set and the goal is to find a combination of stock levels that minimize cost subject to a system target constraint. Sherbrooke (1968, p. 123) mentions that the system approach “focuses management attention on the entire system so that an appropriate combination of system effectiveness and system cost can be selected”. If you fill in a target for the aggregate fill rate, it is perfectly possible that some individual fill rates are lower than the target value. However, the aggregate fill rate is at least as high.

### 6.3. System Approach; Optimizing with aggregate fill rate; Including criticality of parts

<table>
<thead>
<tr>
<th>Total Qty in order</th>
<th>Total Failure rate</th>
<th>Criticality</th>
<th>Lead times</th>
<th>Price</th>
<th>Minimum Quantity</th>
<th>Batch Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
</tbody>
</table>

We noted during the analysis phase of the project that not all B-parts are equally critical. With this model it is possible to differentiate between criticality of parts. The higher the criticality value filled in, the lower the possibility that a part is included in the spare part packages.

### 6.4. System Approach; Optimizing with aggregate fill rate; Including batching of parts

<table>
<thead>
<tr>
<th>Total Qty in order</th>
<th>Total Failure rate</th>
<th>Criticality</th>
<th>Lead times</th>
<th>Price</th>
<th>Minimum Quantity</th>
<th>Batch Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

This model also takes batching into consideration. Only very cheap parts might have a batch size. This extra feature of the model therefore does not have a huge impact in general.

### 6.5. System Approach; Optimizing with expected number of backorders

<table>
<thead>
<tr>
<th>Total Qty in order</th>
<th>Total Failure rate</th>
<th>Criticality</th>
<th>Lead times</th>
<th>Price</th>
<th>Minimum Quantity</th>
<th>Batch Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
</tbody>
</table>

Where all of the previous maximize the aggregate fill rate, this model tries to minimize the expected number of backorder.

---

6.6. System Approach; Optimizing with average supply availability

<table>
<thead>
<tr>
<th>Total Qty in order</th>
<th>Total Failure rate</th>
<th>Criticality</th>
<th>Lead times</th>
<th>Price</th>
<th>Minimum Quantity</th>
<th>Batch Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
</tbody>
</table>

This model maximizes the average supply availability of the spare part package.
7. How to use the tool?
The tool consists of 5 sheets. The first 4 sheets implement 4 different case studies of Marel industries. On the left-hand side one sees the input table that is discussed in Chapter 2. The green table subsequently gives the critical parts package that is generated according to the current way of working. We can analyze this package when pushing the “Analyze Package” button. Further, one can run all the different model that we discussed in Chapter 6 when pushing the button “Determine Package” underneath the right red table. Note the differences in service level measures when using different models.

The last sheet finally draws some graphs to better understand the outcomes of the model optimizing the supply availability in the Poultry case.
### Appendix 1: Screenshot Tool

<table>
<thead>
<tr>
<th>Marel Poultry - Semi automatic filleting system (AMF-SX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis Package</td>
</tr>
</tbody>
</table>

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**ADVANCING FOOD PROCESSING**
Appendix 2: Explanation of the Poisson Distribution

This section evaluates the steady-state behavior for a given base stock policy. Because parts of different stock keeping units do not have interaction, the steady state behavior is evaluated per item. The evaluation is based on Chapter 2 of Van Houtum & Kranenburg (2015).

Consider an arbitrary item $i$, and assume that the basestock level $S_i$ is given. Whenever item $i$ fails, it goes into repair or it is discarded and a new part is ordered. The average repair or resupply time takes on average $t_i$ time units. The state of the spare part system of item $i$ at time instant $t$ can be described by $X_i(t)$, $OH_i(t)$ and $BO_i(t)$, where $X_i(t)$ denotes the number of parts in repair or resupply at time $t$, $OH_i(t)$ denotes the stock on hand of parts at time $t$ and $BO_i(t)$ the number of backorder at time $t$. The amount $X_i(t)$ is also called the pipeline stock. Sherbrooke (2004) shows the relation between $X_i(t)$, $OH_i(t)$ and $BO_i(t)$ by the stock balance equation:

$$OH_i(t) - BO_i(t) = S_i - X_i(t)$$

The aggregate fill rate ($\beta(S)$) is defined as the probability that an arbitrary demand for the total group of items is fulfilled immediately from stock. This can only happen if there is on hand stock available. Since we have assumed that demands for the B-parts arrive according to a Poisson process, an arbitrary arriving demand observes the system in steady state according to PASTA (Poisson Arrivals See Time Averages). Hence, with probability $P\{I_i(S_i) > 0\} = P\{X_i < S_i\}$, a positive stock on hand is observed and the demand can be fulfilled immediately. So, in order to calculate the fill rate, the distribution of the pipeline stock should be calculated. In our model, parts fail according to a Poisson process, and therefore failed parts enter the resupply pipeline according to a Poisson process as well. Each failed part stays on average time $t_i$ in the repair pipeline. The resupply pipeline may be seen as a queueing system with infinitely many servers and service time $t_i$. So the resupply pipeline is an $M|G|\infty$ system and thus we may apply Palm’s theorem.

**Palm’s theorem:** If jobs arrive according to a Poisson process with rate $\lambda$ at a service system and if the times that the jobs remain in the service system are independent and identically distributed according to a given general distribution with mean $EW$, then the steady-state distribution for the total number of jobs in the service system is Poisson with mean $\lambda EW$.

When we apply this theorem to the resupply pipeline, we can say that it is Poisson distributed with mean $m_i t_i$, and:

$$P(X_i = x) = \frac{(m_i t_i)^x}{x!} e^{-m_i t_i}, \quad x \in \mathbb{N}_0$$
Appendix 3: Another example of the greedy procedure

To illustrate, let us assume that we have three different B-parts, which have the following input parameters:

<table>
<thead>
<tr>
<th>Part</th>
<th>Failure rate (per year)</th>
<th>Resupply lead time (in months)</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part 1</td>
<td>15</td>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>Part 2</td>
<td>1</td>
<td>2</td>
<td>3000</td>
</tr>
<tr>
<td>Part 3</td>
<td>21</td>
<td>2</td>
<td>20000</td>
</tr>
</tbody>
</table>

We want to achieve a number of backorders of 0,1. In order to achieve this, we perform a greedy procedure. We start with a solution where all stock levels are set to 0. Obviously, this results in quite a high number of backorders. Then, we calculate the three $\gamma$-values, which is the decrease in EBO relative to the increase in investment costs. As one can see, $\gamma_1$ is the highest in iteration 1. Stock level 1 is increased by one unit and we continue to iteration 1. Then again, $\gamma_1$ turns out to be the maximum. So we increase stock level 1 by one unit.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>$\gamma_3$</th>
<th>K</th>
<th>Inventory 1</th>
<th>Inventory 2</th>
<th>Inventory 3</th>
<th>EBO</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>3.50</td>
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<td>1.9 x 10^{-4}</td>
<td>7.7 x 10^{-6}</td>
<td></td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2.58</td>
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<td>0</td>
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<tr>
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<td>3</td>
<td>0</td>
<td>0</td>
<td>1.41</td>
</tr>
<tr>
<td>4</td>
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<td>0</td>
<td>0</td>
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We need to perform 11 iterations in order to bring the expected number of backorders (EBO) lower than 0,1.