A decision support model for managing empty packaging in a closed-loop supply chain

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A Decision Support Model for Managing Empty Packaging in a Closed-Loop Supply Chain

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A Decision Support Model for Managing Empty Packaging in a Closed-Loop Supply Chain
Note: All numbers used in this report are fictitious and serve for illustrative purposes only.
Abstract

This Master thesis describes the development of a decision support model for managing empty packaging materials in a closed-loop supply chain. In order to do so, we first determine the root causes of the empty packaging problem within the company. In addition, we thoroughly analyze and visualize the current processes regarding empty packaging. With the knowledge gained from the Root Cause Analysis and the current processes, we propose a new process for handling the empty packaging materials in the local warehouses. Then, a Mixed Integer Linear Programming model is developed that forms the basis of the decision support model. The objective of the model is to minimize the total costs regarding empty packaging in the supply chain of the company. The results show that using the decision support model can lead to large cost savings regarding empty packaging, which demonstrates that the added value of the decision support model for the company is considerably high.

Keywords:
Closed-loop supply chains; Returnable packaging; Disposable packaging; Decision support model; Mixed Integer Linear Programming (MILP); Optimization
Preface

This report presents my Master Thesis project in completion of the Master Operations Management and Logistics at Eindhoven University of Technology. This project was conducted at ASML in Veldhoven. In total, this study carried on for nine months with hard work. Moreover, this Master Thesis marks the end of the years which I spent as a student at Eindhoven University of Technology.

I would not have been able to complete this Master Thesis study without the help, support and motivation of many people. Firstly, I would like to thank my mentor and first supervisor, ir. dr. Simme Douwe Flapper for his guidance, support and his always helpful feedback and advice. During the whole project, he never lost his enthusiasm and positivity and even in periods when everything seemed to fail, he was able to get me on track again and gave me new energy to make this project of the right academic quality.

Secondly, I would like to thank my second supervisor, dr. Shaunak Dabadghao for his useful feedback on my project, especially on the mathematical model. Your feedback was very valuable to me and it improved the quality of the model.

Another person that has been of great help during this study was my company supervisor, Javid Koochaki. Thank you for your feedback on my work and the time you invested in me. Your criticism during our meetings made me think and ensured that this project gives theoretical insights as well as practical insights for ASML.

Moreover, I would like to thank my colleagues of the reverse flow team for their help and the pleasant work atmosphere. Extra thanks to Perry van Gestel for all the input and feedback during our meetings; you were of great help for me in understanding the problem.

I would also like to thank my friends, the ones I already had before I came to Eindhoven and the ones that I have met along the way. They made the stressful moments a lot better and we had so much fun the past five years. Even though everyone is now building their own lives in other cities, I hope we can hold on to this amazing friendship.

Next, I would like to express my deepest gratitude to my family. My parents, brother and sister were always there for me during my whole study period. Nothing felt better than to come home after a busy week of studying. The enjoyable moments we had during the weekends were really important for me to stay motivated. I cannot express in words how thankful I am for your endless support.

Finally, the person I would like to thank most is my boyfriend, Luuk, who I am indebted to. Even though you sometimes had no clue where I was talking about, you were always there for me to listen to my struggles. You always had faith in me and even in the periods I was most stressed you stayed positive and helped me to see things in a different light. I cannot thank you enough for your unconditional love and support and for kicking my ass when needed. Thank you so much for always believing in me.

Eefje Linnartz

Eindhoven, December 2018
Executive Summary

This Master thesis is the result of a project conducted at ASML. ASML is a manufacturer of advanced technology systems for the semiconductor industry. In this project, we developed a decision support model for managing empty packaging materials in the supply chain of the company.

Problem Definition  High tech systems such as semiconductor lithography systems are very sensitive to different influences from the outside environment, e.g. dust and moisture. When shipping these systems to different stages in the supply chain, it is of great importance to protect them. Therefore, it is necessary that the parts are packed with the right packaging materials and with the required number of packaging layers. Because of all these packaging layers, ASML has to handle a lot of empty packaging materials within their supply chain and currently, it is very difficult for the local warehouses to make decisions regarding empty packaging materials. As a result, a huge amount of empty packaging materials is stored in the local warehouses worldwide, which occupies space for other more critical stocks and causes high inventory costs. This empty packaging situation at several local warehouses has led to the belief that improvements in managing the empty packaging process are necessary. This leads to the main research question for the project:

Main Research Question:
What to do with empty packaging within the different stages of ASML’s supply chain?

Approach  To answer this research question, we have defined two sub research questions. The first research question is about making the current processes of handling empty packaging within the local warehouses visible and finding the root causes of the empty packaging problem. With the answer of this question, a new process for handling empty packaging in the local warehouses is designed. The second sub research question is answered by developing a decision support model which help the decision-makers of the company what to do with the empty packaging materials. The results of the sub research questions are presented below.

Root Cause Analysis  The Root Cause Analysis and the analysis of the current processes have gained insights in the causes of the empty packaging problem. The main root causes of the problem are the following:

1. No clear instructions for handling packaging, which results in each local warehouse handling the empty packaging materials in a different way.
2. The empty packaging materials are not traceable in the information system of the company, i.e. SAP. Due to this, the empty packaging inventory in the local warehouses is not visible in SAP. Some local warehouses try to make the inventory visible with an Excel list.
3. The X-plant status of the empty packaging materials are not up-to-date. With the X-plant status, the local warehouses can check what to do with the packaging material, i.e. return or scrap. However, if this status is not up-to-date wrong decisions can be made and as a result, the local warehouses just keep all packaging materials in inventory.
4. Within the company, there is no ownership for the empty packaging materials. The focus of the company is on the parts, and not on the packaging materials. This is also represented by the fact that there are no KPIs developed for empty packaging.
5. The 3PL employees with the local warehouses do not have knowledge about the packaging. This results in unclear responsibilities. In addition, the 3PL employees are not allowed to make the return/scrap decision.

III
To-Be Process  Based on the insights gained from the current processes and the root cause analysis, we designed a new process for handling empty packaging in the local warehouses. This process is presented in Figure 1.

With this process, the flow of empty packaging in the local warehouses can be handled more efficiently and the employees in the local warehouses know what to do with the empty packaging materials.

Decision Support Model  The second sub research question was to investigate what a suitable decision support model was for empty packaging within the closed-loop supply chain of the company. We found that a pull inventory management strategy fits the supply chain of the company best and based on this strategy, we developed a Mixed Integer Linear Programming model that forms the basis for the decision support model. The objective of the model is to minimize the total costs regarding empty packaging. This implies that only the costs for the reverse flow of empty packaging materials are included, which are the following: costs for returning empty packaging materials from the local warehouses to the factory warehouse, costs for buying new empty packaging materials, costs for disposal of empty packaging materials, inventory holding costs for holding empty packaging materials on stock in the local warehouses and the factory warehouse, and the backorder costs due to unavailability of empty packaging materials. The model determines, based on the lowest cost, what is most efficient to do, i.e. disposal of empty packaging and buy the packaging new or return the empty packaging material and reuse this packaging.

Results  For the case study, we compared two different scenarios: the current situation (As-Is Scenario) where no empty packaging materials are returned, and all packaging materials are stored or disposed in the local warehouse and the new situation (To-Be Scenario) where the company uses the decision support model for determining what to do with the empty packaging materials in the local warehouses. The results of comparing these two scenarios showed that by using the new process and the decision support model can decrease the total costs of empty packaging in the supply chain by 7.9% in the case the packaging price is €500.00 and 20.0% in the case the packaging price is €1000.00. In addition to this, the cost of buying new empty packaging materials as well as the number of empty packaging materials disposed can be decreased significantly if the decision-support model is used.

Conclusions and Recommendations  Referring to the main research question of this project and with the answers of both sub research questions, we can conclude that we have developed a decision support model that facilitate the decision-making regarding empty packaging in the supply chain of the company. The model suggests, based on the lowest costs, what is optimal to do with the empty packaging in the different stages of the supply chain of ASML. Hence, if the company uses the decision support model, they know what is best to do with the empty packaging materials, i.e. return or dispose the packaging materials.

Based on the potential large cost savings for regarding empty packaging materials in the supply chain of the company, it is concluded that using the developed decision support model makes the closed-loop supply chain more efficient and less expensive. The main recommendations for the company are the following:
• Do a pilot with the new standardized process to check whether the new process is working as it should be.

• Set the threshold value of the first criterium of the X-plant status to €500.00. This value is found to be the optimal value for the scrap/return decision of empty packaging materials.

• Explore the possibilities of determining the real demand of empty packaging and based on this, make a demand forecast which can be used in the developed decision support model.

• Test the decision support model with the modeled closed-loop supply chain first and after the pilot, extend the decision support model with multiple factory warehouses, more local warehouses and more customers.

• Explore the opportunity of using RFID technology for the more expensive empty packaging materials in combination with the decision support model.

Finally, for future research, we recommend researching the effects of relaxing the assumptions in our proposed model. This could make the model more similar to the real system.
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## List of Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>12NC</td>
<td>12 Numeric Code</td>
</tr>
<tr>
<td>3PL</td>
<td>Third Party Logistics</td>
</tr>
<tr>
<td>ASSY</td>
<td>Assembly</td>
</tr>
<tr>
<td>CLSC</td>
<td>Closed-Loop Supply Chain</td>
</tr>
<tr>
<td>CS</td>
<td>Customer Support</td>
</tr>
<tr>
<td>CSCM</td>
<td>Customer Supply Chain Management</td>
</tr>
<tr>
<td>CWH</td>
<td>Central Warehouse</td>
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<tr>
<td>DPI</td>
<td>Detailed Packaging Information</td>
</tr>
<tr>
<td>ESD</td>
<td>Electrostatic Discharge</td>
</tr>
<tr>
<td>FAB</td>
<td>Fabrication Plant</td>
</tr>
<tr>
<td>FSD</td>
<td>Field Service Defect</td>
</tr>
<tr>
<td>FWH</td>
<td>Factory Warehouse</td>
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<tr>
<td>LRF</td>
<td>Local Request Form</td>
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<tr>
<td>LSP</td>
<td>Logistics Service Provider</td>
</tr>
<tr>
<td>LWH</td>
<td>Local Warehouse</td>
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<tr>
<td>MILP</td>
<td>Mixed Integer Linear Programming</td>
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<tr>
<td>RCA</td>
<td>Root Cause Analysis</td>
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<tr>
<td>RL</td>
<td>Reverse Logistics</td>
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<tr>
<td>RTI</td>
<td>Returnable Transport Item</td>
</tr>
<tr>
<td>RTM</td>
<td>Returnable Transport Material</td>
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<tr>
<td>TPD</td>
<td>Technical Product Documentation</td>
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Glossary of Terms

12NC  A 12NC is a twelve-digit Numeric Code which each part and packaging of ASML has. It is a unique code and with this code the part or packaging is identified.

Field Service Defect  Every part taken from the field with a (suspected) defect is qualified by ASML as a Field Service Defect (FSD) part. FSD-parts are suitable to serve as service parts after repair.

Service parts  Parts that have the potential to fail or to degrade and which need to be replaced in the field once or more within the system’s lifetime. Parts that can be lost or damaged during service actions are also considered to be service parts.

Third-Party Logistics  Third-party logistics in logistics and supply chain management is a company’s use of third-party businesses to outsource elements of the company’s distribution and fulfillment of services.

X-plant status  Indicates whether it is economically and technically advantageous to return and repair a part or packaging material.
1 Introduction
This chapter will start with an introduction to the research topic in Section 1.1. The subsequent part of this chapter is organized as follows. Section 1.2 provides some information about the company where this research is conducted. In Section 1.3 the research topic is introduced, and the problem statement will be presented. Subsequently, the scientific relevance and the relevance of this project for the company is motivated in Section 1.4. This chapter will end with an overview of the structure for the remaining chapters of this thesis report in Section 1.5.

1.1 Introduction to the Research Topic
High tech systems such as semiconductor lithography systems are very sensitive to different influences from the outside environment, e.g. dust and moisture. When shipping these systems to different stages in the supply chain, it is of great importance to protect them. Therefore, it is necessary that the parts are packed with the right packaging. Packaging can be defined as the wrapping materials, such as metal, paper, or plastic, employed around an article to contain, handle, protect, and/or transport it (Business Dictionary, 2018; Dileep Kumar, 2006).

In this project, we specifically look at the packaging of service parts of semiconductor lithography systems. These parts, developed by ASML or its suppliers, require a minimum of three packaging layers and in the case of very sensitive parts, the number of packaging layers can go up to five. From the moment the part is being unpacked, the company has to deal with the remaining empty packaging. Some layers are disposed immediately, but some layers are designed in such a way that they can be reused. This type of packaging is called returnable or reusable packaging which can be defined as packaging materials which are used more than once in the same form (Kroon & Vrijens, 1995). Packaging materials which are disposed after one usage are called one-way distribution items (Flapper, 1996) or disposable packaging (Silva, Renó, Sevegnani, Sevegnani, & Truzzi, 2013). Returnable packaging can be of different types, e.g. containers, pallets, boxes, or crates, whereas disposable packaging are usually only cardboard boxes. Despite that returnable packaging can refer to different types of packaging, the term ‘returnable packaging’ is used throughout this research, irrespective of the actual type of the returnable packaging. As the terms ‘returnable packaging’ and ‘reusable packaging’ are defined in the same way, these terms will be used interchangeably. The same applies for the terms ‘disposable packaging’ and ‘one-way distribution items’.

Using returnable packaging instead of one-way packaging materials can lead to many organizational advantages, which are described by Maleki & Reimche (2011):

- The increased use of returnable packaging contributes to a long-term and continuous operating cost advantage, i.e. the expenses related to the daily operations of a business can be decreased.
- The packaging material costs can be decreased, even as the handling and packaging-related labor costs.
- It can bring advantages to environmental concerns, including recycling, reduced material usage and waste disposal.

However, when the use of returnable packaging is not managed properly these benefits will not apply and can even lead to an increase in the logistics costs (Rosenau, Twede, Mazzeo, & Singh, 1996). In addition to this, inadequate management of empty returnable packaging can also cause high inventory costs and too much occupied space in the warehouses due to storage of empty packaging. Looking at this, it seems to be that managing (empty) packaging is a crucial part of supply chain management.
1.2 Company and Background

ASML is a manufacturer of advanced technology systems for the semiconductor industry. The company was founded in 1984 and till today ASML is a world leader in manufacturing these complex machines that are critical for the production of integrated circuits, also called ICs or chips. This organization designs, develops, integrates, markets and services advanced systems used by customers to create chips that power a wide array of electronic, communications and information technology products. For example: chips for mobile phones, laptops, airplanes etc. The customers of ASML are the major global semiconductor manufacturers.

ASML’s corporate headquarter is located in Veldhoven, the Netherlands. Their manufacturing sites and R&D facilities are in the USA, Taiwan and the Netherlands. Overall, ASML has more than 60 offices in 16 countries worldwide (See Figure 1.1).

This Master thesis project is executed within the Customer Supply Chain Management (CSCM) department, which delivers supply chain solutions to provide customers with reliable and affordable production capacity. Furthermore, this department provides affordable services and support platform extensions, ensures that materials are available for the system uptime, and lastly, it enables that customers have early access to new technology and industrialization. In sum, the CSCM department is the connection with the customers and with the goals mentioned before, they maintain good relationships with the customers.

To be precise, this project is executed at the CSCM Reverse Operations team. This team is responsible for returning defect (service) parts, also called FSDs (Field Service Defects), of the lithography machines from the customer back to the supplier for repair. The Reverse Operations team must also manage the reverse flow of empty packaging materials. Whether this reverse flow of empty packaging is in place depends on the type of packaging. Within ASML there are two main packaging types: 1. Standard Packaging and 2. Special Packaging. Within these categories we can define the following two sub categories: a) Disposable Packaging and b) Returnable Packaging. More information about these different packaging categories and types is presented in Section 3.2.
1.3 Problem Definition
This section gives an overview of the problem situation at ASML in Section 1.3.1 and will be concluded by presenting the resulting problem statement in Section 1.3.2.

1.3.1 Initial Problem Situation
In managing (empty) packaging, a logistic as well as a financial objective need to be incorporated (Van der Kamp, 2009). On the one hand, it’s important that each local warehouse has sufficient empty packaging inventory to send back FSDs in the right packaging materials. On the other hand, holding this inventory should be done at the lowest possible costs and with the right proportion of local warehouse space used for empty packaging and spare parts.
Currently, the local warehouses find it very difficult how to handle empty packaging materials, and as a result, they just store all empty packaging materials. The empty packaging situation at some local warehouses has led to the belief that improvements in managing the empty packaging process are necessary. Simplifying the process could help the local warehouses to facilitate the decision-making regarding empty packaging. The following part of this section will discuss the major aspects of the problem situation that underlie this belief, but first, further information is given about the local warehouses of ASML.

Local warehouses
In total, ASML has X local warehouses (also: LWHs or locals) worldwide which are operated by employees of third-party logistics (3PL) providers. The employees which are working in the local warehouses are employees of the 3PL providers. This means that no employees of ASML are working in these warehouses. To ensure that the processes go as smoothly as possible, ASML keeps close contact with the 3PL providers in the local warehouses.

The local warehouses of ASML are usually very close to the customers. Therefore, the packaging with and without parts are transported with truck from the local warehouse to the customer, and vice versa. However, which transport mode is used is dependent on the actual distance. Occasionally, the customer and local warehouse are located next to each other and then the materials are transported with a forklift truck. In addition, the local warehouse and the customer’s fabrication plant (short: customer’s fab) are often one on one, which means that there is one local warehouse for one customer. However, there are cases that this characteristic is not applicable.

The local warehouses have a large amount of spare parts in inventory. This inventory is necessary for satisfying the service levels agreed with the customers. If a part has failed, it can be replaced quickly by transporting the part from the local warehouse directly to the customer, which saves a lot of time. The storage of an unnecessary big amount of empty packaging materials in the local warehouses can disturb the daily operations as described above, which may cause high costs. In addition, the empty packaging materials occupy valuable warehouse space.

Empty packaging process
When a part with packaging arrives at the local warehouse, it must be send to the customer, where the part needs to be unpacked. It is dependent on the number of layers and the specific layer which is to be removed where this unpacking process takes place. Two different options are possible:
1. The part is totally unpacked at the location of the customer. Thus, all layers of the packaging are removed at the fabrication plant of the customer.
2. The part is partially unpacked in the local warehouse. Here, the most outer layer is already removed from the packaging. The other layers are removed at the customer’s fab. More information about these flows of packaging materials can be found in Chapter 4. Due to these two unpacking processes, empty packaging is present both at the local warehouse and at the customer’s fab. Furthermore, a lot of customers do not have (enough) space to store all empty packaging materials. In this case, the empty packaging materials are transported from the customer back to the local warehouse. Once the empty packaging has arrived in the local warehouse, there are three possibilities for handling this empty packaging: 1. Return; 2. Keep; 3. Scrap.

The 3PL employee in the local warehouse must check the information system or ask an CSCM employee what to do with the empty packaging. Currently, the company uses a threshold value for returning or disposing empty packaging materials. Throughout this report, it is assumed that this threshold value is the following:

\[ \text{Packaging price} < \varepsilon X \]

This implies that, if this is true for a specific empty packaging material, the local warehouse employee should dispose the empty packaging material. If the price of the packaging material is above this value, i.e. greater or equal to \( \varepsilon X \), then the packaging material should be returned to the factory warehouse.

The process mentioned above is the way how the empty packaging process currently should be executed. However, this is not the case and each local warehouse handles empty packaging materials differently, i.e. some local warehouses throw away all packaging materials and other local warehouses keep every empty packaging material that they have received from the customer in inventory. This leads to overfull local warehouses and disposal of the wrong packaging materials, which causes unnecessary high costs, i.e. inventory costs and procurement costs.

To conclude: At the final stages of the supply chain, ASML has an empty packaging problem which is getting larger and larger each day.

1.3.2 Problem Statement

For empty packaging, ASML has not yet determined how to manage this process. A properly defined packaging process can contribute to organizational advantages such as a long-term and continuous operations cost advantage and reduced packaging material costs (Maleki & Reimche, 2011). This provides an opportunity for ASML to reduce the occupied space by empty packaging in the local warehouses and reduce their packaging costs. This and the current situation at the customers and especially the local warehouses are the motivations for the company for having researched how the empty packaging process should look like in the future. The aim of this Master thesis project is to develop a decision support model for the stakeholders of this problem to manage the empty packaging process accurately. This leads to the following problem statement for the project:

**Problem Statement:**
A large amount of empty packaging is stored in the local warehouses of the company worldwide, which occupies space for other more critical stocks and causes high inventory costs.
1.4 Relevance of the Project

ASML already did a couple of projects that were related to empty packaging. Nevertheless, empty packaging is still a problem, and since the company is still growing, it means that more parts will be shipped which in turn leads to more empty packaging in the local warehouses. Therefore, the company has a great necessity to get a decision support model and clear processes for empty packaging. This project will contribute to the development of both aspects.

The analysis of data about empty packaging has shown the relevance of this project. The empty packaging inventory in the local warehouses of ASML is enormous, and in 2017, X percent of the total warehouse space was occupied by empty packaging and this percentage is expected to grow. In terms of costs, this comes down to a total inventory holding cost for empty packaging materials of hundreds of thousands of euros in the year 2017. In addition to this, a lot of money is lost by wrongly scrapping packaging materials, while these packaging materials had the potential to be reused. Thus, disposing these packaging materials was in most cases undesired and unnecessary.

The results of the data analysis show that this project is of a great relevance for the company. Furthermore, when the results of this project are implemented within ASML, they can take advantage of it and decrease the costs related to packaging materials.

The focus of this project will be on designing a solution for ASML, such that managing the empty packaging within the supply chain will be more efficient. Nevertheless, this project also contributes to the existing literature about this topic. Combining returnable and disposable packaging into one packaging system is, to the best of our knowledge, not yet researched. Based on this, we can conclude that a decision support model for combining different packaging systems is not yet developed and therefore, this research could fill this gap in the literature. By focusing on two packaging types into one packaging system, it is ensured that new insights are added to the present literature.

All in all, this research will contribute to a more efficient management of empty packaging at ASML, and will offer new insights for other companies and the scientific state-of-the-art.

1.5 Structure of the Thesis

The rest of this report is organized as follows. In the next chapter, Chapter 2, the research design for this project is described. The chapter starts with a discussion of the relevant literature, and based on this, the research questions will be presented. Subsequently, in Chapter 3 the different packaging categories and the packaging types used at ASML are discussed. In the following chapter, Chapter 4, the forward and return flow of the packaging materials are presented. Next, Chapter 5 presents the current processes regarding empty packaging in the local warehouses and the root causes of the empty packaging problem are identified. With the knowledge of the root causes and the insights of the current processes, the new process is designed in Chapter 6. Subsequently, Chapter 7 describes the development of the decision support model for the empty packaging in the supply chain of the company. Chapter 8 discussed the implementation of the model into MATLAB and the model is evaluated on its correctness. In Chapter 9, the results of the model and the results of the sensitivity analysis are presented. In the final chapter, Chapter 10, the main research question is answered. Moreover, we present the conclusions of this study, we give recommendations based on our work, as well as suggestions for future research are presented. Lastly, the academic contribution of this Master thesis project is discussed in this last chapter.
2 Research Design

In this chapter, the research design of this project is discussed. The first section, Section 2.1, includes a literature study in which all the relevant literature will be summarized. Subsequently, in Section 2.2, the main research question and the sub research questions are introduced. In addition, it is explained how the research will be carried out and which methods are going to be used. In Section 2.3 a clarification of the project scope is given.

2.1 Literature Study

In this section, a summary of the literature relevant to the problem is given. This summary is based on a literature review on decision support models for managing empty packaging in a closed-loop supply chain (see Linnartz, 2018) and we refer to this document for full details. The subsequent part of this section is organized as follows. Section 2.1.1 introduces closed-loop supply chains where Returnable Transport Items (RTIs) are included. This section also gives an overview of the concepts used throughout this report. Subsequently, Section 2.1.2 presents an overview of literature in the field of management systems for empty packaging. In the next section, Section 2.1.3, several decision support models for managing empty packaging are presented. Lastly, Section 2.1.4 discusses the contribution of this Master thesis project to the literature.

2.1.1 RTI Closed-Loop Supply Chains

As already introduced in Chapter 1, Introduction, this Master thesis project will be conducted in the field of management systems for empty packaging and decision-making models for empty packaging in a closed-loop supply chain. Before diving into specific details about this research field, it is important to get a better understanding of these concepts. Hereafter, we will give an introduction into the RTI closed-loop supply chains and decision support models for managing RTIs.

According to Kroon & Vrijens (1995) returnable or reusable packaging can be defined as packaging materials which are used more than once in the same form. Packaging materials which are disposed after one usage are called one-way distribution items (Flapper, 1996) or disposable packaging (Silva, Renó, Sevegnani, Sevegnani, & Truzzi, 2013). Returnable packaging can be of different types, e.g. containers, pallets, boxes, or crates, whereas disposable packaging are usually only cardboard boxes.

During this Master thesis, the term "returnable transport item (RTI)" is also used. RTIs are a special type of returnable packaging and can be used for internal transport of materials, components, semi-finished products, and for the distribution of finished products (Hellström & Johansson, 2010). Returnable transport items (RTIs) are defined by ISO (2007) as all means to assemble goods for transportation, storage, handling and product protection in the supply chain which are returned for further usage. RTIs can also be of different types, such as returnable pallets, trays, boxes and crates. Note that freight containers, trailers and other similar enclosed modules are not covered by the term 'returnable transport item'.

In a supply chain, companies often use returnable packaging or RTIs. By using this type of packaging materials, they are closing their supply chain. In this case, we speak about closed-loop supply chains (CLSCs). In a CLSC, the focus is on taking back products from customers and adding new value to these products by reusing the entire product, and/or some of its modules, components, and parts (Guide & Van Wassenhove, 2009). By taking back the products a reverse flow is added to the supply chain and this flow as well as the whole CLSC needs to be managed properly. Nowadays, closed-loop supply chain management is defined by Guide & Van Wassenhove (2009) as "the design, control, and operation of a system to maximize value creation
over the entire life-cycle of a product with dynamic recovery of value from different types and volumes of returns over time. According to Flapper, Van Nunen & Van Wassenhove (2005), a typical closed-loop supply chain has a forward flow and a return flow as presented in Figure 2.1.

According to Glock (2017), the use of decision support models in RTI closed-loop supply chains could facilitate an efficient management of RTI usage. Therefore, the use of decision support models (also called decision support systems) for returnable packaging is also studied during the literature review. Decision support systems (DSS) are computer technology solutions that can be used to support complex decision making and problem solving (Shim et al., 2002). According to Sprague (1980), these systems are mostly interactive systems and can help decision makers utilize data and models to solve unstructured problems. Hence, decision support models can help companies simplifying the decision-making regarding RTIs in their supply chains. In addition, these models ensure that the finished product reaches the customer at the least total cost and/or with a minimal environmental impact (Glock, 2017).

In recent years, the management of closed-loop supply chains has received more and more attention. Closed-loop supply chains do not only contain the traditional forward supply chain activities, the additional activities of the reverse supply chain are also included. These activities of the reverse flow are of great importance. According to Guide, Harris on, & Van Wassenhove (2003) the following additional activities are part of the reverse supply chain:
- Product acquisition to obtain the products from the end-users;
- Reverse logistics (RL) to move the products from the points of use to a point(s) of disposition;
- Testing, sorting, and disposition to determine the product’s condition and the most economically attractive reuse option;
- Refurbishing to enable the most economically attractive of the options: direct reuse, repair, remanufacture, recycle, or disposal, and;
- Remarketing to create and exploit markets for refurbished goods and distribute them.

The above list of activities does not mention the packaging in which the products are shipped. However, for several reasons packaging is a very important part of a product. As mentioned in the research of Flapper (1995), packaging has a couple of functional aspects. These are: protection, transport, marketing, storage, and keeping the products together. Due to these functional aspects of packaging materials, there is a greater probability that the product will arrive undamaged at the next stage of the supply chain. Hence, it can be concluded that packaging activities need to be included to the list of activities for managing the complete closed-loop supply chain. However, until now, most literature has only focused on the management of the forward and the reverse flow of materials and products. The management of reusable packaging materials which are indispensable to make the forward and return flow happen, has just recently gained the attention of researchers. As mentioned in the research of Glock (2017), reusable packaging materials represent an important corporate asset in many industries today. Therefore, it is essential to further investigate this topic.

Within this research, the focus will be on a special type of reusable packaging materials, the so-called returnable transport items (RTIs), such as pallets, trays, boxes and crates. The use of this
type of packaging materials through the different stages of the supply chain can lead to many advantages (see Hekkert et al., 2000; Hellström & Johansson, 2010; Hellström, 2009; Maleki & Reimche, 2011), e.g.:

- Reduced packaging material and waste
- Improved protection and security of products
- More efficient handling and cube utilization
- Better opportunities for outsourcing, pooling and standardization
- Lower CO₂ emissions across the lifecycle of the packaging material

Only if the interaction between product and packaging is adequately managed, the benefits mentioned above can be realized. Therefore, RTIs should be incorporated in the management of closed-loop supply chains. Another reason why it is important to incorporate RTIs in a supply chain is that packaging does not come without waste. A lot of packaging materials have a relatively short lifetime and are one-way distribution items, which means that these materials are only used once and after that one-time use, the materials will be disposed, and, disposal means waste. Therefore, it becomes crucial for companies to include the management of packaging within their forward and reverse supply chain. The addition of RTIs in a closed-loop supply chain is, among others, researched by Glock. In one of his articles (Glock, 2017), he mentions the importance of this type of supply chains and describes RTI closed-loop supply chains as supply chains where returnable transport items (RTIs) are used for shipping products along the different stages of the supply chain. The supply chain starts with loading the RTI. Once this is done, the RTI is sent to a recipient (R) and will be emptied. The empty RTI will be sent back to the sender (S). If necessary, the RTI could be cleaned and/or repaired. These activities could be done at either the sender or the recipient. This process is presented in Figure 2.2.

![Figure 2.2 An example of a RTI closed-loop supply chain (Glock, 2017)](image)

Important to mention is that the focus of an RTI closed-loop supply chain is on the return of empty RTIs, and not on the return of products. To manage this return properly, a decision support model could be developed.

### 2.1.2 Management Systems for Empty Packaging

In this section, the main findings in the field of management systems for empty packaging are discussed.

Managing returnable packaging is a challenging task. Therefore, first, a packaging system need to be set up. This implies that the company needs to decide which type of packaging system fits their supply chain best. Once this is done, the RTI system needs to be managed appropriately to achieve the objectives which are determined for the production and logistics functions. Several activities need to be planned, including the dispatch and return of the packaging materials, cleaning and repair processes and the replacement of damaged or lost RTIs (Glock, 2017). The interdependencies between the products and RTIs make the coordination of an RTI system very challenging. By first defining a management system for empty packaging and then developing a
decision support model could be very helpful in coordinating an RTI system and this makes the management of it less challenging.

Firstly, it was found that some papers compare the performance of different packaging systems based on economic and/or environmental impact. Flapper & Kiesmüller (1999), for example, focused on the economic cost for using a reusable distribution item to distribute a product to a customer taken into account a maximum number of times the distribution can be reused. The packaging systems that are most frequently compared are: returnable packaging vs. disposable packaging (see Silva, Renó, Sevegnani, Sevegnani, & Truzzi, 2013). It has been shown that adding a returnable packaging system in reverse logistics has advantages that could contribute technically, economically, and environmentally to the sustainability of companies.

Besides this, it was investigated by Elia & Gnoni (2015) how two different pallet interchange systems (i.e. direct and postponed interchange) could influence the economic and operational performance of a company. Roy, Carrano, Pazour, & Gupta (2016) studied how three different pallet management strategies (i.e. single-use expendable pallet system, buy/sell program, leased pallet pooling program) could influence these performances. Here, it can be concluded that it is crucial in pallet management that the strategies are coordinated between all up- and downstream customers and the logistics service provider (LSP). Coordination could lead to a more reliable and faster supply chain.

One of the works in the sample (Zhang, Segerstedt, Tsao, & Liu, 2015) looked at two different modes for returnable packaging (i.e. shared vs. dedicated mode). It has been shown that the shared mode has a preference over the dedicated mode due to a reduction in all cost types considered (transportation cost, safety inventory holding cost, and the pipeline inventory holding cost).

A comparison of the strict equal exchange policy and the relaxed equal exchange policy performed by Carrasco-Gallego, Flapper, & Ponce-Cueto (2012a) showed that the first is suitable for situations where the customer demand is relatively constant; the latter fits better if the demand shows trends or seasonality.

The last important finding was that if companies want to combine a disposable and returnable packaging system into one packaging system, the best balance configuration is to use 47.1% reusable and 52.9% disposable packaging materials in the system (see Bortolini, Galizia, Mora, Botti, & Rosano, 2018).

2.1.3 Decision Support Models for Empty Packaging
In this section the main findings in the field of decision support models for empty packaging are presented.

Currently, within the literature, many different decision support models for managing empty packaging have been developed. As already discussed before, several researches have designed models for supporting decision-makers in choosing the best fitting packaging system. Other researchers investigated how returnable packaging can be managed in the most appropriate way and developed a model for this. These researches have led to a lot of insightful results, which can be applied in practice.

Decision-criteria have been developed by Kim & Glock (2014) to show under what conditions it is most economic feasible to use RFID-tagged or non-tagged containers. These criteria could help managers to decide whether it is profitable for the company to implement a tracking system for their RTIs. Furthermore, it was found that when companies implement a RTI safety stock or a
safety stock in combination with a RTI safety return time, this leads to a better performing supply chain.

Besides this, it was investigated by Kim, Glock & Kwon (2014) what the effect was of delays in RTI returns on the total costs of the supply chain. For this, guidelines were developed that could support managers in minimizing these costs. Results indicated that it is most appropriate to select a higher return lot size in case the average return time would increase.

Regarding forecasting of RTI returns, Carrasco-Gallego & Ponce-Cueto (2009) found that if a direct replacement policy is applied within the supply chain, the forecast for sales is approximately equal to the forecast of RTI returns. This implies that companies only need to forecast RTI returns if another type of return policy is used.

Different inventory management strategies have been designed to support companies by managing their RTIs. It was examined by Yun, Lee, & Choi (2011) whether the (s, S)-policy is a good inventory management strategy. Bottani, Montanari, Rinaldi, & Vignali (2015) has developed an inventory management model for RTIs based on the EOQ-model. Furthermore, it was found that tracking returnable packaging with RFID-technology is a good way of making the RTI inventory visible, and as a result, it is easier to manage this (see Mason, Shaw, & Al-Shamma’a, 2012; Kim & Glock, 2014).

Furthermore, decision support tools have been developed to decide on the container fleet size, set appropriate levels of safety stocks at ports, and determine the empty container repositioning decisions (see Dong & Song, 2009; Song & Dong, 2011; Jula, Chassiakos, & Ioannou, 2006). In addition to this, Choong, Cole & Kutanoglu (2002) found that a longer planning horizon has a couple of advantages: it could help shipping companies in managing their empty container distribution, the outsourcing of containers can be better managed, and it is easier to use slower transportation modes.

2.1.4 Contribution to the Literature

The analysis of the literature has shown that most literature focus on the choice between disposable and returnable packaging materials. This type of research looks at what the most economic and/or environmental friendly option is for companies. However, the company under consideration in this Master thesis project is using both disposable and returnable packaging materials. Due to the specifications and characteristics of the parts to be packed, the company will always need to deal with both packaging types. As beforementioned, one of the sampled works identified what the best balance configuration is when companies want to combine the two packaging types. However, how to manage such a packaging system is, to the best of our knowledge, not yet researched. Based on this finding, we can conclude that a decision support model for combining different packaging systems is not yet developed and therefore, we identified this as a gap in the literature.

The literature study (see Linnartz, 2018) is the theoretical basis on which this Master thesis project will be built upon. The knowledge gained from analyzing the state-of-the-art in this literature field is used to provide the company with recommendations on how to manage their empty packaging in the warehouses and to develop a decision support model for the packaging system that fits this company. Keeping in mind the identified literature gap, the Master thesis project will provide new knowledge about combining disposable and returnable packaging into one packaging system. The challenge of this Master thesis is to bridge this gap and provide new knowledge both for the company as well as for the state-of-the-art.
2.2 Research Questions

In the present section, the main research question and the sub research questions are introduced. Given the context and problem statement as discussed in Chapter 1 and the knowledge gained from the literature study in Section 2.1, the following main research question has been defined:

**Main Research Question:**
*What to do with empty packaging within the different stages of ASML’s supply chain?*

The motivation for defining this main research question is as follows. For ASML it is important that they reach the service levels agreed with the customers. One of these service levels is to replace a faulty part as fast as possible. Therefore, ASML supplies the local warehouses with critical spare parts such that a defect part can be replaced with the spare part. In other words, this spare part inventory ensures that time is saved, and this also means saving money. However, when the local warehouses are full of empty packaging materials, this means that less space can be used to store spare parts. Furthermore, a great amount of money is involved in the empty packaging problem, e.g. high inventory and procurement costs. Since ASML has different ways of working in the local warehouses regarding empty packaging, this project tries to find an answer to this question by designing a standardized process such that empty packaging can be better managed. More specifically, the project aims to find a management program that consists of a decision support model to solve the empty packaging problem. The final deliverable of this Master thesis project is a management program that includes this decision support model. The remaining part of this section introduces the sub research questions. With the help of these questions we will be able to answer the main research question.

Two research questions have been defined to answer the main research question. First, knowledge about the current processes must be gained. Since ASML uses many different packaging types, it may be complex to determine the processes. However, a detailed understanding of these processes is important since it provides input for the selection of the decision support model. For a similar reason, it is important to gain knowledge about the root causes of the empty packaging problem. Finding these root causes is an essential part of solving this problem. Therefore, the first sub research question aims to find the root causes of the empty packaging problem. This leads to the first research question:

**Research Question 1:**
*What are the root causes of the empty packaging problem?*

Before this first research question can be answered, an analysis of the packaging used within ASML is executed. The packaging categories will be determined. The last part of this analysis consists of making the forward and return flow of the packaging materials visible. Hereafter, we will continue with answering Research Question 1. To answer this research question and to get a more detailed view of the packaging problem within the local warehouses, a Root Cause Analysis will be conducted. Employees of the CSCM department and employees of other departments who are closely related to (empty) packaging will be interviewed and asked for their view on this problem. During these interviews and with the help of the five-why technique root causes will be identified. More root causes can be identified by sending a short survey to the 3PL employees of the local warehouses. This survey is also used to find out what the current processes regarding empty packaging within the local warehouses are. The insights of the interviews and the current
processes are used to determine the root causes of the empty packaging problem. All gathered information could be helpful to find out which type of decision support model to select and what the focus of the model must be.

The knowledge obtained in Research Question 1 will be used in the selection of the best fitting decision support model. Decision support models are defined as computer technology solutions that can be used to support complex decision making and problem solving (Shim, et al., 2002). Thus, these models provide guidelines to solve unstructured problems. The literature describes many decision support models for managing empty packaging. We need to find out what the most suitable model is for this empty packaging problem. An alternative is to use one (or more) of the existing models as a basis for developing a company specific decision support model. This leads to the second research question:

**Research Question 2:**

*What is a suitable decision support model for managing empty packaging?*

This research question will be answered by first defining criteria that the decision support model must meet. These criteria are determined by reviewing literature about the development of decision support models. This will help us to find the appropriate criteria which is useful to select the right decision support model. Secondly, we will investigate what the available decision support models in the literature are. In Section 2.1.3, we already presented some useful decision support models for managing empty packaging. Moreover, a new process for handling empty packaging materials in the local warehouses of the company is designed. If it is known what the best way of working regarding empty packaging is, we can consider this in the development of the decision support model. From this, the model which is most appropriate for the company's situation is selected. The last part in answering Research Question 2 is to develop the decision support model.

The answers to the two sub research questions provide the answer to the Main Research Question, and based on this, we can give recommendations to the company what to do with the empty packaging in their supply chain.

### 2.3 Project Scope

With the purpose of reducing the size of the problem situation and to achieve enough depth in this Master thesis project, we need to set some boundaries and determine what is in or out of scope. The scope of this project is set as follows:

- The local warehouses work closely together with the customers; therefore, a part of the research will look at the customer side of the problem. However, the focus will be on the local warehouses. The central warehouses (CWH) and factory warehouses (FWH) are only considered as a possible place to reallocate the empty packaging. For the other analyses, these warehouses are not in the scope of this project.
- Only the reallocation and storing of functioning empty packaging will be taken into consideration. As a result, maintenance and repair of the returnable empty packaging are left out of scope.
- Clean assys will be left out of scope. A clean assy is a packaging layer which is disposed after one use (see Chapter 3), and therefore not interesting for this project.
- We will only focus on the packaging materials of service parts. The packaging materials of other type of parts are not included in this research.
3 Packaging at ASML

This chapter provides relevant information about packaging at ASML. In Section 3.1 it is discussed what packaging is and what the functions are of this packaging. The next section, Section 3.2, introduces the different packaging categories.

3.1 Packaging system of ASML

In this section it is discussed what packaging is (Section 3.1.1) and what its functions are (Section 3.1.2). First, some definitions of terms used within ASML are given. These terms will be used repeatedly during this project and therefore need more explanation. It concerns the following terms:

- **Service part materials** are components, sub-assemblies, or assemblies that are used to replace defect components of the lithography systems. These so-called service parts are identical to and interchangeable with the part that it is intended to replace.

- **Disposible packaging materials** are intended to enclose or hold together parts that need to be shipped. In other words, the part that is to be packed can be packed into or onto the packaging material. The most frequently used packaging materials are crates, (cardboard) boxes, containers and pallets. This type of packaging material is not to be returned and/or re-used, and therefore called disposable packaging materials.

- **Returnable packaging materials** are intended to enclose or hold together parts that need to be shipped. After the use of this type of packaging material, it needs to be returned to one of the factory warehouses, such that the packaging material can be used another time. Sometimes, returnable packaging materials are stored at the customer location. In this case, the packaging remains the property of ASML. (ASML, 2015a)

3.1.1 What is Packaging?

As already described in Section 1.1, packaging can be defined as the packing materials employed around an article to contain, handle, protect, display, promote, and/or transport it, and in addition, the packaging keeps the article clean. Within ASML packaging is crucial and this has several reasons. The parts that need to be shipped from ASML to the customers are, in most cases, very expensive and sensitive to external influences. Therefore, packaging of good quality is necessary to protect the parts and to arrive without damages at the customers. More functions of packaging will be presented in Section 3.1.2.

3.1.2 The Functions of Packaging at ASML

Parts can only function properly at their destination if they reach this destination intact. This means that a part needs to be packed properly. Proper packaging makes it possible to identify, handle, transport and store the part in all stages of the logistics chain. It does this in a way which is safe, legal, ergonomic and cost effective. It prevents function loss of the packed parts and it does not contaminate the cleanroom of ASML or its customers. (ASML, 2014a)

Packaging of ASML is indispensable and essential when transporting the parts. That's why each packaging at ASML must meet ten main requirements, which are the following (ASML, 2015b):

The packaging...

1. Enables handling of the product
2. Enables transport of the product
3. Enables storage of the product
4. Protects the product from function loss
5. Complies with the ways of working in ASML logistics (including warehousing, service, planning, etc.)
6. Promotes ASML conform ASML's corporate identity
7. Prevents contamination of the cleanroom and the work center
8. Promotes safety and ergonomics during its use  
9. Is integrally cost effective  
10. Minimize impact on the environment.

3.2 Packaging Categories
A couple of different packaging types can be distinguished at ASML and can be divided into two main categories: Standard Packaging and Special Packaging. These two main categories are divided into two sub-categories: Disposable Packaging and Returnable Packaging. Within these two sub-categories, three packaging types are distinguished: Clean Assys, Transport Assys and Send Assys. The term ‘assy’ is an abbreviation for ‘assembly’ and this abbreviation will be used throughout the rest of this report. An overview of the packaging categories and types is presented in Table 3.1. The following sections will give more information about these categories and types. The scope of this project has been defined with the help of these categories.

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<thead>
<tr>
<th>Category</th>
<th>Sub-Category</th>
<th>Type</th>
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<tr>
<td>Standard</td>
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<td>Send Assy</td>
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<td>Transport Assy</td>
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<td>Returnable</td>
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<td>Special</td>
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<td>Transport Assy</td>
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3.2.1 Standard and Special Packaging

Standard Packaging
Standard packaging includes all generic, off the shelf packaging materials (ASML, 2014b). Packaging materials in this category are not part-specific, which means that all parts that do not need special designed packaging, can be packed with standard packaging. Hence, this type of packaging material is usable for a wide range of parts. Approximately 75% of the total amount of packaging used within ASML is standard packaging. This proves the fact that standard packaging can be used for a lot of different parts. In addition, standard packaging is readily available at the pack locations. An employee who must pack a part with the ‘standard packaging’ indication needs to use his/her own judgement to select the appropriate transport assy and send assy. This is due to that in SAP it is not precisely stated which transport and send assy is required for part with the standard packaging indication. Examples of standard packaging are the following:

- Bags (plastic)
- Fixtures (carton)
- Boxes (carton, wood, plastic)
- Pallets (wood, plastic)

Standard packaging has a couple of advantages over special packaging, especially that this type is generic, relative cheap when compared to the price of special packaging, available worldwide, easy to replace, and can be applied instantly without the need of an engineering change. However, standard packaging also has some limitations. When items are too heavy, large or with exotic sensitivities, they cannot be packed with standard packaging. Furthermore, it is not possible to
pack item sets with standard packaging. Item sets are two or more parts that together form one item and need to be shipped together. Lastly, this packaging type is, in most cases, not intended for circulation. This means that standard packaging is a one-way distribution item and not used multiple times. Thus, after one use, the packaging is disposed. The reason for this is that standard packaging is, as mentioned earlier, cheap. Therefore, it is not needed to store and/or return this packaging. Within ASML, there is the rule that packaging materials that have a value less than X euro need to be disposed after one usage. Even when the packaging could be used another time because it is not damaged, it is scrapped anyway. Thus, in some cases it is technically possible to reuse the packaging, but the threshold value rule avoids this. However, there are exceptions. A couple of standard packaging materials are more expensive (price ≥ €X) and can be used multiple times. In this case, the standard packaging is called returnable packaging.

**Special Packaging**

Special packaging are specific packaging materials designed for a specific product or family of products (ASML, 2014b). If the outcome of the packaging wizard (application in SAP) is "special packaging required", the item cannot be packed with standard packaging. Special packaging is usually specified and developed under responsibility of the ASML packaging group at the specific ASML location. However, this type of packaging is sometimes also developed by the supplier. Approximately 25% of the total amount of packaging used within ASML fall into the special packaging category. Of this 25%, about 10% is disposable packaging and 90% is returnable packaging. There are over 1000 different types of special packaging which can be divided into the three packaging types, i.e. clean assy, send assy, and transport assy. In addition to this, special packaging materials are often very expensive. The prices of special packaging can range between €1000.00 and €10,000.00. Some packaging materials can even have a price higher than €10,000.00. Examples of special packaging are:

- Vacuum packaging
- Support frames
- Insulated crates
- Durable insulated crates
- Custom pallets with wheels
- Packaging (crates, boxes) with special foam
- Transport tools
- Cubes (special type of plastic boxes)
- Plastic cases
- Durable crates
- Flight cases with(out) wheels
- Generic buffered custom pallets
- Airconditioned/temperature regulated containers

It can occur that an item is packed in a combination of special and standard packaging. In this case, the standard packaging is used as part of a special packaging design.

### 3.2.2 Disposable and Returnable Packaging

The definitions of these packaging categories are already described in Section 3.1, but will be repeated here shortly to give a good and complete view of all packaging categories:

- **Disposable packaging** are all the packaging materials that are only used one time and disposed after this use. Thus, the packaging materials in this category are not to be returned and/or re-used.

- **Returnable packaging:** After the use of this type of packaging material, it needs to be returned to one of the factory warehouses, such that the packaging material can be used another time.

To decide whether a packaging material is disposable or returnable packaging, ASML determined the €X-rule which was already presented in Section 1.3.1.'
3.2.3 Clean Assy, Transport Assy, and Send Assy

Clean Assys
Clean assys are always standard packaging and are airtight foils or bags which are wrapped directly around the part. This type of packaging is used to protect the cleanroom part from contamination, moisture and/or electrostatic discharge (ESD) inside the clean room and/or the transport assy. Due to the airtightness of clean assys it is almost impossible to not damage the clean assy while unpacking the part. Furthermore, clean assys need to satisfy the cleanliness of the cleanroom and to prevent contamination of the part and the cleanroom, clean assys are always one-way packaging. In addition, the value of clean assys is usually less than €X, and then the rule is to dispose the packaging after the first usage. Because clean assys are no returnable packaging materials, this type of packaging will not be in scope of this research.

Transport Assy
The transport assy is a packaging material which provides mechanical protection and enables handling of the package in the cleanroom. Transport assys can fall under both main categories (standard and special packaging) and can be disposable or returnable packaging.

Send Assy
Send assys are packaging materials which facilitates transport, storage and handling of its contents in the world outside the cleanroom and the grey area. The grey area is the space before the cleanroom is entered. This area is cleaner than the outside world, but not so clean as in the cleanroom. As well as transport assys, send assys can be standard or special packaging. Send assys are the most outer boxes in which the part is send to the customer.

Transport assys and send assys are in most cases returnable transport materials (RTMs). Usually, RTMs have a value between €1000 and €10,000. Based on the types described previously, Table 3.1 can be adapted and turned into the following table which is presented below in Table 3.2.

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-Category</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>Disposable</td>
<td>Clean Assy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Send Assy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transport Assy</td>
</tr>
<tr>
<td></td>
<td>Returnable</td>
<td>Send Assy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transport Assy</td>
</tr>
<tr>
<td>Special</td>
<td>Disposable</td>
<td>Send Assy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transport Assy</td>
</tr>
<tr>
<td></td>
<td>Returnable</td>
<td>Send Assy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transport Assy</td>
</tr>
</tbody>
</table>
4.1 Forward Flow

As mentioned above, the forward flow is the same for all packaging types. This means that all clean assys, send assys, and transport assys run through the same stages of the supply chain. As is shown in Figure 4.1, the forward flow starts at the supplier. From the supplier, the packaging with part go to the factory warehouse first. Secondly, it goes to the central warehouse and from here the packaging including the part is delivered at the local warehouse. From this place the packaging goes to the customer. At the local warehouse, there are two options:

1. The part is partially unpacked in the local warehouse. In this case, the send assy is already removed from the packaging. The other layers are removed in the grey area and the cleanroom of the customer.

2. The part is totally unpacked at the location of the customer. The packaging of the part stays untouched when it arrives at the local warehouse and with all packaging layers it is transported to the customer. Here, all layers are removed in the grey area and the cleanroom of the customer.

After removing all packaging layers, the packaging is empty. This is the end of the forward flow of the packaging materials.

![Figure 4.1 Packaging Forward Flow](image)

Note: ASML gets service parts from its suppliers with the supplier’s packaging. Before sending the part to the local warehouse and the customer, the outer layer (i.e. the send assy) is removed in the central warehouse. A new send assy with ASML logo is added to the packaging layers and the part is ready to be shipped to the local warehouse.

4.2 Return Flow

The forward flow is finished when the part is removed from the packaging layers. At this point, the clean assy, send assy and transport assy are empty and this is the start of the return flow of the packaging materials.

After removing all packaging layers, the packaging is empty and needs to be transported back to the local warehouse. Note: This is only necessary when we are dealing with returnable packaging
Clean assys are always disposable packaging materials. As a result, this type of assy only has a forward flow and no return flow. This is different for transport assys and send assys. As explained in Section 3.2, transport and send assys are either disposable packaging or returnable packaging. If we are dealing with a transport assy or send assy which is disposable, we only have a forward flow for these packaging types. However, if the transport or send assy falls into the returnable packaging category, there exists a return flow for this packaging types. This return flow is shown in Figure 4.2 and will be explained below.

![Figure 4.2 Packaging Return Flow](image)

First, the empty packaging at the customer needs to transported back to the local warehouse. Here there are two possibilities for the packaging:

1. The packaging is stored in the local warehouse and reused for transporting a defect part back to the central warehouse. As a result, the packaging is returned including the defect part. The packaging and part first are shipped to the central warehouse and as a last step, the packaging including the part are send back to the supplier. Here, the part is repaired, and the packaging could be cleaned and/or repaired.

2. The packaging at the local warehouse is not needed for a defect part. Thus, this packaging material is shipped back to the factory warehouse. Once it is back in the factory warehouse, it should be repaired and/or cleaned such that the packaging is ready to transport a new part.

Currently, both return flows happen not so frequently. Often, it occurs that the stored packaging materials are lost in the local warehouse and the 3PL employees need to order new empty packaging materials to transport a defect part. Another possibility is that the transport or send assy is already disposed at the customer’s plant. Often, the employees at the customer are not aware that they are dealing with returnable packaging and as a result, the packaging material is thrown away. The same applies for the second return flow. In the case that the customer is aware of the returnable packaging, it will be transported to the local warehouse. However, here, there are no clear guidelines what to do with the packaging. Thus, in the local warehouse it could occur that the packaging is still disposed or the 3PL employees store the empty packaging in the local warehouse instead of returning it to the factory warehouse.

As can be read above, the packaging return flow is determined within ASML, however this flow does not take place yet. This causes a major problem in the local warehouses which needs to be solved. This project attempts to provide a solution to this empty packaging problem.
5 Root Cause Analysis

In this chapter the first research question is answered.

Research Question 1:
What are the root causes of the empty packaging problem?

With the help of a Root Cause Analysis (RCA), the root causes of the empty packaging problem are determined. A Root Cause Analysis is a method of problem solving used for identifying the root causes of faults or problems (Wilson, 1993). If the root causes of the problem are known, we can tackle this problem better and we can work to a solution in a more structured way. The subsequent part of this chapter is organized as follows. Section 5.1 describes the results of the analysis of the empty packaging lists of several local warehouses in Country A and B. In Section 5.2 we describe the current (As-Is) processes of the local warehouses. Section 5.3 presents the identified root causes and shows the results of linking these causes to the As-Is process. The last section, Section 5.4, ends this chapter with a conclusion and discussion of the results found in the previous sections. Note that all numbers used within this chapter are fictitious and serve for illustrative purposes only.

5.1 Analysis of Empty Packaging Data

To better understand the empty packaging problem, it is important to analyze data. The data which is available and used for this analysis are two Excel files including a list with empty packaging stored in local warehouses of Country A and B. It was noticeable that the local warehouses of both countries have documented different data regarding empty packaging. All local warehouses are supervised by a local ASML manager. Therefore, it was expected that the way of working and thus also the data that is documented would be the same. However, this is not the case. Table 5.1 gives an overview of the data which is collected by the local warehouses. A 12NC is a twelve-digit Numeric Code which each part and packaging of ASML has. It is a unique code and with this code the part or packaging is identified.

<table>
<thead>
<tr>
<th>Data of local warehouses in Country A</th>
<th>Data of local warehouses in Country B</th>
</tr>
</thead>
<tbody>
<tr>
<td>12NC of the part which was originally in the packaging</td>
<td>12NC of the part which was originally in the packaging</td>
</tr>
<tr>
<td>12NC of the packaging</td>
<td>Description of the part</td>
</tr>
<tr>
<td>Description of the packaging</td>
<td>Arrival date</td>
</tr>
<tr>
<td>Price of the packaging</td>
<td>Closing date (written down if packaging scrapped or returned with part)</td>
</tr>
<tr>
<td>Description of the X-plant status of the packaging</td>
<td>Packaging is used for returning or scrapping the part</td>
</tr>
<tr>
<td>Local warehouse number where empty packaging is stored</td>
<td>The square meters the packaging occupies (Only for some cases)</td>
</tr>
</tbody>
</table>

Note: Both excel files include more data, but this data is not relevant for this project.

The analysis performed in this section has the purpose to gather information about the type (Send Assys, Clean Assys or Transport Assys) and category (Standard or Special Packaging) of the empty packaging which is stored in the local warehouses. With this information, we can see what types of packaging are stored. As is shown in Table 5.1, both countries collect totally different data for the empty packaging inventory. Therefore, the analysis approach is a bit different for the two countries. These approaches and the results of the analyses are explained in the following two sections: Section 5.1.1 and 5.1.2.
5.1.1 Analysis of Empty Packaging in the Local Warehouses of Country A

The local warehouses of Country A have collected more useful data than the local warehouses of Country B. This is due to that they also included the 12NC of the packaging material itself in their list. Thus, it is exactly known what packaging material is stored in the warehouses. In addition, with this code, it is easier to collect data from SAP about the category and type of the packaging material.

Approach

The analysis starts with evaluating the description of the packaging material. Within this description, it is often mentioned what the assy type of the packaging is. For example, the description of the following two packaging materials includes the assy type: SEND ASSY DRY SHIPPER and UNIVERSAL OPTIC SEND ASSY. These descriptions show that the two packaging materials are both send assys. If the description does not include the assy type as beforementioned, it is needed to use SAP. Thus, the next step in this analysis is filling in the 12NC of the packaging in a transaction of SAP that shows some details about the packaging material. Now, we can determine the assy type (if not shown in the description) and the category of the empty packaging. For some packaging materials, the assy type and/or the category were not directly stated in SAP. In this case, other documents, i.e. the Standard Packaging Guide, and if available in SAP the Detailed Packaging Information (DPI) and/or the Technical Product Documentation (TPD), are used to categorize all empty packaging materials on the list. After categorization of all the packaging materials, it is analyzed how often the two categories and three assy types appear in the list. Hereafter, a Pareto chart is made with the data gathered from the categorization. A Pareto chart contains columns sorted in descending order and a line representing the cumulative total percentage. The left vertical axis represents the frequency of occurrence and the right vertical axis is the cumulative percentage of the total number of occurrences. Pareto charts display the data in descending order from highest to lowest frequency of occurrence, which makes it easy to identify the most common problems or issues (ASQ, 2018). Therefore, this type of chart is the most convenient with the purpose of this analysis in mind.

Results of the analysis

The total number of empty packaging materials on the list of Country A are 70 items. The list is created in May 2018. It contains three packaging materials that are in the local warehouse since July 2016. For the other items it is not clear since when they are in inventory. Thus, the data presented in the following tables and figures is data of the period July 2016 till May 2018. It appears to be that 49 of the 70 packaging materials are special packaging and 21 packaging materials fall in the standard packaging category; this is presented in Table 5.2. Figure 5.1 shows the data of Table 5.2 in a Pareto chart.

<table>
<thead>
<tr>
<th>Packaging category</th>
<th>#</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special packaging</td>
<td>49</td>
<td>70.0%</td>
</tr>
<tr>
<td>Standard packaging</td>
<td>21</td>
<td>30.0%</td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
Furthermore, the analysis shows that most empty packaging materials in the local warehouses in Country A are send assys (97.1%). Only 2.9% of the packaging materials are transport assys and no clean assys are found in these warehouses (see Table 5.3). As mentioned earlier, clean assys are out of the scope of this project, because all clean assys are one-way packaging materials and need to be disposed after one use. This analysis has shown that this is the case, because no clean assys are in stock in the local warehouses.

<table>
<thead>
<tr>
<th>Packaging type</th>
<th>#</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Send Assy</td>
<td>68</td>
<td>97.1%</td>
</tr>
<tr>
<td>Transport Assy</td>
<td>2</td>
<td>2.9%</td>
</tr>
<tr>
<td>Clean Assy</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

The last analysis for the empty packaging list of Country A combines the above categories, special and standard packaging, with the assy type of the packaging, send and transport assy. There are no clean assys on the list. By combining the category and the assy type, the following four combinations are possible:

- Special Send Assys
• Standard Send Assys
• Special Transport Assys
• Standard Transport Assys

In Table 5.4 the results of the analysis are presented. 47 special send assys are identified, which comes down to 67.1% of the total and 21 standard send assys, which is 30.0% of all the packaging on the list. Only two items (2.9%) of the combination special transport assy are identified and no standard transport assys are stored in the warehouses. Figure 5.3 shows the Pareto chart of this.

Table 5.4 Packaging Category and Type combined - Local warehouses in Country A

<table>
<thead>
<tr>
<th>Packaging Category &amp; Type</th>
<th>#</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special Send Assy</td>
<td>47</td>
<td>67.1%</td>
</tr>
<tr>
<td>Standard Send Assy</td>
<td>21</td>
<td>30.0%</td>
</tr>
<tr>
<td>Special Transport Assy</td>
<td>2</td>
<td>2.9%</td>
</tr>
<tr>
<td>Standard Transport Assy</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Figure 5.3 Pareto chart of packaging categories and assy types combined in Country A

5.1.2 Analysis of Empty Packaging in the Local Warehouses of Country B

The local warehouses of Country B have collected other data than the local warehouses of Country A. The biggest difference is that the local warehouses of Country B have not included the 12NC of the packaging material in the list. Instead of the packaging 12NC they have included the 12NC of the part. Thus, within the warehouses in Country B, it is a bit harder to categorize these packaging materials.

Approach

In the local warehouses in Country B, they only track the 12NC of the part. During an interview with one of the local warehouse managers of Country B, it was mentioned that this is done to match the part to the original package. In addition, the manager said that in the local warehouses in Country B they only store special send assys. Because this empty packaging list only included the 12NC of the part, it is impossible to check the statement of the manager. This has the following reason: If a part 12NC is filled in in the transaction in SAP, this transaction gives a list with all the packaging materials that are needed for a specific part. This means that all the packaging layers that are needed to pack that part are visible. Thus, due to this, it is not possible to check if the statement of the manager about the send assys is correct, because SAP shows the clean assy, send assy and transport assy. Because only the part 12NC is written down on the empty packaging list and not the packaging 12NC, it is impossible to verify if there are indeed only send assys in the local warehouse. Therefore, it is only checked whether the part indeed needs a send assy of the
special packaging category. Hence, for this analysis of the empty packaging list, we assumed that all packaging materials stored in the local warehouses of Country B are send assys.

The data analysis starts by filling in the 12NC of the part in the SAP transaction. This transaction gives the list of the packaging materials needed to pack the part. Here, it is shown in which packaging category, standard or special packaging, the send assy belongs to. If the packaging category was not shown in SAP, the same documents as within the analysis of country A are used to categorize all empty packaging materials on the list. Again, after the categorization of all packaging materials, it is analyzed how often the two categories appear in the list and a Pareto chart is made with the data retrieved from the first part of the analysis.

**Results of the analysis**

The empty packaging list of Country B consists in total 2359 items. The list includes data about where the empty packaging was used for. According to the list, the empty packaging can be used for return or scrap the part. If this is the case, the row of this specific part has also a closing date. This means that this empty packaging is not available anymore in the local warehouse. Therefore, the data needs to be filtered before the analysis can start. All cases where return or scrap is stated within the “Used for” column are removed from the list which resulted in 1019 remaining items. To reduce the data set to a manageable data set, it is decided to only include the most recent items of the list. Thus, a second filter is applied: only the 12NCs with a start date in May 2018 are included. As an additional constraint, the first four digits of the 12NC of the part needs to be SERV which means that only service parts are included in this analysis. These constraints reduced the data set to a list with 182 empty packaging materials, which is the final data set for this analysis. Table 5.5 displays the amount of special and standard packaging stored in the local warehouses of Country B. In total 155 special send assys and 27 standard send assys were identified. These results show that the manager who was interviewed was not totally right and that they also store standard send assys in the local warehouses. The data of Table 5.5 is visualized in the Pareto chart shown in Figure 5.4.

<table>
<thead>
<tr>
<th>Packaging Category</th>
<th>#</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special packaging</td>
<td>155</td>
<td>85.2%</td>
</tr>
<tr>
<td>Standard packaging</td>
<td>27</td>
<td>14.8%</td>
</tr>
<tr>
<td>Total</td>
<td>182</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

![Figure 5.4 Pareto chart of empty packaging in Country B](image-url)
5.1.3 Total Overview of Empty Packaging in the Local Warehouses

To get a good overview of the categories and types of the empty packaging materials on stock in Country A and B, the results of both analyses are combined. This resulted in a total of 252 empty packaging materials of which 204 items (81.0%) fall into the special packaging category and 48 items (19.0%) fall into the standard packaging category. This is presented in Table 5.6. We assumed that all packaging stored in Country B are send assys, however, it was not possible to verify this assumption. Therefore, the assy type is not included in the total overview. Again, a Pareto chart has been made with the data of Table 5.6 and this has led to chart shown in Figure 5.5.

Table 5.6 Total overview of the categories of the empty packaging in local warehouses of Country A and B

<table>
<thead>
<tr>
<th>Packaging category</th>
<th>#</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special packaging</td>
<td>204</td>
<td>81.0%</td>
</tr>
<tr>
<td>Standard packaging</td>
<td>48</td>
<td>19.0%</td>
</tr>
<tr>
<td>Total</td>
<td>252</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

During the data analysis of the empty packaging materials, it was not possible to indicate whether the packaging fall within the returnable or disposable sub-category defined in Chapter 3. This is due that in SAP it is not visible whether a packaging is returnable or disposable. The only thing that could indicate whether the packaging is returnable or disposable is the X-plant status of the packaging. The X-plant status is a status in SAP that indicates whether a packaging is returnable. Currently, this status is based on the current inventory of the empty packaging materials and the threshold value presented in Section 1.3.1: if the packaging price is less than €X scrap the packaging; if the packaging price is equal or higher than €X return the packaging material. In combination with how many packaging materials are on stock in the local warehouse, the X-plant status is determined. Thus, with the X-plant status, the decision to scrap or return the packaging could be made. However, the X-plant status of the packaging materials is not up-to-date. This is due that the current empty packaging inventory is not known, and because of this, the X-plant status cannot be updated. Therefore, the returnable and disposable sub-category is left out this analysis.

Furthermore, the analysis has shown that the empty packaging materials stored in the local warehouses are most frequently special packaging which are of the type Send Assy. Based on this gained knowledge, we can further define the scope of this project. The project will in further (data) analyses mainly focus on Special Send Assys. However, the decision support model needs to be applicable for all packaging materials. Therefore, we need to take this into account when developing the model.
5.2 As-Is Processes of Empty Packaging in the LWHs in Country B and C

In this section, the current processes regarding empty packaging within the local warehouses are explained.

5.2.1 Empty Packaging: As-Is Process in the Local Warehouse of Country B

The As-Is process of Country B is presented in the swim lane diagram below (see Figure 5.6) and is derived from interviews with a local warehouse manager of Country B. Thus, the As-Is process presented is based on the actual empty packaging processes in all local warehouses in Country B. The process starts at the customer’s fab and could end at both the customer’s fab as well as in the local warehouse.

The process showed in Figure 5.6 is described as follows:

1. At the customer’s fab, the packaging is removed from the part.
2. The empty packaging material is now available.
3. The customer support (CS) engineer checks if the empty packaging is a clean assy.
   - a. If yes: the packaging needs to be scrapped, which means that the packaging is disposed. (End of process)
   - b. If no: go to step 4 of the process.
4. The CS engineer checks if the packaging is damaged.
   - a. If yes: go to step 3a and scrap (dispose) the empty packaging. (End of process)
   - b. If no: the CS engineer sends the empty packaging to the local warehouse.
5. The empty packaging is now available at the local warehouse.
6. The 3PL employee prints an “empty case” label.
7. On this label, the 3PL employee writes the arrival date of the empty packaging in the local warehouse.
8. The 3PL employee also writes down the 12NC number of the part which was originally packed with the packaging on the same “empty case” label.
9. The label is added to the empty packaging material. This is also done by the 3PL employee.
10. The 3PL employee puts the empty packaging in inventory and the empty packaging stays in inventory for at least 90 days.
11. After these 90 days and the packaging is still in storage, which means that the packaging is not used to return the part to the supplier, the 3PL employee checks whether the part is in the consignment stock, i.e. the part has failed and is in stock of the customer.
   - a. If no: the empty packaging material is scrapped. (End of process)
   - b. If yes: the empty packaging material including the part is send back to the supplier to repair the part. (End of process)

As the ninth process step shows, all empty packaging materials are stored for at least 90 days. This 90 day-storage period comes from the assumption made within the company that probably after these 90 days the part will not become defect anytime soon. The probability that the part fails is larger within these 90 days. Therefore, the packaging is kept in storage in this period such that the part could be repacked when it fails. In this case, the part can be packed with the packaging material which was in stock of the local warehouse and then the packaging including the part could be send back to the supplier to repair the part.
Because the local warehouses of Country B have an empty packaging problem, which implies that a huge amount of empty packaging materials is stored in the inventory of the local warehouses and the locals do not know what to do with it, shows that the identified As-Is process has some issues. This has several reasons:

1. The As-Is process is very complex, and the process has too many steps.
2. Everything step is executed manually and not registered in SAP. Some local warehouses keep an Excel list with the empty packaging they have in storage. However, because this list is, again, outside SAP, it is not visible to the people who need to make the decisions about the packaging (scrap/return/keep). In addition to this, the data collected in the Excel list is often not correct.
3. The local warehouses always review the packaging in combination with the part and not as independent item. This means for example: if the part needs to be scrapped, also the packaging material is scrapped, or, if the part needs to be returned for repair, the packaging is also returned.
4. The locals do not make a distinction between different types of packaging, they just store all packaging materials for 90 days.
5. Between the moment of storage and the 90th storage day, there is no review moment to decide if the packaging still needs to be stored.
6. The 90-day storage period could be too long.
7. This As-Is process does not focus on reuse of the packaging materials. Thus, currently, there is no empty packaging return from the local warehouses back to the factory warehouse. The packaging is either scrapped in the local warehouse with or without the part or the packaging including the part is returned to the supplier if the part needs to be repaired.
8. The local warehouses do not check the X-plant status of the empty packaging materials.
It is not clear who is responsible for each of the process activities.

5.2.2 Empty Packaging: As-Is Process in the Local Warehouses of Country C

During a local warehouse visit in Country C, a process was observed that was different than the current process of Country B. The swim lane diagram presented in Figure 5.7 displays the current process regarding empty packaging in the local warehouses of Country C. As is shown in this swim lane diagram, the activities within the customer’s fab are the same for Country B and C. No differences were identified here. Within the local warehouse, there is distinction in the activities and decisions made regarding empty packaging.

The process steps showed in Figure 5.7 are described as follows:

1. At the customer’s fab, the packaging is removed from the part.
2. The empty packaging material is now available.
3. The CS engineer checks if the empty packaging is a clean assy.
   a. If yes: the packaging needs to be scrapped, which means that the packaging is disposed. (End of process)
   b. If no: go to step 4 of the process.
4. The CS engineer checks if the packaging is damaged.
   a. If yes: go to step 3a and scrap (dispose) the empty packaging. (End of process)
   b. If no: the CS engineer sends the empty packaging to the local warehouse.
5. The empty packaging is now available at the local warehouse.
6. An 3PL employee prints an "empty case" label and puts that on the empty packaging.
7. The 3PL employee documents the data of the empty packaging in an Excel list.
8. The 3PL employee places the empty packaging in inventory at the same place where all the other empty packaging materials are stored. (Most frequently: End of process)
9. It is checked whether the packaging material in inventory has a value greater than €X.
   a. If no: the packaging has a price less than €X and the packaging material is scrapped. (End of process)
   b. If yes: the empty packaging has a price higher than €X. In this case, the 3PL employee follows a work instruction designed in 2014 to return the packaging to the factory warehouse. This work instruction is presented in Appendix A – Process Flow of Work Instruction 2014. After following all steps of the work instruction, the empty packaging is ready to be returned to the factory warehouse. (End of process)

In most cases, the process ends after placing the empty packaging material in inventory, thus, after process step 8. Then, the packaging stays in inventory for an unknown period. The storage period of empty packaging in the local warehouses of Country C can even go up to several years. The ninth process activity shown in the swim lane diagram is only executed if the 3PL employees have no other critical things to do. Thus, if other work has been done and there is some time left, the 3PL employees of the local warehouse perform the activities of process step 9. The dotted line between step 8 and 9 represents this.
The empty packaging situation in Country C seems to be somewhat better than in Country B. This is because the local warehouse space in Country C is relatively less occupied by empty packaging materials than in Country B. In the latter, a lot more square meters of the total warehouse space are occupied by empty packaging. The following reasons are identified why the empty packaging situation is better in the local warehouses of Country C:

1. A bit more focus on the empty packaging itself, which is represented in the way they document the empty packaging data.
2. The usage of the work instruction shows that they are aware of the fact that some packaging materials are valuable and need to be returned to the factory warehouse for reuse.
3. Empty packaging is returned to the factory warehouse occasionally. Not so often, but if the empty packaging inventory in the local warehouse gets too large they try to make some time to follow the work instruction and return the empty packaging.

However, despite of that the local warehouses of Country C seems to be doing a better job regarding empty packaging than Country B based on the size of the empty packaging inventory, we recognized that also here the As-Is process has a couple of issues. This is reflected in empty packaging materials staying in the local warehouses of Country C for more than one year. The following problems with the current process are identified:

1. The empty packaging materials are stagnated in the local warehouse after step 8. It is not clear for what time period the empty packaging materials are in inventory before step 9 is started, but mostly this is more than one year.
2. If they proceed with the ninth process step, it is very time consuming to follow the work instruction and return one empty packaging material to the factory warehouse.
3. The scrap decision is only based on the price of the packaging.
4. The local warehouses of Country C do not use SAP in the process activities 5 till 8. They only use Excel to document the packaging which they place in storage.

5. The X-plant status of the empty packaging is only checked if there is time to execute process step 9.

6. In combination with the process steps of the work instruction, this process becomes really complex with too many steps.

During the local warehouse visit in Country C, the local warehouse manager was interviewed to identify more issues regarding empty packaging. Two main problems were identified:

- There are no KPIs for empty packaging. This results in keeping the empty packaging in storage as long there is enough warehouse space. Only if there is some time left, they will perform the steps of the work instruction to review if a packaging needs to be returned or must be scrapped. Thus, currently, the empty packaging is not returned or scrapped, and the empty packaging inventory is getting larger. Note that KPIs must be defined by the CSCM employees. This has not been done yet and thus, no local warehouse uses KPIs for empty packaging.

- The 3PL employees in Country C know, in most cases, what to do with the empty packaging. But because they do not have enough time and other things are more critical to do first, the packaging stays in the local warehouse for a long time period. Thus, it can be concluded that the lack of KPIs for empty packaging and the lack of time, seem to be the main causes for the empty packaging problem in the local warehouses of Country C.

We also identified some problems with the existing work instruction that is used by the local warehouses in Country C. These problems are the following:

1. It is very time consuming to follow the work instruction.
   - In the local warehouse of Country C, it took the 3PL employee 20 minutes for one item while skipping some steps of the work instruction.
   - For example: before booking the empty packaging in stock in SAP, an email need to be sent to Inventory Control department. The 3PL employee now skipped this step to save time. Otherwise, he had to wait two or more working days to receive an answer, which makes following the work instruction even more time consuming.
   - Another reason why he skipped this step was that now he had some time to pay attention to empty packaging, but it could occur that during waiting on the answer from inventory control, another more critical task comes along and the 3PL employee cannot finish returning this empty packaging.

2. The work instruction contains several crucial mistakes (e.g. in the first process step of the work instruction the 3PL employees have to decide whether the packaging is empty and based on that proceed with the right steps. However, if they say the packaging is empty they are directed to the steps for handling a packaging including a part and vice versa. Thus, the process contains a mistake already in the first step of the process). This makes following the work instruction very difficult for the 3PL employees.

3. The work instruction is way too complex because it consists of too many process steps. This makes it complicated for the local warehouse employees and the probability that mistakes are made is higher with so many steps. Sometimes the English of the warehouse employees is not so good, therefore, the process description must be very clear and understandable for all education levels. However, this is currently not the case.

4. The work instruction is designed and implemented in all locals worldwide in 2014 and since that time, the work instruction has never been updated. In addition, after 2014, a couple of processes regarding parts changed, which has an influence on the (empty)
packaging process. Despite those changes, the work instruction has never been updated, which makes the work instruction outdated and it is not usable anymore.

5. No tracking of data after implementing the work instruction.
   - They did not track the number of returned empty packaging materials.
   - In addition, it was not tracked whether the warehouse space occupied by empty packaging was reduced.

6. No evaluation has been taking place to verify whether the work instruction was working well and whether the locals used it (in the right way).

7. The decision to return or scrap an empty packaging material is in this work instruction dependent on the X-plant status of the packaging. However, the X-plant status of the packaging is often not up-to-date. This results in 3PL employees making the wrong decision without even knowing this may not be the right decision.

8. After following the steps of the work instruction, the 3PL employees are still not finished. This is due to the work instruction does not contain the steps for planning the return and arranging the transport, which also takes time. The 3PL employees are responsible for these tasks. The work instruction only contains the steps for making the empty packaging ready for return and not for the actual physical return.

9. The €X threshold used to make the return/scrap decision for packaging materials is based on the threshold for parts. It was assumed that for packaging the threshold could be the same as for parts, so they took over this rule from parts to packaging. However, it could be that this rule is not applicable for packaging or that a higher or lower threshold would better, because packaging materials have different characteristics than parts. Thus, the €X threshold is also outdated.

Now the current processes regarding empty packaging are known, we can identify the root causes for the empty packaging problem.

5.3 The Root Causes of the Empty Packaging Problem

In this section, the root causes for the empty packaging problem are presented. First, in Section 5.3.1, it is explained which approach is used to determine the root causes and the root causes are presented. Subsequently, the results of linking the root causes to the As-Is process are described in Section 5.3.2. Note that in the previous two sections (Section 5.2.1 and 5.2.2) already several causes for the huge amount of empty packaging in the local warehouses are identified. Some of these causes are identified as root causes and these are presented in the following section.

5.3.1 Determination of the Root Causes

The Root Cause Analysis started with interviewing stakeholders of this problem. In total, eight employees of ASML has been interviewed to determine all the root causes. Due to confidentiality reasons, we cannot mention the names or other details of the interviewees. The following employees are interviewed:

- Local warehouse manager of Country B
- Local warehouse manager of Country C
- Local warehouse manager of Country D
- Two employees of the Logistic Service Operations department
- Three employees of the Customer Supply Chain Management department

To identify all the root causes, the five-why technique is used. This is a technique used to explore the cause-and-effect relationships underlying a particular problem. The primary goal of the technique is to determine the root cause of a problem by repeating the question "Why?". Each
answer forms the basis of the next question. The first question asked within each interview was: “Why do we have empty packaging materials in the local warehouses?”. The number of iterations of asking “Why” were dependent on who was interviewed. After conducting the interviews, approximately 25 root causes were identified. It appeared that some of the causes were about the same. Thus, these causes are combined into one cause. Hereafter, it was decided to divide the root causes into five categories to get a clear overview. The following five categories are used to classify the root causes:

1. Processes: root causes which are due to process issues, i.e. the processes regarding empty packaging within the supply chain of the company.
2. Information System: root causes which are due to the organization and settings of the information system.
3. Material: the aspects of the packaging materials, e.g. the characteristics of the packaging materials (size and type), that cause the empty packaging problem within the local warehouses.
4. People: the aspects of the employees within the company (e.g. knowledge of packaging materials, agreements that are made between employees, etc.) that result in the empty packaging problem.
5. Environment: the aspects of the environment (e.g. the size of the local warehouse) which cause the empty packaging problem.

After defining the above categories, the root causes identified during the interviews and during the analysis of the As-Is processes can be divided among the categories which is presented in Table 5.7. Some root causes are mentioned by more than one employee. Therefore, behind each root cause, the number of times the root cause is mentioned is displayed in between brackets. Due to confidentiality reasons, we cannot show which employee mentioned which root cause. Below Table 5.7, additional information is given about the different root causes.

### Table 5.7 Overview of the identified root causes

<table>
<thead>
<tr>
<th>Processes</th>
<th>Information System</th>
<th>Material</th>
<th>People</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unclear process at LWH -&gt; Scrap part = scrap packaging (4)</td>
<td>7. No predefined end-destination for empty packaging (3)</td>
<td>12. Packaging handled in combination with part -&gt; only packaging + part return, NO empty packaging return (3)</td>
<td>15. No good alignment with CS engineers (2)</td>
<td>19. Store all packaging for at least 90 days -&gt; a lot of packaging needs to be stored in LWH (3)</td>
</tr>
<tr>
<td>2. Nobody plans the empty packaging now (2)</td>
<td>8. As soon as SERV is created -&gt; packaging not visible in SAP (6)</td>
<td>13. High ratio of special packaging (3)</td>
<td>16. No ownership -&gt; Focus on part, not on packaging -&gt; No KPIs for packaging (6)</td>
<td>20. Local warehouses too small (1)</td>
</tr>
<tr>
<td>3. No return process for empty packaging -&gt; only packaging + part return and LWH never sends back EMPTY packaging (6)</td>
<td>9. Packaging not traceable in SAP -&gt; Non-SAP registered inventory -&gt; empty packaging only in excel lists (8)</td>
<td>14. 12NC label of packaging not readable -&gt; type of packaging unknown (2)</td>
<td>17. Returning empty packaging not mandatory (3)</td>
<td></td>
</tr>
<tr>
<td>4. Criteria for scrap/return not clear (3)</td>
<td>10. Wrong categories in ZPACK -&gt; a lot of things about pack not/wrong in SAP (2)</td>
<td>18. 3PL employees don’t have knowledge about packaging -&gt; Unclear responsibilities -&gt; Not allowed to make return/scrap decision</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

31
so store all packaging (5)

11. X-plant status packaging not up-to-date (6)

 Processes

1. The processes at the local warehouses are unclear. Thus, if the X-plant status of the part is scrap, it could be that the packaging is still reusable. However, in this case, the locals will also scrap the packaging.

2. To return a part for repair, an employee of the CSCM Reverse Operations team has to plan when to return the part. For packaging return, this should also be done. However, currently, nobody is planning the packaging return.

3. Within the local warehouses there is no process to return the empty packaging. The locals only know how to return packaging including a part, but not the empty packaging itself. Thus, the empty packaging is never send back to the factory warehouse by the locals.

4. For the employees within the local warehouses, it is not clear what the criteria are to scrap or return packaging. Sometimes, they scrap a very expensive packaging, but store a cheap cardboard box.

5. For empty packaging there are no clear guidelines for storing. This means that the employees in the local warehouses put the empty packaging just somewhere where there is space with the result that nobody remembers where the specific packaging is placed. As a result, the packaging could not be scrapped or returned after the specified storage time.

6. ASML has no standardized instructions which is used in all local warehouses. As a result, all local warehouses handle empty packaging in their own manner. Thus, each local warehouse has its own way of working.

 Information System

7. No-predefined end-destination for empty packaging means that nowhere is stated where the packaging material needs to go to when it is not used for returning the defect part. For example: for parts it is clear what the end-destination is dependent on its phase in the life-cycle: defect and repairable → return to supplier for repair; defect and not repairable → scrap. For empty packaging materials this is not known. As a result, the packaging stays within the local warehouse.

8. In the forward flow of a part, the part goes from the supplier to the factory warehouse. In the factory warehouse, the part becomes a service part. This means that the first four digits of the 12NC of the part are changed to four letters, SERV, which is called the creation of a service part. As soon as this is created, the packaging is not visible anymore in SAP. This is due to settings in SAP.

9. All empty packaging materials stored in the local warehouses are not booked in SAP as inventory. Thus, it is not shown in SAP what the actual inventory of a specific empty packaging material is. Some locals keep a list of the empty packaging inventory in Excel. However, this is outside SAP and thus, the packaging inventory is not traceable.

10. ZPACK is the system within SAP that informs manufacturing how to pack the part. In some cases, the packaging categories stated in SAP and ZPACK are not correct, e.g. ZPACK states that special packaging is needed, while the packaging that is written down is standard packaging.
11. The X-plant status is a status in SAP that indicates whether a part or packaging is repairable. With this status, the decision to scrap or return the packaging could be made. If this status is not up-to-date, the local warehouses are not able to make the right decision what to do with the packaging.

Material
12. In most local warehouses, they handle the packaging materials in combination with the part. Thus, they do not view empty packaging as an independent item. This means that the packaging is only returned if the defect part is to be returned and the empty packaging itself is never returned.
13. High ratio of special packaging materials means that most packaging materials that come available in the local warehouses are special packaging. Within the local warehouses, the procedure is to store the packaging when it is special. This results in a lot of special packaging materials stored in the warehouses.
14. If the 12NC label on the packaging is no longer readable, it is not possible to look up the packaging in SAP. Therefore, the type and category of the packaging is unknown, so also unknown what to do with the packaging.

People
15. The CS engineers are the employees who unpack the part at the customer site. The procedures regarding empty packaging within the local warehouses and the customer are not aligned with one another. This leads to the CS engineer sending back all the empty packaging materials to the locals, even if the packaging material is a one-way packaging, which results in a lot of empty packaging materials in the local warehouses.
16. No ownership: the main focus of ASML is on the parts and not on the empty packaging materials. This means that employees are trained to deliver and return parts. No employees are trained who only focus on packaging, thus, also no KPIs for packaging are determined.
17. For the local warehouses it is not mandatory to return packaging materials which can be used more than one time. Thus, the local warehouses either just store the packaging, or they scrap the packaging.
18. The 3PL employees don't have knowledge about packaging. This has to do with the fact that the responsibilities are unclear and the 3PL employees are not allowed to make return/scrap decision, so all packaging is stored.

Environment
19. It is already explained in Section 5.2 why the locals use this 90-day storage period. In addition, it was said that this 90-day storage period could be too long.
20. The local warehouses could be too small and as a result, they are full of empty packaging very fast.

The root causes presented in Table 5.7 are transformed into a Fish Bone diagram. To ensure it is clear how to read a fish bone diagram, an example fish bone diagram is added (See Figure 5.8) and a reading description is given:
- Read from left to right and from the most upper cause to the lowest cause of the arrow.
- Start reading at the upper left category.
- Then, start with the upper cause closest to the arrow of the category (cause 1). This cause is the main cause.
- Next, if the line of the main cause is bending, this means that this cause has a sub-cause. Read this sub-cause (sub-cause 1a) first before going to the next cause (cause 2).
- If all causes of the arrow are read, continue with the next category (Category B).
• From Category B, the graph continues with the causes of the lower left category. Here, start reading the causes which are closest to the thick arrow. Thus, read again from top to bottom.

![Fish Bone Diagram Example](image)

**Figure 5.8 Example: How to read a fish bone diagram**

Note: Within the example fish bone diagram presented in Figure 5.8 no distinction is made between importance of categories and the corresponding causes. All causes are treated as equally important. This is also the case in the fishbone diagram which is presented next. If the root causes are linked to the As-Is process and these results are combined with the number of times a root cause is mentioned during the interviews, a statement could be made about whether a root cause is of high or low importance. Now it is clear how to read the fish bone diagram, we present the fish bone diagram with the identified Root Causes. This diagram is displayed in Figure 5.9.

![Fish Bone Diagram of the Root Causes](image)

**Figure 5.9 Fish Bone diagram of the Root Causes**

The root causes presented in the fish bone diagram presented in Figure 5.9 were already explained before, thus more information about the root causes can be found on the previous pages.
The literature is also searched to identify root causes for the empty packaging problem. It was found that most articles mention causes for empty container movements (e.g., Song & Dong, 2015) or empty packaging shortages (e.g., Martinus, 2010). Both topics are different than the problem, i.e., an empty packaging surplus in the local warehouses, we are investigating. In addition to this, within the supply chain of the company, currently there are no empty packaging movements. However, in the future, the company wants to have empty packaging movements to decrease the surplus of empty packaging inventory in the local warehouses. Because the focus of the articles found is different than our focus, we mention the root causes found in the literature with an explanation why the root cause is also applicable for the empty packaging problem described in this research.

The causes that are mentioned by Song & Dong (2015) are the following:

1. **Trade imbalance**: the trade in one direction is more than that in the other direction.
   - This research: more new parts go to customer than defect parts need to be returned to the supplier, which means that more empty packaging is available in the inventory of the local warehouses than what is actually needed. Thus, an excess inventory situation is developed by trade imbalance.

2. **Uncertainty**: this represents the unpredictable elements that affect the container transport system. Uncertainty may occur during the operations in the container transport chain (e.g., equipment breakdown, resource unavailability, etc.) or during the interfaces with the external environment (e.g., customer demand).
   - This research: it is uncertain when parts become defective and need to be sent back to the supplier. As a result, it is also uncertain if and at what moment the empty packaging is needed to return the part.

3. **Container size and type**: there exist several different types of containers that vary in their dimensions as well as the cargos they are designed to carry. The shortage of empty containers could happen because the size or types of available empty containers do not match customer requirements.
   - This research: within ASML two main packaging categories and three packaging types exist. In these categories more than 10,000 unique packaging materials can be distinguished. Besides this, a lot of the packaging materials used are part specific, which means that a packaging material could only be used for one specific part and thus, could not be used for another part. This makes the empty packaging problem even more complex. However, this third cause found in the article results in an empty container shortage and within this research there is no shortage but excess inventory. Therefore, this cause is only partly applicable.

4. **Lack of visibility**: if containers are not visible in the transport chain, there is no timely and accurate information of the container status and locations, which makes it extremely difficult for the shipping lines to manage their container fleet in the most effective way.
   - This research: some local warehouses keep an Excel list with empty packaging inventory, but this inventory is not visible in SAP and these lists do often not include the right data. This makes it difficult to manage empty packaging in the local warehouses in an effective way.

Another article that mentions an applicable root cause for the empty packaging problem is the research of Boile, Theofanis, & Mittal (2004). The cause that is mentioned is the following:

5. **New container prices vs. cost of inspecting and moving empties**: new container prices were very low compared to the cost of re-positioning, or storing and inspecting old containers. As a result, the option to purchase new was more appealing to ocean carriers than moving empties.
   - This research: it is cheaper and easier to order new packaging materials than to return empty packaging to the factory warehouse for cleaning and repair so that the packaging can be reused. This results in even more empty packaging stagnated in the local warehouses.
Lastly, Martinus (2010) attempts to find root causes for an empty packaging shortage. Thus, again, these causes are not totally related. However, one of the causes he described could also be a root cause for this research:

6. **No directly identifiable person responsible for returning packaging.**

   - This research: within the company there is not one specific person who is responsible for the inventory of empty packaging within the local warehouses and the locals are not allowed to make decisions about returning or scrapping the packaging. As a result, the packaging is not properly managed, and the locals store all packaging to be sure they do not scrap the wrong packaging materials.

According to Song & Dong (2015), trade imbalance is the fundamental reason for empty container repositioning. In addition, this main root cause accounts for the largest share for requiring empty container repositioning. The objective of these articles (Boile, Theofanis, & Mittal, 2004; Martinus, 2010; Song & Dong, 2015) is to minimize empty container movements. However, in this case, empty packaging movements are needed to decrease the inventory space occupied by empty packaging materials. Because the articles used to find more root causes have another objective than this research, the root causes found in the literature are not incorporated in the fishbone diagram and not used for further analysis.

### 5.3.2 Linking the Root Causes to the As-Is Processes

This section links the identified root causes to the process steps of the As-Is processes of Country B and C presented in Section 5.2. The total number of times a root cause is linked to the As-Is processes of both countries are summed, so we get an overall view of how often a root cause is linked. Subsequently, the number of times a root cause was mentioned during the interviews is multiplied to the number of times a root cause was linked. This is done to map the overall impact of the different root causes of the empty packaging problem and to determine which of the many causes is the most prominent, the so-called 'main root cause' (Andersen & Fagerhaug, 2006). We multiply the number of times a root cause is linked with the number of times a root cause was mentioned to analyze which root causes are most crucial to investigate further and to solve.

Table 5.8 shows the overview of the root causes linked to the As-Is process of Country B. The numbers in the first column represent the root causes and the numbers of the first row represent the process steps of the As-Is process. Thus, the numbers of the first row correspond to the numbers presented in the As-Is process in Figure 5.6 which is part of Section 5.2.1. The last column shows the number of times a root cause was linked to a process step. In Table 5.8, only process step 3a and step 6 till 11b of the As-Is process of Country B are included in the table. For the other process steps, it was not possible to link any of the root causes. Therefore, these are not included in further analysis.

<table>
<thead>
<tr>
<th>Process step</th>
<th>RC</th>
<th>3a</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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<th>11a</th>
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</table>
The root causes that are most often linked to the As-Is process of Country B are root cause 3, 6, 7, 8, 9, 11, 16 and 18. These root causes of the empty packaging problem fall within the processes, information system and people category.

Table 5.9 presents the results of linking the root causes to the As-Is process of Country C. This table has been built up in the same manner as explained for Table 5.8. For the As-Is process of Country C, only process step 3a and 6 till 9b are included in this analysis. Thus, the numbers of the first row correspond to the numbers presented in the As-Is process in Figure 5.7 which is presented in Section 5.2.2.

<table>
<thead>
<tr>
<th>Process step RC</th>
<th>3a</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>9a</th>
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<td>X</td>
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<td>X</td>
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</tr>
</tbody>
</table>

The root causes that are most often linked to the As-Is process of Country C are root cause 6, 11 and 16. These root causes of the empty packaging problem are classified within the processes, information system and people categories.
Table 5.10 shows the total number of times a root cause was linked to the As-Is processes of Country B and C. The number of times a root cause was linked to the As-Is process of Country B was added to the number of times a root cause was linked to the As-Is process of Country C, which resulted in the table below.

Table 5.10 Total time the root causes are linked to the As-Is Processes

<table>
<thead>
<tr>
<th>Root cause</th>
<th>#Times linked – Country B</th>
<th>#Times linked – Country C</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
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<td>6</td>
<td>12</td>
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<tr>
<td>9</td>
<td>6</td>
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<tr>
<td>11</td>
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</tr>
<tr>
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</tr>
<tr>
<td>14</td>
<td>3</td>
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<td>4</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
<td>1</td>
<td>6</td>
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<tr>
<td>16</td>
<td>6</td>
<td>6</td>
<td>12</td>
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<tr>
<td>17</td>
<td>1</td>
<td>4</td>
<td>5</td>
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<td>18</td>
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<td>5</td>
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<td>1</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

To get an even better view of the importance of all root causes, another analysis is conducted. We multiply the number of times a root cause was linked to the number of times a root cause was mentioned during interviews. The results of this is presented in Table 5.11. Note that the number of times a root cause is mentioned is presented in brackets behind the root cause in Table 5.7 Overview of the identified root causes in Section 5.3.1.

Table 5.11 Most important root causes

<table>
<thead>
<tr>
<th>Root Cause</th>
<th># Times linked</th>
<th># Times mentioned</th>
<th>Results of multiplying</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>4</td>
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</tr>
<tr>
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<td>72</td>
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<tr>
<td>10</td>
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</tr>
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<td>11</td>
<td>12</td>
<td>6</td>
<td>72</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 5.10 gives a graphical representation of the results of multiplying the number of times a root cause was mentioned and the number of times a root cause was linked. This figure shows that root cause 6 has the highest importance with a value of 84, followed by root cause 9, 11, and 16 with a value of 72. Root cause 18 has the third highest importance value, i.e. 55.

Due to time constraints, it is not possible to tackle all identified root causes during this project. Therefore, we decided to focus on the root causes with the three highest importance values. This implies that during this project, we focus on solving in total five root causes. These root causes are the following: root cause number 6, 9, 11, 16, and 18. Table 5.12 presents an overview of the five root causes that are solved during this project.

Table 5.12 Root Causes with the highest importance

<table>
<thead>
<tr>
<th>Processes</th>
<th>Information System</th>
<th>People</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. No clear instructions for handling packaging -&gt; Each LWH has own way of working</td>
<td>9. Packaging not traceable in SAP -&gt; Non-SAP registered inventory -&gt; empty packaging only in excel list</td>
<td>16. No ownership -&gt; Focus on part, not on packaging, -&gt; No KPIs for packaging</td>
</tr>
<tr>
<td></td>
<td>11. X-plant status packaging not up-to-date</td>
<td>18. 3PL employees do not have knowledge about packaging -&gt; Unclear responsibilities -&gt; Not allowed to make return/scrap decision</td>
</tr>
</tbody>
</table>

Due to root causes 6, no clear instructions for handling empty packaging, the local warehouses store a lot of empty packaging materials, which comes down to a total inventory holding costs for
empty packaging materials worldwide of hundreds of thousands of Euros in the year 2017, which is expected to increase if the empty packaging problem is not solved. Because of root cause 9 and 11 empty packaging materials are disposed while these packaging materials had potential to be reused. This has led, for example, to the disposal of three empty packaging materials with a value of approximately ten thousand euros in the local warehouses of Country A in May 2018. If this happens each month, the costs for buying these packaging materials new will increase considerably. Root cause 16 and 18 result in empty packaging materials stored in the local warehouses for a long period. In the first half of 2018, the local warehouses in Country A stored empty packaging materials with a total value of almost ninety thousand euros. Some empty packaging materials had the potential to be reused; these packaging materials have a value of approximately sixty-five thousand euros. This shows that these root causes are not only important in terms of number of times linked to the As-Is processes and number of times mentioned by the employees, but also in terms of costs these root causes have a high importance to be solved.

5.4 Discussion and Conclusion

In this chapter we investigated the first research question:

Research Question 1:
What are the root causes of the empty packaging problem?

To answer this question, we first reviewed what categories and types of packaging are most often stored in the local warehouses. The analysis showed that special packaging is most often stored and besides this, send assys are most frequently available in the local warehouses. Therefore, this research focuses on special packaging and send assys. However, the decision support model to be developed is general and applicable for all packaging categories and types.

Subsequently, the current process regarding empty packaging in the local warehouses have been mapped and some problems with this current process were identified. The main problems are:

- The current processes are complex with too many steps. In addition to this, each local warehouse has a different way of working.
- The local warehouses always review the packaging in combination with the part and not as independent item. This means for example: if the part needs to be scrapped, also the packaging material is scrapped, or, if the part needs to be returned for repair, the packaging is also returned.
- The decision to scrap an empty packaging is only based on the price of the packaging.
- This As-Is process does not focus on reuse of the packaging materials. Thus, currently, there is no empty packaging return from the local warehouses back to the central warehouse. The packaging is either scrapped in the local warehouse with or without the part or returned to the supplier if the part needs to be returned.
- The local warehouses do not check the X-plant status of the empty packaging materials.

Before starting to develop the decision support model, a To-Be process needs to be made which solve the problems of the As-Is process.

As the last part in answering the first research question, a Root Cause Analysis has been performed. The most important root causes are determined. The root causes that will be tackled during this project are the following:

- Root cause 6: There are no clear instruction for handling empty packaging materials, which results in each local warehouse having its own way of working.
• Root cause 9: The packaging materials are not traceable in SAP. This is due to that the empty packaging materials in the local warehouses are not booked in SAP as inventory.
• Root cause 11: The X-plant status of the empty packaging materials is not up-to-date.
• Root cause 16: There is no ownership within the company for empty packaging materials. The focus of ASML is on the parts and not on the empty packaging materials. As a result, no KPIs are determined for the empty packaging materials.
• Root cause 18: 3PL employees in the local warehouses don't have knowledge about packaging, they are not allowed to make the scrap/return decision and the responsibilities regarding empty packaging are unclear.

The problems with the current processes and the root causes are considered to design the ideal empty packaging process. This process is presented in the next chapter, Chapter 6. This To-Be process will form the basis for the decision support model.
6 Design of the New Process

In this chapter, the new process for empty packaging in the local warehouses is designed. The new process is the first step in solving the root causes identified in Chapter 5. The second step is the development of the decision support model which is done after the new process has been designed. Section 6.1 presents the To-Be process and explains the process steps. Subsequently, Section 6.2 elaborates on what the inputs and outputs and who the supplier(s) and customer(s) are of the new process. Last, Section 6.3 shows the process for determining the X-plant status of the empty packaging.

6.1 To-Be Process

Based on the findings of the As-Is processes and the Root Cause Analysis, a new process for handling empty packaging in the local warehouses is designed and presented in Figure 6.1.

![Figure 6.1 To-Be process](image)

The process shown in Figure 6.1 is explained as follows:

**Start** The process starts with an empty packaging coming available at the local warehouse. This can either be due to:

- a. Unpacking the part at the customer and sending the empty packaging to the local warehouse.
- b. Scrapping the part at the customer’s fab or in the local warehouse, and as a result an empty packaging remains.

1. The first step in the process is to check whether the packaging is on the scrap list. This list includes the packaging materials that can be scrapped immediately (see Appendix B – Packaging Scrap List). For these materials it is not necessary to proceed with the other steps. Thus, for this process step there are two options:

- a. If no, which means the concerned packaging is not on the list, it is worth it to further investigate the packaging in order to find out what we have to do with that empty packaging material. Thus, go to step 2 of the process.
- b. If yes, which means that the concerned packaging is included in the scrap list, the empty packaging material is not worth it to investigate further and can be scrapped immediately. Thus, go to step 9 of the process.

2. Determine the 12NC of the packaging material so it is known what kind of packaging we are dealing with. After this step, two things must be done: 1) Filling in the empty packaging form, so go to step 3 of the process; 2) Checking whether there is a FSD available for the packaging, so go to step 4 of the process.

3. Document the data of the packaging in an empty packaging form. The form is an Excel sheet. With the data collected in this form and combined with the stock registered in SAP, the X-plant status can be kept up-to-date. The following data is to be documented:

- a. 12NC of the packaging
- b. Description of the packaging
- c. Quantity: how much of the packaging is available?
- d. Arrival date of the packaging in the local warehouse
- e. Local warehouse code: where is the packaging located? (e.g. the code of the local warehouses is denoted by an abbreviation of the country's name and two numbers)
- f. Price of the packaging
g. 12NC of the part which was originally in the packaging
h. FSD available for this packaging: yes or no

4. With the 12NC of the packaging, it can be checked whether there is a FSD available for the packaging. Only if there is a FSD available for the packaging, it can be checked what the X-plant status for the packaging is. Sometimes it is possible that a packaging that is not on the scrap list has not yet a FSD. Then this must be requested to be able to check the X-plant status of that packaging.
   a. If no FSD available, the FSD is to be requested → Go to step 5 of the process.
   b. If yes, the X-plant status of the packaging can be checked → Go to step 6 of the process.

5. If there is no FSD available for the packaging, a local request form (LRF) is to be send to request the FSD. Important to mention here is that the local warehouses have to wait until the FSD is created before they proceed with step 6 of the process.

6. Now the 12NC of the packaging with FSD is available and the packaging data is documented in Excel, the X-plant status of the packaging is checked. The X-plant status gives two possible statuses for the packaging:
   a. Return the packaging.
      → If the X-plant status gives ‘return’ as a result, go to step 7 in the process.
   b. Scrap the packaging.
      → If the X-plant status gives ‘scrap’ as a result, go to step 9 in the process.

Note that the X-plant status presented in SAP is a two-letter code which represent the abovementioned statuses. Thus: X-plant status VM means that the packaging is “economic unrepairable”, and therefore it needs to be scrapped; X-plant status VC represents “return to the factory warehouse in Country E”, and therefore the packaging needs to be returned to the mentioned location. This location could be the factory warehouse in Country E as in the example, but it is also possible that the packaging is to be returned to the factory warehouse in Country A or D.

7. The X-plant status of the packaging is ‘return’. Thus, the packaging needs to be returned to location mentioned in the status. Therefore, the packaging is booked in SAP as FSD, only then the packaging can be returned.

8. If the packaging is booked in SAP, it is ready to send the packaging to the factory warehouse. In the factory warehouse, the packaging will either be returned to the supplier or cleaned in the factory warehouse and made ready for another usage.

9. The X-plant status of the packaging is ‘scrap’. Thus, the packaging will be scrapped and disposed in the local warehouse. For this step, it is not needed to book the packaging in SAP.

End The process can end in two different ways:
   a. After step 8, sending the packaging to the factory warehouse, the process ends.
   b. After step 9, scrapping the packaging in the local warehouse, the process also ends.

This To-Be process represents the new standardized way of working for the local warehouses. For the local warehouses of Country C, the new process is simplified compared to the existing process flow of the work instruction. However, for the local warehouses of Country B, this process is completely new and totally different than their current way of working, and therefore, this process may be a bit more complex for the local warehouses in Country B. However, this process makes it a lot easier to manage the empty packaging inventory in the local warehouses. The main differences between the To-Be process and the As-Is processes are the following:

1. The focus is on the empty packaging itself, which can be seen in:
   a. The 12NC of the packaging is determined. Note: the 12NC of the part is only used to look up the 12NC of the packaging in SAP in this case of where the packaging 12NC is not visible on the packaging material. If the 12NC of the packaging is known, the 12NC of the part is not used anymore.
b. In the As-Is processes, a flow for returning a packaging including a part was available. In the To-Be process, the focus is on empty packaging return only, and therefore, the beforementioned flow is no longer included.

c. In the new process, the packaging is scrapped or returned, dependent on the result of the X-plant status. Thus, instead of storing all empty packaging materials for a specific period, the goal is now to scrap or return the packaging immediately after it comes available in the local warehouse. Storing the empty packaging is not allowed anymore. This ensures that the packaging will not be stagnated in the local warehouses.

2. The X-plant status of the packaging is determined and will be kept up-to-date. Dependent on the packaging, the X-plant status is reviewed once a month. For more stable packaging, the time between two reviews will be longer. After checking the X-plant status, it is immediately clear what to do with the packaging (scrap or return).

a. It is no longer needed to check if the packaging is a complete cardboard and/or what the value of the packaging is. This is already incorporated in the X-plant status.

b. X-plant status is based on all the parameters that are needed to make the right decision how to handle the empty packaging.

3. The packaging scrap list will prevent that employees in the local warehouses and the CSCM employees have to spend a lot of time on packaging. In the local warehouse, this list prevents to unnecessarily proceed with the whole process while from the beginning it is sure that the packaging is to be scrapped. For the CSCM employees, the list ensures that less packaging materials must be reviewed on their X-plant status.

4. Empty packaging is returned to the factory warehouse instead of stagnation in the local warehouse. In addition, packaging materials are not scrapped anymore while this is not required.

5. SAP is already included in the first step of the process. Packaging is now traceable and visible in SAP.

6. The new process contains three points where decisions have to be made. However, these decisions are already made in advance by the CSCM employees. To explain further:

a. Process step 1: The local warehouses only have to check the packaging scrap list and act accordingly. In Country E, the decision has been made whether a packaging material must be placed on that list.

b. Process step 6: The X-plant status is kept up-to-date by the CSCM team. Thus, they make the decision what to do with the empty packaging based on the calculations behind the X-plant status. Due to this the warehouse employees only have to check the X-plant status and follow the process according to the result.

Based on the abovementioned differences with the current way of working, we can conclude that the new process is clearer and will prevent that empty packaging is stagnated in the local warehouses and that the warehouse employees always make the right decision about what to do with the empty packaging.

6.2 SIPOC Analysis

To make sure it is clear for all stakeholders who is responsible for each process step of the To-Be process, a SIPOC analysis has been used to clarify the responsibilities, inputs and outputs of each activity of the To-Be process. A SIPOC diagram is a tool used to identify all the relevant elements of a process by summarizing the inputs and outputs of all process steps and it helps to identify those processes that have the greatest impact (Pyzdek & Keller, 2014). The acronym SIPOC stands for suppliers, inputs, process, outputs and customers. As discussed by Mishra & Kumar Sharma (2014), the suppliers are those who supply goods or services. Inputs are the resources such as people, raw material, information and finance that are put into a system to obtain a desired
output. The process converts the inputs into the desired outputs. Finally, it reaches the customers to whom it is supplied.

In a flow chart representing a process, a diamond shape represents a decision. This is also the case in the flow chart of the new process, represented in Figure 6.1. In this process, it is very important to make clear who has to make the decisions. Therefore, this SIPOC analysis has been performed. Based on interviews with several employees of the CSCM department, it is determined who exactly has to make the decisions in the new process. This is presented in Table 6.1. This table presents the SIPOC analysis of the To-Be process.

In the new process, in total three decisions need to be made. The determination of the X-plant status is for the return or scrap decision the most important. This determination is done by the CSCM team and the 3PL employees in the locals only have to check the status and execute the right process step based on the status. Thus, the new process is designed in such a way that the 3PL employees do not have to make decisions. This makes the empty packaging process easier and less time-consuming for the local warehouses.

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Input</th>
<th>Processes</th>
<th>Output</th>
<th>Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSCM</td>
<td>List with empty packaging materials and criteria for scrapping packaging immediately</td>
<td>1. Packaging on scrap list?</td>
<td>Decision to go further with the process (if no) or decision to scrap the packaging (if yes)</td>
<td>3PL employees in LWH</td>
</tr>
<tr>
<td>3PL employees in LWH</td>
<td>Empty packaging and unknown packaging 12NC</td>
<td>2. Determine 12NC of packaging</td>
<td>12NC of the packaging material</td>
<td>3PL employees in LWH</td>
</tr>
<tr>
<td>3PL employees in LWH</td>
<td>Packaging 12NC; Description of the packaging; Quantity; Arrival date of the packaging; Site code; Packaging price; Part 12NC; FSD available?</td>
<td>3. Fill in the empty packaging form</td>
<td>Data for determination of the X-plant status and to keep X-plant status up-to-date</td>
<td>CSCM</td>
</tr>
<tr>
<td>CSCM; SAP</td>
<td>Regular 12NC of the packaging</td>
<td>4. FSD for packaging available ?</td>
<td>Yes → packaging 12NC with FSD; No → local request form</td>
<td>3PL employees in LWH; CSCM (in case of LRF)</td>
</tr>
<tr>
<td>3PL employees in LWH</td>
<td>Blank local request form</td>
<td>5. Send LRF (Local request form for FSD)</td>
<td>Filled in form to request FSD for packaging</td>
<td>CSCM</td>
</tr>
<tr>
<td>CSCM</td>
<td>12NC of the packaging FSD</td>
<td>6. Check X-plant status?</td>
<td>X-plant status of the packaging → scrap or return</td>
<td>3PL employees in LWH</td>
</tr>
<tr>
<td>3PL employees in LWH</td>
<td>X-plant status “return”; 12NC of the packaging</td>
<td>7. Book in SAP as FSD</td>
<td>Packaging booked in SAP as FSD</td>
<td>3PL employees in LWH</td>
</tr>
</tbody>
</table>
3PL employees in LWH | Empty packaging | Reusable empty packaging; More local warehouse space for critical parts | Factory warehouse; Local warehouse
---|---|---|---
3PL employees in LWH | X-plant status “scrap” | Packaging is disposed; More local warehouse space for critical parts | Local warehouse

The analysis has shown that there are in total five different key players in the new process, which are the following:

1. The local warehouse
2. The factory warehouse in Country E
3. The 3PL employees in the local warehouse
4. The CSCM team
5. The information system SAP

As shown in the table above, the 3PL employees in the local warehouses and the CSCM team are most frequently the supplier of the inputs or the customer of the outputs of the processes.

This SIPOC analysis has shown three important aspects for the new process:

1. What data is required to execute the new process: the inputs.
2. What data results from the process steps: the outputs.
3. Who has to do what in the new process: the supplier of the inputs and the customer of the outputs. It shows which stakeholder is responsible for each step of the process.

Thus, with the results of the SIPOC analysis the responsibilities have been made clear for each stakeholder. As a result, it is now possible to inform the stakeholders about what they have to do with empty packaging in the local warehouse and they are able to act accordingly.

### 6.3 New Way of Determining the X-plant Status

For the To-Be process to work, it is crucial that the X-plant status is determined in the right manner. The X-plant status indicates whether it is economically and technically advantageous to return the packaging. If the X-plant status is not up-to-date, this can have negative consequences for the local warehouse. Because then, the 3PL employees are not informed correctly and it is possible that the 3PL employees proceed with the wrong process step and do the wrong thing with the packaging. Therefore, it is essential to determine the X-plant status in the correct way and keep it up-to-date. Hence, in this section it is described how the X-plant status needs to be determined, but first we shortly describe how the X-plant status is currently determined.

The old way of determining the X-plant status was not based on formulas; only the price of the packaging and whether there is a need for the packaging material are used as decision criteria. However, determining whether a packaging material is needed in the future is not possible for all packaging materials due to data unavailability. Therefore, only an employee with a lot of experience and knowledge about the parts and the packaging is able to determine the X-plant status. Based on his experience he could say whether it was best to scrap (i.e. dispose) or return the packaging. Because of his knowledge he could determine the status, but this was often not based on logical decision criteria. In addition, another problem with this is that only this specific employee can adapt the X-plant status and no other employees. Therefore, a process for determining the X-plant status with better decision criteria needs to be developed.

In the new way of determining the X-plant status for packaging materials, the status is dependent on the following parameters:
1. The price of the new packaging
2. Demand for the packaging
3. Demand for the part(s)
4. The actual inventory of the packaging
5. Profitability of returning the packaging

Note that the demand for the packaging is related to the demand for the parts. If a part has a high demand rate, this means that the packaging to pack the part also has a high demand rate.

The new way of determining the X-plant status is shown in Figure 6.2.

![Flowchart for determining X-plant status](image)

The figure above shows how to determine the X-plant status. The determination starts with checking the new buy value of the packaging, i.e. the price of the new packaging. The threshold value for scrapping or returning the packaging is now set to $€X$. A sensitivity analysis must show what the most advantageous value is. If the value is indeed larger than $€X$, we can go to the next step. If the new buy value of the packaging is less than $€X$, the packaging will be scrapped.

After determining the value of the packaging, it is to be checked if the actual inventory of the packaging is larger than X years of demand. Also, in this case, a sensitivity analysis has to prove what the best value for X is. If the actual inventory of the packaging is more than the X years demand, the packaging must be scrapped. Because this indicates that more packaging materials are in stock than what is needed. Thus, if yes, the packaging is scrapped and if no, we have to proceed with the next step of the determination.

Within this last step, it has to be checked whether it is profitable to return the packaging. How to determine this, is presented in Section 6.3.3. This is important to know because we do not want to return packaging if it is more expensive to return the packaging than to buy this packaging new. If it is profitable to return the packaging, the X-plant status is set to “return”. If it is not profitable to return the packaging the X-plant status is set to “scrap”.

The next sections will provide more information about the criteria for determining the X-plant status. The new buy value, actual inventory in combination with the years of demand, and the profitability of returning the packaging will be discussed in Section 6.3.1, 6.3.2, and 6.3.3 respectively.
6.3.1  Criterion 1: New Buy Value of the Packaging
The first criterion is the value of buying a packaging material new. Thus, in other words: the new buy value of the packaging. As default, the threshold value for buying a packaging new or returning is set to €X. This value is taken over from parts and therefore, a sensitivity analysis has to give more insight in the most optimal value for this threshold.

6.3.2  Criterion 2: Actual Inventory greater than X Years Demand
The second criterion consists of two aspects. The first aspect is the actual inventory of empty packaging in all local warehouses. The local warehouses have to fill in the packaging data in an Excel list and with this Excel file, it is determined what the actual worldwide inventory of a specific packaging 12NC is. The actual inventory value is compared with the second aspect of this criterion, which is the number of years of demand. The years of demand represent the total amount of empty packaging materials we want to have in the system worldwide.
To give an example: Worldwide, we have in total 15 items of a packaging material in inventory. For this packaging the number of years demand is 2 and the usage of this packaging is 1 per month (i.e. we need 1 item of this packaging each month), and thus 12 per year. We multiply the 12 items we use per year by the years of demand. The result is that in total we want to have 24 items of this packaging material in the factory warehouse inventory. Now we compare the usage per year with the actual inventory. We only have 15 items in inventory, which means that the packaging materials must be returned to the factory warehouse.
For each packaging it is dependent on the demand what the number of years demand will be. Thus, in addition, we need to determine to demand for the packaging and for the part.

Demand for the packaging and the parts:
This is based on real and future demand which depends on the demand for the parts that are to be packed with that packaging material.
The part demand is also based on real and future demand. Demand for the packaging is related and dependent on the demand for the parts. If we know the demand for the part and we know which packaging is needed for that part even as which other parts can be packed with that packaging, we can translate the demand for the part to the demand for the packaging.

6.3.3  Criterion 3: Profitability to Return
This criterion calculates whether it is profitable to return the empty packaging to the factory warehouse. The calculations for this are on packaging 12NC level, thus, for each specific packaging these calculations are executed. In the case where returning an empty packaging to the factory warehouse is more expensive than the new buy value of that packaging, the packaging will not be returned. How to determine this is presented in Figure 6.3.
Figure 6.3 Determination whether it is profitable to return an empty packaging

For the determination whether it is profitable to return an empty packaging, we need the following cost parameters:

- Price of a new packaging
  - The transportation costs from the packaging supplier to the factory warehouse is also considered in this price.

- Handling costs: these costs are not applicable if a new packaging material would be bought
  - Cleaning costs in the factory warehouse.
  - Administration costs for making the empty packaging ready for return, i.e. costs for booking the packaging into SAP by an employee, etc.
  - Warehouse costs: applies for both the local warehouse and the factory warehouse.

- Transportation costs from the local warehouse to the factory warehouse
  - Dependent on volume and weight of the packaging
  - This cost is sometimes based on the volume, sometimes on the weight
    - If packaging has a high volume but low weight the transport price is based on its volume
    - If a packaging weighs a lot but is small the transport cost is based on its weight
    - So, transportation cost is the maximum of the costs for its volume or weight
  - Duty costs

- Repair costs
  - In most cases, these costs are low. This is because the packaging materials are often not damaged, so then only small reparations are needed.
  - Note that the exact costs of repair are known after the packaging has been returned and repaired, that is why for the determination of the X-plant status an average value for the repair costs is used.
6.4 Conclusion and Discussion

In this chapter, we presented the new process for empty packaging materials in the local warehouses. Furthermore, a SIPOC analysis has been performed to make the responsibility of each player in the process clear. Lastly, we showed how to determine the X-plant status of the packaging materials.

By using the new process, the company can already improve the empty packaging situation in their supply chain. In addition to this, by designing this new standardized process for the local warehouse, we solved root cause 6. Now, there is a clear instruction for the local warehouses how to handle empty packaging materials and each local warehouse has, after implementing the new process, the same standardized way of working. Furthermore, the new process includes SAP (i.e. packaging materials are booked in SAP), which makes the packaging materials traceable and visible. By this, we solved root cause 9. Additionally, with the new process and the new way of determining the X-plant status, it is much easier for the CSCM department to keep the X-plant status of the packaging materials up-to-date and thus, we can conclude that also root cause 11 has been tackled.

With the SIPOC analysis, the responsibilities of all players regarding empty packaging materials have been made clear, which also tackles root cause 18.
7 Development of the Decision Support Model

Within this chapter, the mathematical model that forms the basis of the decision support model is developed and explained. This will provide an answer to the second research question:

**Research Question 2:**
What is a suitable decision support model for managing empty packaging?

This chapter is organized as follows. We start with an explanation of the modeled closed-loop supply chain (CLSC) in Section 7.1. This CLSC is used as a basis for the mathematical model. In Section 7.2, the mathematical model with the objective function and its constraints are presented. Section 7.3 explains how the different cost parameters are determined. Subsequently, Section 7.4 presents the values of the input parameters which are used for the mathematical model. Lastly, in Section 7.5, a conclusion is given, and the second research questions is answered.

7.1 The Modeled Closed-Loop Supply Chain

Before we can start defining the mathematical model, we first need to define the closed-loop supply chain and the activities within all stages of this supply chain. Besides this, some assumptions will be made to simplify the model. In Chapter 4, Packaging Flows, we already presented the forward flow and return flow of the packaging materials. In this section, we will dive into more detail.

As a basis for the model the closed-loop supply chain presented in Figure 7.1 is used. The dashed arrows represent the flow of empty packaging materials and the non-dashed arrows display the flow of full packaging materials (i.e. packaging including a part).

![Diagram](image)

*Figure 7.1 The modeled closed-loop supply chain*
Figure 7.1 shows that the modeled closed-loop supply chain consists of one packaging supplier, one factory warehouse, four local warehouses in different countries and each local warehouse has one customer. In the factory warehouse, the local warehouses and the customers, empty packaging materials can be disposed, which is represented by the dashed arrows out of the warehouses and the customers.

Based on interviews with the middle management and some experts in the field of empty packaging within the company, it is decided that the mathematical model should be based upon a pull inventory control policy. In this pull system, the CSCM employees check the current on-hand inventory of empty packaging at the local warehouses worldwide. Based on the on-hand inventories, the costs of returning empty packaging and the demand for the empty packaging materials, the decision is made whether empty packaging needs to be returned or scrapped. In the return decision, it is also determined from which local warehouse the packaging needs to be returned. How many packaging materials need to be returned to the factory warehouse is dependent on the demand for that packaging. This means that packaging is only returned if there exists a future demand for the packaging material. In this way, it is prevented that empty packaging materials are returned to the factory warehouse and that unnecessary costs are made. Furthermore, the model needs to calculate what the costs are of buying a new packaging at the supplier and transporting this to the factory warehouse. Then, it will be compared which option (i.e., supplier or local warehouses) gives the minimum costs to get the packaging in the factory warehouse to satisfy the demand.

Thus, in this pull inventory control model, the upstream facility, the factory warehouse, checks the current on-hand inventory at the downstream facilities, the local warehouses, before empty packaging materials are returned (Roy, Carrano, Pazour, & Gupta, 2016). Important to mention is that the pull decision (returning the empty packaging) moves the packaging based on demand (Wanke & Zinn, 2004). This indicates that if there is no future demand for an empty packaging, it is not returned, and the decision will be to scrap this packaging at the local warehouses.

The pull inventory policy as beforementioned is clarified with the following example:

Assume that the supply chain in this example consists of the factory warehouse (FWH), three local warehouses (LWH) and the packaging supplier (see Figure 7.2). Each local warehouse has its own empty packaging stock for a specific packaging material. It is assumed that the packaging supplier has an infinite stock and can always deliver new packaging materials.

![Diagram of pull inventory control policy]

**Figure 7.2 Example of the pull inventory control policy**

A packaging with X-plant status “return” is considered, which means that the packaging needs to be returned to the factory warehouse. Assume that for this specific packaging, the safety stock at the factory warehouse is 10, which indicates that the factory warehouse wants 10 items of that packaging on stock. Furthermore, the safety stock for this packaging is 1 empty packaging item at each local warehouse. Local warehouses 1, 2 and 3 have 4, 6 and 5 items on stock, respectively.
Based on the safety stock and the maximal number of items that is allowed to have on stock in the local warehouse, it is calculated which combination of returning gives the lowest costs. If the amount of packaging items that remain after returning is larger than the safety stock, these remaining packaging items are scrapped locally.

Next, more details are given about the different stages of the closed-loop supply chain presented in Figure 7.1.

**Factory warehouse:**
- The factory warehouse wants to minimize the procurement cost of buying new packaging materials.
- In the factory warehouse, the empty packaging materials are filled with parts. One packaging material can be used to pack different parts, however, in some cases the packaging material can only be used for one specific part.
- The factory warehouse is responsible for the activities of making the empty packaging materials ready for reuse. These activities always include cleaning the empty packaging, and only in some cases repairing the packaging material.
- The factory warehouse is also responsible for purchasing new packaging materials.

**Local warehouses:**
- If the local warehouse receives the packaging material including a part, it is assumed that it is delivered the same day to the customer.
  - Local warehouses and customer are usually less than 50 km away from each other and therefore, it is possible to deliver the full packaging materials the same day at the customer.
  - The transportation mode that is used for the shipment of full packaging materials from the local warehouse to the customer is dependent on the distance. Usually, trucks are used. If the customer is located directly next to the local warehouse, the full packaging materials are transported to the customer with a forklift truck.

**Supplier:**
- It is assumed that the supplier has an infinite stock of empty packaging materials, which implies that if a new empty packaging item is ordered by the factory warehouse, the supplier can always deliver this packaging.

**The packaging materials (RTIs):**
- RTIs can be damaged, but do not deteriorate through time. As a result, there is no maximal preset number of times the RTI can be reused.
- RTI pool shrinkage can occur, which is due to: RTI loss, RTI theft, disposals due to non-repairable damages and the RTI has never been returned.
- It is assumed that an RTI cannot be damaged or lost at the factory warehouse, but it can be disposed there because of non-reparability.
- The mathematical model will consider one specific packaging material (RTI).

**New packaging materials:**
- Packaging materials are purchased by the factory warehouse according to a periodic (monthly) review. Thus, each month the on-hand inventory of the local warehouses is checked, as well as the demand for empty packaging materials. Based on this and the lowest costs, it is determined which local warehouse must return how many packaging materials and how many new packaging materials need to be ordered.
- The demand of packaging is assumed to follow the same demand pattern as the part which is to be packed with that packaging.
• The unit price of new RTIs is constant and known. The price does not depend on order quantity and time of ordering.
• There is a positive, fixed and known lead time for new RTIs and this time is independent on the order quantity.

Transport of RTIs between factory warehouse and local warehouse
• For the forward flow, i.e. packaging including a part, air freight transport is used.
• For the return flow, i.e. empty used packaging materials, two transport modes are possible: air freight or ocean shipments.
• The mathematical model that is defined in the next section includes the lead times for air freight shipments for both the forward and return flow.
• The costs for shipping the full packaging from the factory warehouse to the local warehouse is not considered in the objective function of the model.
• The costs for delivering the full RTIs from the local warehouse to the customer and the empty RTI from the customer to the local warehouse is not considered in the model.
• Only the transportation cost of shipping empty packaging from the local warehouse to the factory warehouse and the transportation cost from the packaging supplier to the factory warehouse is considered in the model. This is due to that the company is only interested in the costs of the reverse flow of the empty packaging materials.

7.2 The Mathematical Model
As already explained in the previous section, the mathematical model is based on a pull inventory control policy. The objective of the model is to minimize the total costs of empty packaging within the supply chain. The total costs consist of the backorder costs, inventory holding costs, purchasing costs, returning costs and the disposal costs. Below, the used parameters, the decision variables, the objective function and the constraints are presented and explained. Additionally, the assumptions made to simplify the model are presented. Note that the model is built for one specific empty packaging material. Thus, all parameter values relate to one packaging material.

List of symbols
\( \alpha_{c,s} \) Fraction of empty packaging items returned from customer \( c \) to local warehouse \( s \) after emptying the packaging material, \( 0 \leq \alpha_{c,s} \leq 1 \), where \( s = \text{country A, B, C and D} \).
\( BP_{c,s}(t) \) Backorders for full packaging units at customer \( c \) of local warehouse \( s \) in period \( t \), where \( s = \text{country A, B, C and D} \). The number of backorders at the customer are measured at the end of period \( t - 1 \), after demand has occurred and after full packaging materials are shipped to the local warehouses.
\( C_{B,c,s} \) Backorder cost per full packaging unit missing at customer \( c \) of local warehouse \( s \), where \( s = \text{country A, B, C and D} \).
\( C_{D,E} \) Cost for disposing one packaging unit in the factory warehouse in Country E.
\( C_{D,s} \) Cost for disposing one packaging unit by warehouse \( s \), where \( s = \text{country A, B, C and D} \).
\( C_N \) Cost for buying one unit of an empty packaging material new. This cost corresponds to the price of the packaging material.
\( C_{R,E} \) Cost for cleaning and repairing an empty packaging unit at the factory warehouse in Country E.
\( C_{\text{tot}}(T) \) Total cost of the closed-loop supply chain regarding empty packaging over planning horizon \( T \).
\( C_{T,N} \) Cost for transporting a new empty packaging material from supplier \( N \) to the factory warehouse in Country E.
\( C_{T,s} \) Cost for transporting an empty packaging material from local warehouse \( s \) to the factory warehouse in Country E, where \( s = \text{country A, B, C and D} \).
\( C_{V,N} \) Variable cost for getting a new empty packaging unit from supplier \( N \) to the factory warehouse in Country \( E \). This cost is calculated as follows: \( C_{V,N} = C_N + C_{T,N} \).

\( C_{V,S} \) Variable cost for returning one empty packaging unit from local warehouse \( s \) to the factory warehouse in Country \( E \), where \( s = \) country \( A, B, C \) and \( D \). This cost is calculated as follows: \( C_{V,S} = C_{T,S} + C_{R,NL} \).

\( CB_{H,E} \) Cost for holding one empty packaging unit in stock at the factory warehouse in Country \( E \) in period \( t \), after new and returned empty packaging materials have arrived in the factory warehouse and after full packaging materials are shipped to the local warehouses and empty packaging materials are disposed.

\( CB_{H,S} \) Cost for holding one empty packaging unit in stock at local warehouse \( s \) in period \( t \) after empty packaging materials have arrived from the customer and empty packaging materials are returned to the factory warehouse and after empty packaging materials are disposed, where \( s = \) country \( A, B, C \) and \( D \).

\( DP_{c,s}(t) \) Demand of customer \( c \) of local warehouse \( s \) for full packaging units in period \( t \), where \( s = \) country \( A, B, C \) and \( D \). This demand occurs at the beginning of period \( t \).

\( IB_{max,s} \) Maximum storage space for empty packaging materials in warehouse \( s \), where \( s = \) the factory warehouse in Country \( E \) and the local warehouses in country \( A, B, C \) and \( D \).

\( IB_{E}(t) \) On-hand empty packaging inventory in the factory warehouse in Country \( E \) in period \( t \). This on-hand inventory is measured at the beginning of period \( t \), before demand occurs, before empty packaging materials arrive from the local warehouse and the packaging supplier, before full packaging materials are shipped to the local warehouse and before empty packaging materials are disposed.

\( IB_{s}(t) \) On-hand empty packaging inventory in local warehouse \( s \) in period \( t \), where \( s = \) country \( A, B, C \) and \( D \). This on-hand inventory is measured at the beginning of period \( t \), before demand occurs, before empty packaging materials arrive from the customer, before empty packaging materials are returned to the factory warehouse and before empty packaging materials are disposed.

\( IP_{c,s}(t) \) On-hand inventory of full packaging materials (i.e. packaging including a part) at customer \( c \) of local warehouse \( s \) in period \( t \), where \( s = \) country \( A, B, C \) and \( D \). This on-hand inventory is measured at the beginning of period \( t \), before demand occurs, before full packaging materials arrive from the local warehouse and before full packaging materials are emptied.

\( IP_{s}(t) \) On-hand inventory of full packaging materials (i.e. packaging including a part) in local warehouse \( s \) in period \( t \), where \( s = \) country \( A, B, C \) and \( D \). This on-hand inventory is measured at the beginning of period \( t \), before demand occurs, before full packaging materials arrive from the factory warehouse and before full packaging materials are shipped to the customer.

\( L_{c->s} \) Lead time of shipping an empty packaging from customer \( c \) to local warehouse \( s \), where \( s = \) country \( A, B, C \) and \( D \).

\( L_{N->E} \) Lead time of shipping a new empty packaging from the new packaging supplier \( N \) to the factory warehouse.

\( L_{E->s} \) Lead time of shipping a full packaging from the factory warehouse to local warehouse \( s \), where \( s = \) country \( A, B, C \) and \( D \).

\( L_{s->c} \) Lead time of shipping a full packaging from local warehouse \( s \) to customer \( c \), where \( s = \) country \( A, B, C \) and \( D \).

\( L_{s->E} \) Lead time of returning an empty packaging from local warehouse \( s \) to the factory warehouse in Country \( E \), where \( s = \) country \( A, B, C \) and \( D \).

\( N \) Supplier of new empty packaging units.

\( SB_{E}(t) \) Safety stock of empty packaging materials at the factory warehouse in Country \( E \). Measured at the beginning of period \( t \), after demand has occurred and before empty packaging materials arrive in the warehouse, before full packaging materials are shipped from the factory to the local warehouse, before the local
warehouse returns empty packaging materials to the factory warehouse and before the warehouses dispose empty packaging materials.

\( SB_s(t) \)

Safety stock of empty packaging materials at warehouse \( s \), where \( s = \) Country A, B, C, D and E. Measured at the beginning of period \( t \), after demand has occurred and before empty packaging materials arrive in the warehouse, before full packaging materials are shipped from the factory to the local warehouse, before the local warehouse returns empty packaging materials to the factory warehouse and before the warehouses dispose empty packaging materials.

\( t \)

Planning period; \( t = 1, \ldots, T \), and \( t \) is in months.

\( T \)

Length of the planning horizon.

The main decisions to be made are: I) When to order how much new empty packaging from the new packaging supplier? II) When to let which local warehouse return how much used empty packaging and how much? To make the mathematical model complete, the forward flow of full packaging units is also considered, which lead to a couple more decisions to be made: i) When to ship how much full packaging units from the factory warehouse to the local warehouses? ii) When to ship how much full packaging units from the local warehouse to the customer? iii) How much full packaging units to be emptied at the customer? This leads to the decision variables defined below.

List of decision variables

\( QB_{c,s}(t) \)

Number of full packaging items emptied at the customer of the local warehouse at the end of period \( t \) after full packaging materials arrive at the customer. These packaging materials have the potential to be returned to local warehouse \( s \), where \( s = \) country A, B, C and D.

\( QB_{d,E}(t) \)

Number of empty packaging items disposed at the factory warehouse at the end of period \( t \), after empty packaging materials from the packaging supplier and the local warehouses have arrived in the factory warehouse and after full packaging materials are shipped to the local warehouses.

\( QB_{d,s}(t) \)

Number of empty packaging items disposed at local warehouse \( s \) at the end of period \( t \), after empty packaging materials have arrived from the customer in the local warehouse and after empty packaging materials have been returned to the factory warehouse, where \( s = \) country A, B, C and D.

\( QB_{N\rightarrow E}(t) \)

Number of new empty packaging items shipped from the new packaging supplier \( N \) to the factory warehouse in Country E at the beginning of period \( t \), after demand occurred.

\( QB_{S\rightarrow E}(t) \)

Number of used empty packaging items returned from local warehouse \( s \) to the factory warehouse in Country E at the beginning of period \( t \), after empty packaging materials have arrived from the customer, after demand occurred and before empty packaging materials are disposed, where \( s = \) country A, B, C and D.

\( QP_{E\rightarrow s}(t) \)

Number of full packaging units shipped from the factory warehouse to local warehouse \( s \) in period \( t \), where \( s = \) country A, B, C and D. This is measured at the beginning of period \( t \), after empty packaging materials arrive from the packaging supplier and the local warehouses, after demand occurred and before empty packaging materials are disposed.

\( QP_{s\rightarrow c}(t) \)

Number of full packaging units shipped from local warehouse \( s \) to customer \( c \) in period \( t \), where \( s = \) country A, B, C and D. This is measured at the beginning of period \( t \), after full packaging materials from the factory warehouse arrived in the local warehouse.

Figure 7.3 represents the simplified version of the closed-loop supply chain with the parameters and decision variables defined above. Note that the figure shows only one local warehouse and
customer. The mathematical model which is developed in this section contains four local warehouses and four customers.

Figure 7.3 Simplified version of the closed-loop supply chain with decision variables and parameters
Before the mathematical model is defined, first a list of assumptions is given below.

**List of assumptions**

- We assume the following sequence of events within the factory warehouse:
  1. The on-hand inventory of empty packaging materials is measured at the factory warehouse.
  2. New packaging materials arrive at the factory warehouse.
  3. The returned empty packaging materials arrive at the factory warehouse.
  4. Demand for parts occurs.
  5. Empty packaging materials are 'ordered' from the local warehouses.
  6. The order for new empty packaging materials is placed.
  7. Full packaging materials are shipped to local warehouse.
  8. Empty packaging materials are disposed.

- The following sequence of events is assumed for the local warehouses:
  1. The on-hand inventory of empty and full packaging materials is measured.
  2. Full packaging materials from the factory warehouse arrive.
  3. Full packaging materials are shipped to the customer.
  4. Empty packaging materials returned from the customer arrive in the local warehouse.
  5. The local warehouse returns empty packaging materials to the factory warehouse.
  6. Empty packaging materials are disposed.

- It is assumed that new packaging supplier $N$ always has sufficient new empty packaging materials in stock, which means that $I_N(t) = \infty$. Thus, supplier $N$ can always deliver the materials that are ordered by the factory warehouse.

- The values of the above defined cost parameters, $CP_{b,s}$, $C_{D,E}$, $C_{D,S}$, $C_{H,E}$, $C_{H,S}$, $C_N$, $C_{R,E}$, $C_{tot}(T)$, $C_{T,N}$, $C_{T,S}$, $C_{V,N}$, $C_{V,S}$, do not change during the planning horizon.

- Cost parameter, $C_{b,s}$, are paid immediately after the backorders of the customer have been measured at the end of the period after demand has occurred.

- The disposal costs in the factory warehouse and the local warehouses, $C_{D,E}$ and $C_{D,S}$ respectively, are directly paid after disposal of packaging units.

- At the beginning of the period, before empty packaging materials have arrived and before demand has occurred, the on-hand inventory is measured, and immediately after measuring the holding costs, $CB_{H,E}$ and $CB_{H,S}$, are paid.

- The variable costs of getting a new empty packaging from the packaging supplier $C_{V,N}$, which consists of the transport costs $C_{T,N}$ and price of the packaging $C_N$ are paid after directly after new empty packaging materials are ordered.

- The variable return costs $C_{V,S}$, which includes the transport cost $C_{T,S}$ and the repair and cleaning costs $C_{R,E}$ are paid immediately after empty packaging materials are returned from the local warehouse to the factory warehouse.

- We assume that empty packaging materials are first returned from the local warehouse to the factory warehouse and after returning, the remaining empty packaging materials in the local warehouse are disposed.

- The inventory on-hand at the local warehouses at time $t = 0$ is zero: $IB_s(0) = 0$, $\forall s$

- The on-hand inventory at the factory warehouse at time $t = 0$ is zero: $IB_E(0) = 0$

- It is assumed that each local warehouse delivers packaging including parts to a single customer.

- We assume that the parts to be packed with the packaging materials are always available. This implies that backorders at the customer occur due to missing empty packaging materials and not because of unavailability of the part.

- No fixed order, transport and setup costs.

- It is assumed that the full packaging materials and the empty packaging materials arrive just in time (JIT).
One period in planning horizon $T$ is assumed to be one month. Thus, $t$ is one month.

It is assumed that air freight shipments are used for both the forward and return flow. Hence, the assumed costs for transportation and the lead times are all for air freight shipments.

Following the above notation and assumptions, we can formulate the problem as a Mixed Integer Linear Programming model with the objective function and restrictions presented below. The model will be solved with a scenario-analysis based simulation.

**Objective function:**

$$\text{Min } C_{\text{tot}}(T) = \sum_{t=2}^{T+1} \left[ CB_{H,E} \cdot IB_{E}(t) + \sum_{s} CB_{H,S} \cdot IB_{S}(t) \right]$$

$$+ \sum_{t=2}^{T} \left[ C_{d,E} \cdot QB_{d,E}(t) + \sum_{s} C_{d,S} \cdot QB_{d,S}(t) \right]$$

$$+ \sum_{t=2}^{T} \sum_{s} C_{V,N} \cdot QB_{N \rightarrow E}(t) + \sum_{t=2}^{T} \sum_{s} C_{V,S} \cdot QB_{S \rightarrow E}(t)$$

$$+ \sum_{t=1}^{T} \sum_{s} C_{B,c,s} \cdot BP_{c,s}(t)$$

(1)

Objective function (1) indicates the expected total relevant empty packaging costs over the planning horizon $T$. The first term denotes the cost for holding empty packaging on stock in the factory warehouse and the local warehouses. The second term indicates the costs for disposing empty packaging materials in the factory warehouse and in the local warehouses. The third term reflects the cost for buying new empty packaging materials from the packaging supplier. The fourth term represents the cost for returning empty packaging materials from a local warehouse to the factory warehouse. The fifth term of the objective function denotes the backorder costs due to backorders at the customer of a local warehouse.

**Subject to:**

Constraints (2) to (5) represent the availability of empty packaging in the factory warehouse.

$$IB_{E}(t) = IB_{E}(t - 1) + QB_{N \rightarrow E}(t - 1 - L_{N \rightarrow E})$$

$$+ \sum_{s} QB_{S \rightarrow E}(t - 1 - L_{S \rightarrow E}) - QB_{d,E}(t - 1)$$

$$- \sum_{s} QB_{E \rightarrow S}(t - 1) \quad \forall t \in \{1, ..., T\}$$

(2)

Constraint (2) represents the mass balance for the inventory on-hand at the factory warehouse. This constraint considers the inventory on-hand at the factory warehouse at the end of the previous period, the number of new empty packaging materials ordered $L_{N \rightarrow E}$ periods earlier, the number of used empty packaging materials returned $L_{S \rightarrow E}$ periods earlier from the local warehouses to the factory warehouse, the amount of empty packaging materials disposed at the end of the previous period, the number of full packaging materials shipped to the local warehouses in the previous period and the safety stock in the current period.
\[ IB_E(t) \geq 0 \quad \forall t \in \{1, \ldots, T\} \quad (3) \]

Constraint (3) ensures that the inventory on-hand of empty packaging materials at the factory warehouse is non-negative.

\[
IB_E(t - 1) + QB_{N \rightarrow E}(t - 1 - L_{N \rightarrow E}) + \sum_s QB_{S \rightarrow E}(t - 1 - L_{S \rightarrow E}) - QB_{d,E}(t - 1) \]
\[
- \sum_s QP_{E \rightarrow S}(t - 1) \geq SB_E(t) \quad \forall t \in \{1, \ldots, T\} \quad (4)
\]

Constraint (4) represents that the on-hand empty packaging inventory in the factory warehouse must be greater or equal to the safety stock in the factory warehouse.

\[ IB_E(t) \leq IB_{\text{max},E} \quad \forall t \in \{1, \ldots, T\} \quad (5) \]

Constraint (5) denotes that the on-hand empty packaging inventory in the factory warehouse cannot exceed the maximum storage capacity for empty packaging materials in this warehouse. Note that in this model \( IB_{\text{max},E} \) represents a fraction of the maximum storage capacity at the factory warehouse. This is due to that the model is applicable for one specific packaging material and the storage capacity is for all packaging materials that exist in the company.

\[ IB_s(t) = IB_s(t - 1) + \alpha_{c,s} QB_{c,s}(t - 1 - L_{c \rightarrow s}) - QB_{s \rightarrow E}(t - 1) - QB_{d,s}(t - 1) \quad \forall t \in \{1, \ldots, T\}; \forall s \in \{A, B, C, D\} \quad (6) \]

Constraint (6) represents the mass balance for the inventory on-hand at the local warehouses. This constraint considers the on-hand inventory of the previous period, the fraction of the delivered full packaging materials that is returned empty from the customer to the local warehouse \( L_{c \rightarrow s} \) periods earlier, the number of packaging units that are returned from the local warehouse to the factory warehouse in the previous period and the number of packaging units that are disposed within the local warehouse in the previous period.

\[ IB_s(t) \geq 0 \quad \forall t \in \{1, \ldots, T\}; \forall s \in \{A, B, C, D\} \quad (7) \]

Constraint (7) ensures that the inventory on-hand of empty packaging materials at the local warehouses is non-negative.

\[
IB_s(t - 1) + \alpha_{c,s} QB_{c,s}(t - 1 - L_{c \rightarrow s}) - QB_{s \rightarrow E}(t - 1) - QB_{d,s}(t - 1) \geq SB_s(t) \quad \forall t \in \{1, \ldots, T\}; \forall s \in \{A, B, C, D\} \quad (8)
\]

Constraint (8) represents that the on-hand empty packaging inventory in the local warehouses must be greater or equal to the safety stock of the local warehouses.

\[ IB_s(t) \leq IB_{\text{max},s} \quad \forall t \in \{1, \ldots, T\}; \forall s \in \{A, B, C, D\} \quad (9) \]

Constraint (9) denotes that the on-hand empty packaging inventory in the local warehouses cannot exceed the maximum storage capacity for empty packaging materials. Note that in this model \( IB_{\text{max},s} \) represents a fraction of the maximum storage capacity at the local warehouses.
This is due to that the model is applicable for one specific packaging material and the storage capacity is for all packaging materials that exist in the company.

\[ IP_s(t) = IP_s(t-1) + QP_{E\rightarrow s}(t-1 - L_{E\rightarrow s}) - QP_{s\rightarrow c}(t-1) \quad \forall t \in \{1, ..., T\}; \forall s \in \{A, B, C, D\} \]  

Constraint (10) denotes the mass balance for the inventory on-hand of full packaging materials (i.e. packaging materials including a part) at the local warehouses. The inventory on-hand of the previous period is considered, as well as the full packaging materials arriving in the local warehouse and the full packaging materials shipped to the customer in the previous period.

\[ IP_s(t) \geq 0 \quad \forall t \in \{1, ..., T\}; \forall s \in \{A, B, C, D\} \]  

Constraint (11) ensures that the inventory on-hand of full packaging materials at the local warehouses is non-negative.

\[ IP_{c,s}(t) = IP_{c,s}(t-1) + QP_{s\rightarrow c}(t-1 - L_{s\rightarrow c}) - QB_{c,s}(t-1) \quad \forall t \in \{1, ..., T\}; \forall s \in \{A, B, C, D\} \]  

Constraint (12) reflects the mass balance for the on-hand inventory of full packaging materials (i.e. packaging including a part) at the customer of the local warehouse. This on-hand inventory is dependent on the on-hand inventory of full packaging materials in the previous period, the number of full packaging materials received from the local warehouse which send to the customer \(L_{s\rightarrow c}\) periods earlier and the number of full packaging materials which were emptied in the previous period.

\[ IP_{c,s}(t) \geq 0 \quad \forall t \in \{1, ..., T\}; \forall s \in \{A, B, C, D\} \]  

Constraint (13) ensures that the on-hand inventory of full packaging materials at the customer of the local warehouse is non-negative.

\[ BP_{c,s}(t) = BP_{c,s}(t-1) + DP_{c,s}(t-1) - QB_{c,s}(t-1) \quad \forall t \in \{1, ..., T\}; \forall s \in \{A, B, C, D\} \]  

Constraint (14) represents the backorders at the customer of the local warehouse, which is dependent on the backorders of the previous period, the customer demand of the previous period and the number of full packaging units emptied at the customer in the previous period.

\[ BP_{c,s}(t) \geq 0 \quad \forall t \in \{1, ..., T\}; \forall s \in \{A, B, C, D\} \]  

Constraint (15) ensures that the backorder quantity at the customer of the local warehouse and the customer demand in period \(t\) are non-negative.

\[ QB_{c,s}(t) \geq 0, \quad QB_{d,E}(t) \geq 0, \quad QB_{d,s}(t) \geq 0, \quad QB_{N\rightarrow E}(t) \geq 0, \quad QB_{S\rightarrow E}(t) \geq 0, \quad QP_{E\rightarrow s}(t) \geq 0, \quad QP_{s\rightarrow c}(t) \geq 0 \quad \forall t \in \{1, ..., T\}; \forall s \in \{A, B, C, D\} \]  

Constraint (16) ensures that all decision variables are non-negative.
7.3 Determination of Cost Parameters

This section describes in detail how the cost parameters defined in Section 7.2 are determined. First, it is shown how the inventory holding costs per packaging unit are calculated. Then, it is presented how the transport costs are determined. Hereafter, we show the more detailed formulas for the variable return costs, the cost of buying a packaging new, the backorder costs and the disposal costs.

7.3.1 Inventory Holding Costs

The inventory holding cost parameters per warehouse are presented in Table 7.1. For the inventory holding cost of the local warehouse in Country C and the factory warehouse in Country E, no data was available. Therefore, we assumed that the inventory holding cost for these warehouses are the average of the costs for the local warehouses in Country A, B, C and D. Furthermore, it is assumed that the holding cost rates for empty and full packaging materials are the same.

Table 7.1 Inventory holding costs per warehouse

<table>
<thead>
<tr>
<th>Warehouse</th>
<th>Costs in €/m²/month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country A</td>
<td>( H_A = \sim 8.00 )</td>
</tr>
<tr>
<td>Country B</td>
<td>( H_B = \sim 7.00 )</td>
</tr>
<tr>
<td>Country C</td>
<td>( H_C = \sim 8.00 )</td>
</tr>
<tr>
<td>Country D</td>
<td>( H_D = \sim 10.00 )</td>
</tr>
<tr>
<td>Country E</td>
<td>( H_E = \sim 8.00 )</td>
</tr>
</tbody>
</table>

The parameters needed to calculate the different holding costs are the following:

- \( CB_{H,E} \): Cost for holding one empty packaging unit at the factory warehouse in Country E in period \( t \).
- \( CB_{H,s} \): Cost for holding one empty packaging unit one period at local warehouse \( s \), where \( s \) = country A, B, C and D.
- \( H_E \): Holding cost in euros per m² in the factory warehouse in Country E.
- \( H_s \): Holding cost in euros per m² in local warehouse \( s \), where \( s \) = country A, B, C and D.
- \( L \): Length of the packaging unit.
- \( W \): Width of the packaging unit.
- \( WS \): Warehouse space in m² occupied by the full or empty packaging unit.

The warehouse space occupied by a packaging unit is determined by calculating the area of the packaging material:

\[
WS = L \times W
\]

The cost for holding an empty packaging unit one period in the factory warehouse in Country E is calculated as follows:

\[
CB_{H,E} = H_E \times WS
\]

Lastly, the cost for holding an empty packaging unit one period in the different local warehouses is calculated in the following way:

\[
CB_{H,s} = H_s \times WS
\]

7.3.2 Transportation Costs

The transportation cost parameters per local warehouse and the new packaging supplier are presented in Table 7.2. It was assumed that the transport costs from the local warehouse in Country C and the transport cost from getting a new packaging from the packaging supplier is equal. This was assumed due to data unavailability about the transport cost from the packaging supplier to the factory warehouse. The packaging supplier is located in Country C; therefore, we
were able to assume that these costs are equal to the transport costs from the local warehouse in Country C to the factory warehouse. Note that the costs presented in Table 7.2 are the transportation costs of airfreight shipments.

\[ \text{Table 7.2 Transportation cost from the local warehouses/packaging supplier to the factory warehouse} \]

<table>
<thead>
<tr>
<th>From ... to FWH</th>
<th>Average cost per kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country A</td>
<td>( T_A = \sim 5.00 )</td>
</tr>
<tr>
<td>Country B</td>
<td>( T_B = \sim 6.00 )</td>
</tr>
<tr>
<td>Country C</td>
<td>( T_C = \sim 1.00 )</td>
</tr>
<tr>
<td>Country D</td>
<td>( T_D = \sim 2.00 )</td>
</tr>
<tr>
<td>Packaging supplier</td>
<td>( T_N = \sim 1.00 )</td>
</tr>
</tbody>
</table>

The parameters needed to calculate the different transport costs are presented below:

- \( C_{T,N} \): Cost for transporting a new empty packaging material from supplier \( N \) to the factory warehouse in Country E.
- \( C_{T,S} \): Cost for transporting an empty packaging material from local warehouse \( s \) to the factory warehouse in Country E, where \( s = \) country A, B, C and D.
- \( H \): The height of the packaging unit.
- \( L \): The length of the packaging unit.
- \( T_N \): Average cost (€/kg) for transporting a new packaging unit from the packaging supplier to the factory warehouse in Country E.
- \( T_S \): Average cost (€/kg) for transporting one packaging unit from local warehouse \( s \) to the factory warehouse in Country E, where \( s = \) country A, B, C and D.
- \( V_F \): Volume factor, which is 6000 in the case of airfreight.
- \( W \): The width of the packaging unit.
- \( W_a \): Actual weight of the empty packaging material.
- \( W_c \): The chargeable weight of an empty packaging materials. This is the weight where the transport cost (\( T_S \) and \( T_N \)) multiplied with and this is the maximum between the actual weight \( W_a \) and the volume weight \( W_v \).
- \( W_v \): The volume weight of the empty packaging material.

The volume weight of the empty packaging material is calculated as follows:

\[ W_v = \frac{L \times W \times H}{V_F} \]

The chargeable weight of a packaging material. The chargeable weight is the maximum between the actual weight \( W_a \) and the volume weight \( W_v \):

\[ W_c = \max\{W_a, W_v\} \]

The cost for transporting an empty packaging unit from a local warehouse to the factory warehouse in Country E is determined in the following way:

\[ C_{T,S} = T_S \times W_c \]

The cost for transporting a new empty packaging unit from the packaging supplier to the factory warehouse in Country E is calculated as follows:

\[ C_{T,N} = T_N \times W_c \]
7.3.3 Cost for Returning an Empty Packaging Unit
The cost to return one empty packaging unit is calculated as follows:

\[ C_{V,s} = C_{R,E} + C_{T,s} = C_{R,E} + (T_s \times W_c) \]

The parameters used in the return cost formula are defined as presented below:
- \( C_{R,E} \): Cost for cleaning and repairing an empty packaging unit at the factory warehouse in Country E.
- \( C_{T,s} \): Cost for transporting an empty packaging material from local warehouse \( s \) to the factory warehouse in Country E, where \( s = \text{country } A, B, C \text{ and } D \).
- \( C_{V,s} \): Variable cost for returning one empty packaging unit from local warehouse \( s \) to the factory warehouse in Country E, where \( s = \text{country } A, B, C \text{ and } D \).

7.3.4 Cost for Buying a New Empty Packaging Unit New
The costs for buying a new empty packaging is calculated as follows:

\[ C_{V,N} = C_N + C_{T,N} = C_N + (T_N \times W_c) \]

The parameters used in the new buy cost formula are defined as presented below:
- \( C_N \): Cost for buying one unit of an empty packaging material new. This cost corresponds to the price of the packaging material. This value is determined by using SAP.
- \( C_{T,N} \): Cost for transporting a new empty packaging material from supplier \( N \) to the factory warehouse in Country E.
- \( C_{V,N} \): Variable cost for getting a new empty packaging unit from supplier \( N \) to the factory warehouse in Country E.

7.3.5 Penalty Cost for Backorders
If an empty packaging is not available at the right time, the part cannot be shipped to the customer. Therefore, a penalty costs for this is added in the objective function. These costs are the backorder costs. Due to unavailability of data, we had to make some assumptions for these costs:
- It is assumed that the penalty costs for backorders are equal for all customers of the local warehouses. This implies that, in contrast to the transportation costs and inventory holding costs, the backorders costs are not location-specific.
- Shipping a part to the customer in the right quantity and at the right time is extremely important for the company. Thus, not being able to ship a part to the customer due to empty packaging unavailability should bring a high penalty for the company. Therefore, it is assumed that the backorder costs are relatively high to prevent backorders as much as possible.

The parameter needed to calculate the backorder costs is the following:
- \( C_{B,c,s} \): Backorder cost per full packaging unit missing at customer \( c \) of local warehouse \( s \), where \( s = \text{country } A, B, C \text{ and } D \).

To calculate the backorder costs of the CLCS, the cost parameter \( C_{B,c,s} \) is multiplied by the backorder quantities of the different customers.

7.3.6 Disposal Costs
No data was available about the disposal costs. Therefore, we also assumed some things about these cost parameters:
- The disposal costs are equal for all local warehouses, which implies that these costs are not location-specific.
• Besides that, the disposal costs are equal for all local warehouses, and it is assumed that disposing an empty packaging unit in the factory warehouse has the same costs as disposal in the local warehouses. Thus: $C_{D,NL} = C_{D,S}$.

The cost parameters needed to calculate the disposal costs are the following:

- $C_{D,E}$: Cost for disposing one packaging unit in the factory warehouse in Country E.
- $C_{D,S}$: Cost for disposing one packaging unit by warehouse $s$, where $s = \text{country A, B, C and D}$.

To calculate the total disposal costs, the disposal cost parameter, $C_{D,NL}$ in the case of disposing in the factory warehouse and $C_{D,S}$ in the case of disposing in one of the local warehouses, is multiplied with the number of empty packaging units that are disposed and the resulting two terms (i.e. total disposal costs in the local warehouses and total disposal costs in the factory warehouse) are added to get the overall total disposal costs.

7.4 Input Parameters of the Model

In this section, the data input needed for the model is discussed. First, it is explained how the demand for empty packaging units is determined. Subsequently, the lead times from one stage to the other stage of the closed-loop supply chain are presented.

7.4.1 Demand Input

To solve the mathematical model defined in Section 7.2, a demand input is needed. Thus, data need to be gathered about the demand for empty packaging materials. Within the information system of the company, the demand for the packaging materials is not visible. Therefore, another way of finding the demand for empty packaging has been developed.

Instead of the demand for parts or packaging materials, it is decided to use the past usage of the parts and translate this to the usage of the packaging materials. The usage of the parts is known and easier to retrieve than the (future) demand of the parts, however, this usage data was not available in SAP for the author, therefore, the data is retrieved from SAP by an employee of the CSCM department. The data has been made available for the author in an Excel file. With this Excel file, the monthly usage of the parts is known. In addition, in SAP we can generate a list where each part to be packed with a specific packaging material is displayed. It could be that a packaging material is only used to pack one part, but the packaging material could also be used for different parts. With this list and the known usage per part, it is possible to translate the monthly usage of the parts to the monthly usage of the packaging materials.

The following steps are followed to find the usage of empty packaging materials:

1. **Find all packaging materials in SAP with MRP-controller BJ1.**

MRP is the abbreviation for Material Requirements Planning. BJ1 is the code that specifies the MRP-controller of a material group. The MRP-controller of a material group is an employee of the CSCM department of the company and this employee has the responsibility over these materials. Packaging materials with MRP-controller BJ1 are the packaging materials for which it is unclear what to do with it when they arrived empty in the local warehouses. In total, 4839 unique packaging materials with MRP-controller BJ1 have been found.

2. **The second step is to find all packaging FSDs.**

If the packaging material does not have an FSD version, the packaging cannot be returned. Thus, to make the packaging ready for return, an FSD version of the packaging needs to be requested. If this has been done, the abbreviation ‘FSD’ is added to the 12NC of the packaging, e.g.
In total, 517 packaging FSDs were found. In the list with packaging FSDs, 73 packaging materials with packaging type “Clean Assy” are found. Removing these from the list results in a list which contains 444 packaging materials.

5. **The next step is to filter out the parts which are not service parts.**

First, part 12NCs that start with 4022 are deleted and only part 12NCs that start with SERV are selected. By setting this filter, only service parts are included in the list. Then the service parts which have no MRP-controller, which have MRP-controller XXX or CSL are deleted. The remaining list contains 2414 service parts divided over 357 packaging materials. With this list, the usage for the parts is found, and this usage is translated to the usage of the packaging materials.

6. **Go to the usage file for service parts. Type in the part 12NC number and look for the monthly usage. Copy and paste this into the packaging and part list.**

Doing this sixth and last step for each of the 2414 service parts, the past usage of the packaging materials is known. Figure 7.4 shows an example of a packaging material (displayed in column “Pack 12NC”) that is used to pack eight unique service parts (presented in column “Part 12NC”). The columns right from the part 12NC, i.e. period 1 to 13, represent the monthly usage of the service parts.

To determine the total usage for the packaging material, the usage per month of all service parts is added and this represents the usage of the packaging material. This is presented in Figure 7.5. Note that Figure 7.4 and Figure 7.5 are examples and that the Excel file with the monthly packaging usage contains the usage of in total 45 periods.

The monthly usage of the packaging material presented in Figure 7.5 represents the worldwide usage of that packaging per month. This implies that this usage is the total monthly usage of a specific packaging material. The demand input for the model needs the usage per customer of the
local warehouse. Therefore, it is assumed that the customers of the different local warehouses each have a different fraction of the total usage. This fraction is based on the size of the local warehouses. Based on this, we can argue that the part and packaging usage per customer is in relation with the size of the local warehouse. Thus, if a local warehouse is large we assume that this is due to a large customer with a high demand for parts. The fractions of the total usage are assumed to be the percentages as presented below in Table 7.3.

<table>
<thead>
<tr>
<th>Local warehouse in ...</th>
<th>Fraction of total demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country A</td>
<td>30%</td>
</tr>
<tr>
<td>Country B</td>
<td>30%</td>
</tr>
<tr>
<td>Country C</td>
<td>10%</td>
</tr>
<tr>
<td>Country D</td>
<td>30%</td>
</tr>
</tbody>
</table>

7.4.2 Lead Times

Within the mathematical model, the lead times from the one stage to the other stage in the supply chain are included. Thus, also for these lead time parameters an input is needed. Table 7.4 shows the overview of the real lead times and the lead times used in the mathematical model. As can be seen in the table, those lead times are different. This is due to that the real lead times are in weeks; however, the demand input of the model is in months, and therefore it is decided to make one period in the model a month. Therefore, the real lead times are transformed to months. This leads to the lead times presented in Table 7.4.

<table>
<thead>
<tr>
<th>From ... to ...</th>
<th>Real Lead Time (in weeks)</th>
<th>Simulation Lead Time (in months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From customer to local warehouse</td>
<td>$1 \leq L_{C\rightarrow S} \leq 4$</td>
<td>$L_{C\rightarrow S} = 1$</td>
</tr>
<tr>
<td>From packaging supplier to factory warehouse</td>
<td>$L_{N\rightarrow E} = 6$</td>
<td>$L_{N\rightarrow E} = 2$</td>
</tr>
<tr>
<td>From factory warehouse to local warehouse</td>
<td>$L_{E\rightarrow S} = 1$</td>
<td>$L_{E\rightarrow S} = 1$</td>
</tr>
<tr>
<td>From local warehouse to customer</td>
<td>$L_{S\rightarrow C} &lt; 1$</td>
<td>$L_{S\rightarrow C} = 0$</td>
</tr>
<tr>
<td>From local warehouse to factory warehouse</td>
<td>$L_{S\rightarrow E} = 1$</td>
<td>$L_{S\rightarrow E} = 1$</td>
</tr>
</tbody>
</table>

The lead times presented in the last column of Table 7.4 are processed in the mathematical model. The planning horizon of the model is from 1 to $T$. If the lead time of a decision variable is larger than 1, we get a negative value for $t$. For example: Constraint (2) includes the decision variable $QB_{N\rightarrow E}(t)$ measured at the beginning of period $t - 1 - L_{N\rightarrow E}$. If $t = 1$ and $L_{N\rightarrow E} = 2$, the decision variable is then: $QB_{N\rightarrow E}(-2)$. This is a value outside our planning horizon. Therefore, some assumptions need to be made about these cases. Table 7.5, Table 7.6 and Table 7.7 represent the assumed values of the decision variables if the value for $t$ is outside the planning horizon.

Table 7.5 shows the values which are assumed for decision variable $QB_{N\rightarrow E}(t - 1 - L_{N\rightarrow E})$. This decision variable appears in constraint (2), (3) and (4). As can be seen in the table, from period $t \geq 4$, it is not necessary anymore to assume values for the decision variable; from this period the model determines the values, and these can be greater or equal to zero.

<table>
<thead>
<tr>
<th>Period</th>
<th>$QB_{N\rightarrow E}(t - 1 - L_{N\rightarrow E})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td>$QB_{N\rightarrow E}(-2) = 0$</td>
</tr>
</tbody>
</table>
Table 7.6 presents the values for the decision variables $QB_{S \rightarrow E}(t - 1 - L_{S \rightarrow E})$, $QB_{c,s}(t - 1 - L_{c \rightarrow s})$ and $QP_{E \rightarrow s}(t - 1 - L_{E \rightarrow s})$ for periods $t = 1$ and $t = 2$. From period $t \geq 3$, it is not needed anymore to assume values; from this period the model determines the values of these decision variables. The decision variables $QB_{S \rightarrow E}(t - 1 - L_{S \rightarrow E})$, $QB_{c,s}(t - 1 - L_{c \rightarrow s})$ and $QP_{E \rightarrow s}(t - 1 - L_{E \rightarrow s})$ appear in constraint (2), (3), (4), constraint (6), (7), (8), and constraint (10) and (11) respectively.

Table 7.6 Assumed values for decision variables $QB_{S \rightarrow E}, QB_{c,s}, QP_{E \rightarrow s}$

<table>
<thead>
<tr>
<th>Period</th>
<th>$QB_{S \rightarrow E}(t - 1 - L_{S \rightarrow E})$</th>
<th>$QB_{c,s}(t - 1 - L_{c \rightarrow s})$</th>
<th>$QP_{E \rightarrow s}(t - 1 - L_{E \rightarrow s})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td>$QB_{S \rightarrow E}(-1) = 0$</td>
<td>$QB_{c,s}(-1) = 0$</td>
<td>$QP_{E \rightarrow s}(-1) = 0$</td>
</tr>
<tr>
<td>$t = 2$</td>
<td>$QB_{S \rightarrow E}(0) = 0$</td>
<td>$QB_{c,s}(0) = 0$</td>
<td>$QP_{E \rightarrow s}(0) = 0$</td>
</tr>
<tr>
<td>$t \geq 3$</td>
<td>$QB_{S \rightarrow E}(t - 1 - 1) \geq 0$</td>
<td>$QB_{c,s}(t - 1 - 1) \geq 0$</td>
<td>$QP_{E \rightarrow s}(t - 1 - 1) \geq 0$</td>
</tr>
</tbody>
</table>

Table 7.7 displays the assumed value for decision variable $QP_{S \rightarrow c}(t - 1 - L_{S \rightarrow c})$ which appears in constraint (12) and (13). For this decision, only the value in the case of period $t = 1$ is needed to assume. From period $t = 2$, the model can determine this decision variable.

Table 7.7 Assumed value for decision variable $QP_{S \rightarrow c}$

<table>
<thead>
<tr>
<th>Period</th>
<th>$QP_{S \rightarrow c}(t - 1 - L_{S \rightarrow c})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td>$QP_{S \rightarrow c}(0) = 0$</td>
</tr>
<tr>
<td>$t \geq 2$</td>
<td>$QP_{S \rightarrow c}(t - 1) \geq 0$</td>
</tr>
</tbody>
</table>

7.4.3 Input On-Hand Inventory

To let the MILP model work properly, a couple of assumptions need to be made about the on-hand inventory in the first period. These assumptions are presented below.

For the on-hand empty packaging inventory in the factory warehouse and the local warehouses in the first period need to be equal or greater than the safety stock in those warehouses. Otherwise, no feasible solution can be found. Thus, this implies the following:

- $IB_{E}(1) = SB_{E}(1)$
- $IB_{S}(1) = SB_{S}(1)$ for $s \in \{A, B, C, D\}$

The on-hand inventory of full packaging materials in the local warehouses and the customers in the first period is assumed to be zero:

- $IP_{s}(1) = 0$ for $s \in \{A, B, C, D\}$
- $IP_{c,s}(1) = 0$ for $s \in \{A, B, C, D\}$

For the on-hand full packaging inventory, no safety stock has been included in this model. Therefore, it is assumed zero on-hand inventory for full packaging in the first period. In this case, the customer demand triggers that the factory warehouse ships full packaging units. If already a value greater than zero was assumed for these stocks, this influences the decision variables of the model, which in turn influences the total costs.

In the local warehouses, the company want to have minimal empty packaging inventory. Due to this, the initial safety stock of one specific empty packaging material is set to one in each local warehouse. In addition, it is undesired to have too many empty packaging materials on stock. Therefore, the maximum empty packaging inventory that the local warehouses can have is set to ten empty packaging units.

- $SB_{s}(t) = 1$ and $IB_{\text{max},s} = 10$
The same applies for the initial safety stock of empty packaging materials in the factory warehouse, which is also set to one empty packaging unit. The maximum number of empty packaging units that the factory warehouse can have in inventory is also set to ten units.

- \( SB_E(t) = 1 \) and \( IB_{max,E} = 10 \)

Furthermore, it is assumed that the backorder quantity at the customers of the local warehouses in the first period is zero:

- \( BP_{c,s}(1) = 0 \) \( \forall s \in \{A, B, C, D\} \)

7.5 Discussion and Conclusion

In the present chapter, we investigated the second research question and developed the decision support model that determines what to do with the empty packaging materials in the local warehouses. The second research question was stated as follows:

Research Question 2:
What is a suitable decision support model for managing empty packaging?

To answer this question, we developed a mathematical model for the closed-loop supply chain of the company with the focus on the reverse flow of empty packaging materials. The design of the mathematical model is based on the specification of inputs, output, constraints and the objective of the company. In our view, the developed mathematical model is a good solution for the empty packaging problem, since it satisfies the requirements of the company and the characteristics of the supply chain.

The company uses a pull inventory management strategy for the empty packaging in the local warehouses: each month the company checks the on-hand empty packaging inventory in the local warehouses and based on the lowest cost, the empty packaging is returned from the local warehouses or ordered new from the packaging supplier and disposed in the local warehouses. Thus, the mathematical model which was to be developed needed to include this inventory strategy.

The mathematical model which was found to be most suitable for this pull inventory management strategy used within the company for the empty packaging is a Mixed Integer Linear Programming model. The objective of the model is to minimize the costs regarding empty packaging. The costs included in the objective function are: the inventory holding costs for empty packaging in the factory warehouse and the local warehouses, the return costs, the cost of buying new empty packaging materials, the disposal costs for both the factory warehouse and the local warehouses, and the backorder costs.

Based on the lowest costs while satisfying the constraints, the MILP model determines what the best option is of getting empty packaging at the factory warehouse (i.e. returning the empty packaging materials from the local warehouses or buying the empty packaging materials new).

The next chapter will discuss the implementation of the mathematical model into a software tool and the model is verified and validated. Besides this, the results of the model will be discussed, and a sensitivity analysis will show us the impact of different values for the input parameters defined previously in Section 7.4.
8 Implementation and Evaluation of the Model

The mathematical model for empty packaging defined in Chapter 7 is too complicated to solve manually. For this reason, the model is programmed into a software tool to generate the results of the model. After implementing the model into the program, we must evaluate the model. Section 8.1 presents the software program that is chosen to solve the MILP model. In the next section, Section 8.2, describes the implementation of the model into the software program. Lastly, Section 8.3 discusses the evaluation of the model, which is done by model verification and validation. Note that all numbers used for the verification and validation of the model are fictitious and serve for illustrative purposes only.

8.1 Software Tool

In this section, the software tool that has been used for implementing the mathematical is presented and it is explained why this program has been chosen.

The previously developed mathematical model is a Mixed Integer Linear Programming model. This model is an optimization model which can be implemented into several optimization software programs, i.e. Excel Solver, MATLAB, CPLEX, Gurobi, etc.

For the company, the preferred and optimal situation is to use a software tool without having to buy extra licenses. In the case the company need to buy extra licenses, not every employee can use the program which makes is less flexible. Furthermore, the program must be easy to use in the daily operations of the employees. In choosing the best fitting software program, it is also necessary to consider the required steps needed to program the mathematical model and whether the software program can execute the required steps. Furthermore, it is important that the author of this project is familiar with the program and the programming language.

After discussing the possible software programs, Excel Solver/VBA and MATLAB seemed to be the two best options. For the company, a tool in Excel would be the optimal case. However, implementing the mathematical in Excel was too complicated. In addition to this, Excel Solver has a limit of 200 decision variables and 100 constraints for linear problems. The MILP model we have developed has 22 decision variables per period. Thus, with the Excel Solver we could only simulate 9 periods which are not sufficient periods if the company wants to have a good representation of the real world. MATLAB, however, is a software program that can handle a lot more decision variables and constraints, which makes it a lot easier to implement the program and the results will give a better representation of the real world. One disadvantage of using MATLAB is that the employees within the reverse operations team are not so familiar with MATLAB. However, with a short training in which the script is explained will be enough for the employees to use to program. Therefore, it is decided to develop a tool in MATLAB.

8.2 Model Implementation in MATLAB

The MILP model is implemented in MATLAB with the available data in November 2018. As already explained in Section 7.4.1, Demand Input, we have data for in total 45 periods, i.e. 45 months. Note that this is data of the past. Despite that we have data for more periods, it is decided, in consultation with the company, to implement the model into MATLAB for 28 periods, i.e. 28 months. This has the following reason. The model was programmed for all 45 periods for which demand data was available. Thus, this model had 990 decision variables (22 in each period) and 405 constraints. MATLAB was not able to solve this model and to get a feasible integer solution. Therefore, we had to check for how many periods MATLAB was able to determine an integer solution, which was for 28 periods.

A MILP model can be solved in MATLAB based on two approaches: The Problem-Based Optimization Setup and the Solver-Based Optimization Problem Setup. The first approach represents the objective and constraints symbolically. This makes it easier to create and debug.
The latter approach represents the objective and constraints as functions or matrices. With this approach it is harder to create and debug a MILP. For this reason, it is chosen to use the problem-based approach to create our model. However, the MILP model is solved using the solver-based approach.

The MATLAB script starts with the definition of all the cost and input parameters. It is easy to adapt these parameters to see the impact on the total costs of the closed-loop supply chain. Furthermore, the data about the packaging materials (i.e. demand per period, price, length, width, height, volume and weight) is available in an Excel file which is read by MATLAB. After the cost and input parameters, the decision variables are defined, and the objective function is determined. Hereafter, all constraints are programmed.

For the company, a very detailed work instructing (i.e. manual) is written and a training is provided to learn the employees how to work with the tool. Note that also a simplified version of the model is implemented in Excel. The MATLAB tool is for more periods and with a demand forecast the company can proactively decide what to do with the empty packaging materials. The Excel tool is only for one period and is especially helpful in determining the X-plant status of the packaging materials. A manual is also written for the Excel tool.

8.3 Model Evaluation: Verification and Validation

In this section, the model is evaluated. Before we can let the model run and get results, we need to check if the model in MATLAB is correct. This will be done by verification and validation of the model. According to The Global Harmonization Task Force (2004), verification and validation are independent procedures that are used together for checking that a product, service, or system (in this case, the MILP model in MATLAB) meets the requirements and specifications and that it fulfills its intended purpose. In Section 8.3.1, the model is verified and in Section 8.3.2 the model is validated. Note that all tests done to verify and validate the model are done with the model for 24 periods. The reason for this is that if the model with 24 periods is valid, we assume that the model is also valid if more periods are added. In addition, 24 periods represent a period of two years. For the company, this amount was sufficient to do the analyses for.

8.3.1 Verification of the Model

According to Sargent (2009), model verification is defined as “ensuring that the computer program of the computerized model and its implementation are correct”. In other words, verification is about answering the question if we did do the things right. Thus, we need to find out if the model is correctly translated into the programming language of MATLAB as we intended.

The MILP model is verified by the executing the following three points:
- Tracing the operation in the mathematical model,
- Checking consistency of the outputs of the simulation model, and
- Various extreme value checks.

This section presents these steps of the verification of the simulation model.

Tracing the operation in the MILP model

When programming the MILP model in MATLAB, we first started with a simple model, and then added the details until the final mathematical model of the whole closed-loop supply chain was reached. This implies that we have started with programming the mathematical model for one local warehouse, one customer and two periods. This was model is debugged and occurring errors are solved. When this model was working, first additional local warehouses and customers are added, and after that, more periods are added to the model. Each time modifications are applied to the model, it is debugged with MATLAB’s run controller. If errors occurred, it was found out where the error exactly comes from and then corrected immediately. After each correction,
the model is debugged again. With this procedure of programming the mathematical model in MATLAB, it is certain that the flow of full and empty packaging through the supply chain is modeled as intended and that all formulas are programmed correctly. In the end, it is in this way ensured that the mathematical model developed in Chapter 7 is correctly translated into MATLAB.

The consistency check of the outputs
To check whether the outputs of the MILP model are consistent, we did the following. The demand rate for each local warehouse is set to a small value ($DP_{cs}(t) = 2$) and the number of periods is kept small ($T = 10$). In this way it is easier to keep track of the different values of the decision variables and parameters per period. With this input parameters, we let the model run and with the resulting outputs, it was manually step-by-step checked whether the values for the different decision variables in each period make sense.

To give an example: if two full packaging units are shipped from the local warehouse to the customer, the customer must empty two full packaging units in the same period. This is due to the lead time from the local warehouse to the customer. This lead time is rounded to zero months, which implies that if the full packaging arrives at the local warehouse, it is immediately shipped to the customer. Thus, this full packaging can be emptied in the same period by the customer.

We started with looking at how many new packaging units are ordered in the first period. These packaging units will arrive in period 3 and shipped as full packaging units to the local warehouses in the same period. The full packaging units arrive one period later in the local warehouses and are shipped immediately to the customer where the full packaging units are emptied. In the next period, period 5, a fraction of the packaging units emptied by the customer arrive at the local warehouse and these are disposed here or returned to the factory warehouse. If the empty packaging units are returned, these will arrive one period later in the factory warehouse.

This procedure is executed for a couple of different demand scenarios:
- All customers have the same demand in all periods.
- The customers have different demand, but the demand is equal in each period.
- The customers have different demand, and the demand is also different in each period.

In all scenarios, the outputs were consistent and as expected.

Extreme value checks
This check is performed to see whether the MILP model provide plausible outputs to extreme values of the input parameters. The model with 24 periods is used for these tests. The results of five extreme cases are checked and compared with the results of the original scenario. In all checks, the MILP model has provided the expected results. Therefore, we can conclude that the programmed MILP model seems to be working and is providing the correct results.

Note that all numbers used for the extreme value checks are fictitious and serve for illustrative purposes only, i.e. the values of the model parameters are assumed values.

1. Zero customer demand
In this test, the demand rates of the customers of the local warehouses are set to zero ($DP_{cs}(t) = 0$). Thus, the demand for full packaging units is zero in all simulated periods. Since there is no demand, it is expected that no empty and full packaging materials are in the system. In addition, we expect that the optimal objective value is zero. Note that the total costs will be greater than zero because the total cost function is programmed as a function with the objective function value and the constant costs.

Running the MILP model with zero demand rates for all customers results, as expected, in the decision variables being all zero. Furthermore, the optimal objective function is zero and the total costs are €1015.20, which includes the inventory holding costs for empty packaging in the factory.
warehouse and the local warehouses over 24 months. This is due to the safety stock in each period for both type of warehouses which is one, thus, each period the warehouses have one empty packaging unit on stock.

2. Very high customer demand
For this test, the demand rates of all customers of the local warehouses are set to 100 \( (DP_c(t) = 100) \). Thus, in each period (i.e. per month), all four customers want to have 100 full packaging units. Because the customer demand is very high, the factory warehouse orders a lot of empty packaging materials in the first period to prevent backorders. In period \( t = 1 \), the factory warehouse orders 2000 packaging units, which results in a cost of €4,000,000 for buying these new empty packaging materials from the packaging supplier, in the case of the assumed packaging price of €2000. The total costs are €10,856,000, thus, approximately 36.8% of the total costs are the costs of buying new empty packaging materials.

In most periods, the on-hand inventory of empty packaging materials in the local warehouses is only one empty packaging unit, which equals the safety stock in these warehouses. This implies that the local warehouses return the empty packaging materials as soon as possible such that the factory warehouse does not have to make more costs by ordering new empty packaging materials. The return costs over all periods are €3,680,000, which is also a large share (33.9%) of the total costs.

In period \( t = 20, t = 21 \) and \( t = 22 \), the local warehouses in Country C reached the maximum inventory level after returning empty packaging materials, thus, in these periods this local warehouse also disposed some empty packaging materials. This also applies for the local warehouse in Country B in period \( t = 18, t = 20 \) and for local warehouse A in period \( t = 19 \). The factory warehouse and the local warehouse of Country D never dispose empty packaging materials. This implies that, to minimize the total costs, the factory warehouse must use every empty packaging material that is delivered.

The results of this test showed values for the decision variables and the total costs that are reasonable and logic.

3. The fraction of empty packaging units returned from the customer to the local warehouse after emptying the full packaging material \( (\alpha_{c,s}) \) is zero.
If the value for \( \alpha \) is zero, this means that the customer does not send any of the full packaging which they have emptied back to the local warehouse. This implies that the local warehouse does not receive any empty packaging units and due to this, the local warehouse cannot return or dispose packaging. Therefore, it is expected that the factory warehouse orders a lot of new empty packaging units.

The values for the decision variables \( QB_{d,s}(t) \) and \( QB_{s\rightarrow F}(t) \) are, as expected, all zero for all periods and all local warehouses. This implies that no empty packaging units are returned from the customer to the local warehouses. As a result, the local warehouses only have the assumed safety stock in their inventories. Due to that no additional empty packaging arrive in the local warehouses, they cannot dispose or return anything. The results show that more new empty packaging units are ordered from the supplier than when a value greater than zero is used for \( \alpha_{c,s} \).

4. Very high inventory holding costs
If the holding costs for empty packaging units in the local warehouses and factory warehouse are very high, these warehouses will try to keep the on-hand inventory of empty packaging units as low as possible. Furthermore, we expect that the number of empty packaging materials disposed in the local warehouses and the factory warehouse will increase. In addition, it is expected that the number of empty packaging materials returned to the factory warehouse will increase.

In the case where the inventory holding costs are equal to the assumed values presented in Section 7.3.1, the total costs are €364,880. In the case where we assume a very high inventory
holding costs \( H_s = H_E = €500 \text{ per m}^2/\text{month} \), the total costs are €429,680, which is an increase in the costs of 17.7%.

Furthermore, it was found that only the local warehouse in Country B disposes four empty packaging materials due to the high inventory holding costs, whereas in the case with the normal inventory holding costs this warehouse does not dispose any empty packaging material.

In addition, the factory warehouse orders one new empty packaging materials less than in the normal case. The number of returned empty packaging materials have been decreased by 1.3%, which is not what was expected. However, this is logical looking at the decrease in empty packaging materials ordered at the packaging supplier. This implies that the factory warehouse ships less full packaging materials to the customers and as a result, the local warehouses receive less packaging materials from the customer which can be returned to the factory warehouse.

5. **Very high disposal costs**

In this case, the costs for disposal of one empty packaging unit within the local warehouses and the factory warehouse is very high \( C_{D,E} = C_{D,S} = 1000 \). If the disposal costs are very high, it is expected that no empty packaging materials are disposed.

In the case where the disposal costs are low, i.e. \( C_{D,E} = C_{D,S} = 10 \), the local warehouses in country A, B, C and D dispose in total 16 empty packaging materials. As expected, the local warehouses and the factory warehouse do not dispose any empty packaging material. The costs are not so much higher in the case of very high disposal costs, i.e. cost increase of €2200.00. This is because the model determines all possibilities and identifies high costs for disposing of empty packaging materials. The objective of the model is to minimize the costs; thus, the model is preventing the high disposal costs by not disposing empty packaging materials.

8.3.2 Validation of the Model

Model validation can be defined as the “substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model” (Sargent, 2009). In other words, validation is about answering the question if we did do the right thing. In the article of Irobi, Andersson & Wall (2004), it is stated that a ‘correct’ model could at best be judged as one which is ‘closest’ in representation to the real system. Thus, taking into account the objectives of the study, the validation must check if the mathematical model is a correct representation of the closed-loop supply chain under consideration.

The MILP model is validated by using the following three methods:

- Degenerate tests
- Face validity
- Internal validity

**Degenerate tests**

According to Irobi, Andersson, & Wall (2004), the degeneracy of the model’s behaviour is tested by appropriately selecting the values of the input and internal parameters of the model. An example that is presented in this paper is to test to see if the average number in the queue of a single server continues to increase when the arriving rate is larger than the service rate. Several degenerate tests are executed to see whether the MILP model in MATLAB give the expected results if the input parameters change. Some examples of these tests include increasing and decreasing of the demand for empty packaging materials, packaging price, and lead times. All tests gave the expected results.

**Face validity**

This validation technique is often used to determine whether the logic used in the model is correct and if the input-output relationship is reasonable (Sargent, 2009; Irobi et al., 2004). The correctness of the logic behind the model is checked by having several meetings with employees of the company. By asking people who are familiar with the supply chain, we have ensured that
the logic used in the MILP model is correct. Whether the input-output relationship is reasonable is checked by comparing the output of the model with the ones of the real system, which appeared to be the case.

**Internal validity**

As discussed in the paper of Sargent (2009), a large amount of (internal) stochastic variability in the outputs of the model could be a sign of uncorrect and questionable results. Therefore, we need to test how variable the outputs of the model are by running the model several times. We did multiple replications with the same input parameters and compared the results. The internal validity of the model is checked by running the model 3 times for 24 periods. In all runs, the same input parameters are used (see Appendix C – Values of the Input Parameters of the Internal Validity Test). The results of the simulation runs are presented below in Table 8.1, Figure 8.1, and Figure 8.2.

<table>
<thead>
<tr>
<th>Run</th>
<th>Total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>€364,880</td>
</tr>
<tr>
<td>2</td>
<td>€364,880</td>
</tr>
<tr>
<td>3</td>
<td>€364,880</td>
</tr>
</tbody>
</table>

Table 8.1 shows that the total costs determined by the model during the three simulation runs are exactly the same. To show that the values of all decision variables are exactly the same in the three runs, we give two examples of the decision variables in the following two figures (see Figure 8.1 and Figure 8.2).

Figure 8.1 shows that the number of empty packaging materials which are returned from the local warehouse in Country D to the factory warehouse are the same for all three runs.
Figure 8.2 shows that the factory warehouse ships the same amount of full packaging materials to the local warehouse during each run. Note that the values for the other decision variables are also the same for each run.

The results presented above show that the output of the model has no variability. Each run gave exactly the same values for the total costs and the decision variables. Therefore, we can conclude that the model has internal validity.

8.4 Conclusion and Discussion

In this chapter, the implementation of the mathematical model into MATLAB is discussed and we evaluated this model. For the evaluation of the model we used two techniques: model verification and model validation.

Model verification is needed to ensure that the computer program of the computerized model and its implementation are correct. To check if this was the case, we used three different techniques:

1. Tracing the operation in the MILP model in MATLAB
2. Consistency check of the outputs of the MATLAB model
3. Extreme value checks

With these techniques, the model is verified. The results of the extreme values checks were all as expected and logically explainable. Hence, based on first two verification techniques and the extreme value checks, it can be concluded that the MILP model is implemented correctly in MATLAB.

Validation of the model is essential because we want to ensure that we did do the right things. Thus, the validation must check if the MILP model is a correct representation of the closed-loop supply chain of the company. To validate the model, three different validation techniques are used:

1. Degenerate tests
2. Face validity
3. Internal validity

Several degenerate tests were performed to see what happens to the results of the MILP model if the input parameters are changed. All tests gave the expected results. The face validity of the model was tested by checking whether the logic behind the model is correct. For this, we discussed the model with some employees of the company and based on this, we could conclude that the model has face validity. The last test includes the internal validity of the model. The results of this test showed that the outputs of the model are relatively consistent. Based on the three validation tests, we can conclude that the MILP model implemented in MATLAB is valid and that we did do the right things.
9 Case study

This chapter describes the results of the case study within the company. The developed Mixed Integer Linear Programming model is applied to data of the company. The company is most interested whether the empty packaging materials should be returned from the local warehouses or new empty packaging materials should be ordered and the empty packaging materials in the local warehouses should be disposed. During the case study, this will be determined by the model. This chapter is organized as follows. Section 9.1 describes the experimental set-up of this case study. Section 9.2 discusses the results after running the model several times for different scenarios. Subsequently, Section 9.3 presents the sensitivity analysis executed to test the impact of the different scenarios and different input parameters. Lastly, this chapter ends with a conclusion in Section 9.4. Note that all numbers used in this chapter are fictitious and serve for illustrative purposes only.

9.1 Approach

In this section, the different scenarios are explained. First, we model the current situation (As-Is situation) of the company, i.e. no empty packaging materials are returned, and all empty packaging materials stay in the local warehouses, as explained in Chapter 5. The company has no data available about the procurement costs of new empty packaging materials and inventory holding costs of empty packaging materials. To be able to check if the developed mathematical model gives better results than the current situation, we should make a scenario in the MILP model that represents the current situation. The current situation is modeled in the MILP by removing the decision variables for returning the empty packaging materials, i.e. \( Q_{B_{s-e}}(t) \) is removed from the model. By removing these decision variables, there is no longer a return option. Thus, the empty packaging materials need to be bought new and empty packaging materials stay within the local warehouses and are possibly disposed.

If the total costs for the current situation are known, we can compare these results with the results of the model developed in Chapter 7 which considers returning of empty packaging materials (To-Be situation). We distinguish between the following two scenarios:

- Scenario A – As-Is situation without returning empty packaging materials
- Scenario B – To-Be situation with returning empty packaging materials

In these scenarios, the assumed values of the input parameters presented in Appendix D – Values of the Input Parameters for the Scenario Analysis are used. All values are kept the same during running the model for both scenarios. Only the decision variables are different, namely: Scenario A does not include the decision variables for returning empty packaging materials. Thus, this scenario has 18 decision variables, whereas Scenario B has 22 decision variables because all decision variables defined in Section 7.2 are included.

The next section, Section 9.2, presents the results of both scenarios.

9.2 Results

This section presents the results of the two scenarios described in the previous section. First, we show the results of Scenario A, which represents the current situation. Next, the results of Scenario B are presented, which includes the To-Be situation where empty packaging materials can be returned. This scenario analysis is divided into two parts: an analysis in which we assume that the packaging price is €500 (Section 9.2.1) and an analysis in which the assumed packaging price is €1000 (Section 9.2.2). Note that for both cases the input parameters presented in Appendix D – Values of the Input Parameters for the Scenario Analysis are used. In addition, the model with 28 periods is used for the scenario analysis. As already mentioned before, 24 periods (i.e. 24 months) are sufficient as analysis period for the company. However, to give the company an even better view of the costs per period, it is decided to use the model with 28 periods. We end this section with a short conclusion of the main findings in Section 9.2.3.
9.2.1 As-Is and To-Be Scenario Analysis in case the Packaging Price is €500

As presented in Figure 9.1, the total costs over 28 periods for Scenario A, the As-Is scenario, are €265,030 and the total costs over 28 periods for the Scenario B, the To-Be scenario, are €244,110. Thus, by using the developed decision support model with return options the company can save in total €20,920 over 28 periods. This means that on average €747.14 per month can be saved if the price of an empty packaging is €500.

![Figure 9.1 Overview of the total costs for the As-Is and To-Be scenarios (C_N=500)](image)

The results for the decision variables, \( Q_{B,I}(t) \), \( Q_{B,S}(t) \), and \( Q_{B,N-E}(t) \), are presented below.

The factory warehouse orders less new empty packaging materials, which is presented in Figure 9.2. In total, 317 new packaging materials are shipped from the packaging supplier to the factory warehouse in the As-Is Scenario and only 253 new packaging materials are ordered in the To-Be scenario, which is a decrease of 20.2%.

![Figure 9.2 Number of empty packaging materials shipped from the packaging supplier to the FWH (C_N=500)](image)

It was found that in the As-Is scenario the local warehouses in country A, B and C dispose in total the same amount of empty packaging materials as in the To-Be scenario. The number of empty packaging materials disposed in local warehouse C differ a bit per period (see Figure 9.5). The local warehouse of country A and B dispose exactly the same amount of empty packaging materials in each period, which can be seen in Figure 9.3 and Figure 9.4.

Note that the factory warehouse has not disposed any empty packaging material in both scenarios.

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Figure 9.4 Number of empty packaging materials disposed in the local warehouse of Country B (C_N=500)

Figure 9.5 Number of empty packaging materials disposed in the local warehouse of Country C (C_N=500)

Figure 9.6 shows the amount of empty packaging materials which are disposed in the local warehouse of Country D. In the As-Is scenario, this local warehouse disposed in total 72 empty packaging materials. In comparison with the To-Be scenario this is a lot, because in this scenario
the local warehouse disposed only 7 empty packaging materials. This implies that an increase of 90.3% in the amount of empty packaging materials have occurred.

The difference in the results is explainable by the fact that in the To-Be scenario the local warehouse of Country D also returns empty packaging materials to the factory warehouse. This local warehouse returns in total 66 empty packaging materials. The other local warehouses do not return empty packaging materials, which is the reason that the number of empty packaging materials disposed in these local warehouses are the same in the As-Is and To-Be scenario.

9.2.2 As-Is and To-Be Scenario Analysis in case the Packaging Price is €1000

Figure 9.7 presents that the total costs for Scenario A, the As-Is scenario, are €414,320 over 28 periods. The total costs over 28 periods for Scenario B, the To-Be scenario, are €331,310. This means that the company can save €83,010 over 28 periods, which indicates a cost saving of €2964.64 on average per month in the case the packaging price is €1000.

The results for the main decision variables, $QB_{d,E}(t)$, $QB_{d,s}(t)$, and $QB_{N \rightarrow E}(t)$, are presented below.

In both scenarios, it was found that the values for the decision variable $QB_{d,E}(t)$ were zero in both scenarios and for all periods. This implies that the factory warehouse has not disposed any empty packaging materials in both cases.
In Figure 9.8, it is shown that the factory warehouse orders less new empty packaging materials in the To-Be scenario than in the As-Is scenario. The packaging supplier ships in total 282 new empty packaging materials to the factory warehouse in the As-Is scenario, whereas the packaging supplier only ships 117 new empty packaging materials to the factory warehouse in the To-Be scenario, which is a decrease of 58.5%.

![Empty packaging materials shipped from the supplier to the FWH](image)

*Figure 9.8 Number of empty packaging materials shipped from the packaging supplier to the factory warehouse (C_N=1000)*

In the case where the packaging price is €1000, all local warehouses dispose less empty packaging materials. The local warehouse of Country C disposes over all periods 14 empty packaging materials less in the To-Be scenario than in the As-Is scenario, 4 vs. 18 respectively, which is a decrease of 77.8%. See Figure 9.9 for a visual representation of the number of empty packaging materials disposed in the local warehouse of Country C per period.

![Empty packaging materials disposed in the LWH of Country C](image)

*Figure 9.9 Number of empty packaging materials disposed in the local warehouse of Country C (C_N=1000)*

Figure 9.10 shows that the local warehouse in Country B has disposed 64 empty packaging materials in the current situation and 16 empty packaging materials in the new situation, which is a decrease of 75.0%.
Furthermore, in local warehouse A, 85.9% less empty packaging materials have been disposed, which is the biggest decrease of all local warehouses: 64 empty packaging materials disposed in the As-Is scenario versus 9 empty packaging materials disposed in the To-Be scenario (see Figure 9.11).

Figure 9.12 shows that the local warehouse in country D has disposed 64 empty packaging materials in the current situation, whereas in the To-Be situation this local warehouse has disposed 11 empty packaging materials, which is a decrease of 82.8%.
9.2.3 Summary of the Main Findings

The results of the case study presented in the previous two sections (Section 9.2.1 and 9.2.2) show us that the developed decision support model is an efficient tool for determining what to do with empty packaging materials in the supply chain of the company. In addition to this, using the model can save a lot of costs regarding empty packaging materials. Especially the cost of buying new empty packaging materials can be decreased significantly. Next to this, the number of empty packaging materials disposed at the local warehouses decreases considerably. Dependent on the price of the packaging, €500 or €1000, the decrease in the total costs are 7.9% and 20.0% respectively.

9.3 Sensitivity Analysis

In this section, the results of the sensitivity analysis are presented. Section 9.3.1 describes the results of the sensitivity analysis for the price of the packaging materials. Next, Section 9.3.2 discusses what happens to the results if the safety stock level changes. In Section 9.3.3, we show what impact different lead times have on the outputs of the model. Subsequently, it is tested in Section 9.3.4 whether changing the disposal costs has an influence on the results. Finally, a sensitivity analysis based on different customer demand patterns is done to look at the impact on the total costs and other outputs of the model. Note that all sensitivity analyses are performed for the model with 24 periods. This is done due to that the model with 28 periods was not able to find a feasible solution for all scenarios we wanted to investigate.

9.3.1 Sensitivity Analysis: Price of the Packaging Material

The company is especially interested in determining a threshold value that indicates whether an empty packaging material can be disposed or need to be returned. The decision-making rule that the company currently uses is a threshold value which is determined for defect parts, which states that packaging materials below €X need to be scrapped and above this value the packaging materials need to be returned. Empty packaging materials are not comparable with parts, due to totally different characteristics. Therefore, we performed a sensitivity analysis to see what the model decides to do with the empty packaging materials if the price of packaging material is changing. Based on the sensitivity analysis, we can determine a threshold value specific for packaging materials.

The different packaging prices used in this analysis are the following:

1. \( C_N = 100 \)
2. \( C_N = 500 \)
3. \( C_N = 750 \)
4. \( C_N = 1000 \)
5. \( C_N = 2000 \)

The values of the other input parameters can be found in Appendix E – Values of the Input Parameters for the Sensitivity Analyses.

The total costs of these five scenarios are presented in Figure 9.13.
This figure shows that if the price of the packaging decreases the total costs also decreases. A packaging price of €2000 gives the highest total costs, which is €366,530. The least total costs (€117,110) are in the case where the packaging is €100. This indicates that if the packaging price decreases with 95.0%, the total costs decrease with 68.0%. An overview of the decreases in percentages is presented in Table 9.1. The decreases in the total costs as the packaging prices decrease are logic because buying new empty packaging materials is cheaper for a lower packaging price.

<table>
<thead>
<tr>
<th>Packaging price</th>
<th>Total costs</th>
<th>Decrease in price in %</th>
<th>Decrease in costs in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>€2000</td>
<td>€366,530</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>€1000</td>
<td>€283,450</td>
<td>-50.0%</td>
<td>-22.7%</td>
</tr>
<tr>
<td>€750</td>
<td>€256,970</td>
<td>-62.5%</td>
<td>-29.9%</td>
</tr>
<tr>
<td>€500</td>
<td>€211,230</td>
<td>-75.0%</td>
<td>-42.4%</td>
</tr>
<tr>
<td>€100</td>
<td>€117,110</td>
<td>-95.0%</td>
<td>-68.0%</td>
</tr>
</tbody>
</table>

Regarding the values of the decision variables, we found the following things.

If the packaging price is €100 or €500, no empty packaging materials are returned from the local warehouse in Country C (see Figure 9.14).
Figure 9.15 shows that the local warehouse in Country B only returns empty packaging materials if the packaging price is €2000 or €1000. Thus, if the packaging price is €100, €500 or €750, this local warehouse does not return empty packaging materials to the factory warehouse.

![Empty packaging materials returned from the LWH in Country B to the FWH](image)

*Figure 9.15 Number of empty packaging materials returned from the local warehouse in Country B*

In Figure 9.16, it is presented that the local warehouse in Country A does not return empty packaging materials if the packaging price is €100 or €500.

![Empty packaging materials returned from the LWH in Country A to the FWH](image)

*Figure 9.16 Number of empty packaging materials returned from the local warehouse in Country A*

Figure 9.17 shows that the results for the local warehouse in Country D are different than the previously described results. This local warehouse does not return empty packaging materials only in the case the packaging price is €100.

Based on the results, we can conclude that packaging materials with a packaging price less than €500 are not interesting to return to the factory warehouse in terms of total costs.
It was found that the local warehouse in Country C disposed a higher amount of empty packaging materials when the packaging price is €500 in comparison with the case where the packaging price is €1000: 17 packaging materials vs. 3 packaging materials, respectively. The local warehouses in country A, B and D dispose in total more empty packaging materials if the packaging price decreases, which is presented in Table 9.2. This is due to that these local warehouses are larger than the local warehouse in Country C, thus, these local warehouses receive more empty packaging materials from the customer and as a result, they can return or dispose a larger number of empty packaging materials. All local warehouses dispose empty packaging materials. However, the results show that all local warehouses dispose clearly a lot more empty packaging materials if the price decreases (see Table 9.2).

Table 9.2 Overview of the total number of empty packaging materials disposed over all periods

<table>
<thead>
<tr>
<th>Local warehouse</th>
<th>Packaging price €2000</th>
<th>Packaging price €1000</th>
<th>Packaging price €750</th>
<th>Packaging price €500</th>
<th>Packaging price €100</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>10</td>
<td>13</td>
<td>60</td>
<td>64</td>
</tr>
<tr>
<td>B</td>
<td>12</td>
<td>10</td>
<td>62</td>
<td>60</td>
<td>64</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>8</td>
<td>4</td>
<td>8</td>
<td>66</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16</strong></td>
<td><strong>31</strong></td>
<td><strong>82</strong></td>
<td><strong>145</strong></td>
<td><strong>212</strong></td>
</tr>
</tbody>
</table>

Note that within the factory warehouse, no empty packaging materials have been disposed. Thus, for all packaging price scenarios, zero empty packaging materials are disposed. This indicates that all new empty packaging materials and all returned empty packaging materials are used to pack parts in order to ship the parts to the customers.

9.3.2 Sensitivity Analysis: Safety Stock at the Different Warehouses

To illustrate the impact of the safety stock level on the decision what to do with the empty packaging materials in the supply chain, a safety stock sensitivity analysis is conducted. This section presents the results of this sensitivity analysis.

**Sensitivity Analysis Safety Stock Local Warehouses**

Table 9.3 displays the results of increasing the safety stock level within the local warehouses with one packaging unit each run (i.e. from $SB_L(t) = 1$ to $SB_L(t) = 5$). Note that the safety stock level of the factory warehouses stays one ($SB_F(t) = 1$) during this analysis. It is found that this increase has almost no impact on the total costs.
Table 9.3 Overview of the results of the sensitivity analysis for the safety stock in the local warehouses

<table>
<thead>
<tr>
<th>( SB_i(t) )</th>
<th>Total costs</th>
<th>Cost increase in €</th>
<th>Cost increase in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>€283,450</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>€283,450</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>€283,450</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>€284,800</td>
<td>€1350.00</td>
<td>0.48%</td>
</tr>
<tr>
<td>4</td>
<td>€284,800</td>
<td>€1350.00</td>
<td>0.48%</td>
</tr>
<tr>
<td>5</td>
<td>€283,450</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The values of the decision variables are the same in the case where the safety stock level in the local warehouses is 0, 1, 2, and 5 and in the case where the safety stock level in the local warehouses is 3 and 4. This can also be seen in the total costs: in these periods the total costs are equal. The differences found in the values are very small and the value only changed a bit per period (see e.g. Figure 9.18).

Figure 9.18 Number of empty packaging materials returned from the LWH in Country C to the FWH

Sensitivity Analysis Safety Stock Factory Warehouse

Table 9.4 presents the results of the sensitivity analysis in which the safety stock of the factory warehouse is changed from 1 to 5 (i.e. increasing \( SB_E(t) = 1 \) to \( SB_E(t) = 5 \)). Note that the safety stock level of the local warehouses stays one in this analysis. Also, in this case, changing the safety stock level has only a small influence on the total costs, namely a maximal increase of 0.02% and a decrease of 0.48%. Furthermore, the values of the decision variables changed a bit, but no significant changes within these values are found.

Table 9.4 Overview of the results of the sensitivity analysis for the safety stock in the factory warehouse

<table>
<thead>
<tr>
<th>( SB_E(t) )</th>
<th>Total costs</th>
<th>Cost different in €</th>
<th>Cost difference in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>€284,830</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>€283,450</td>
<td>-€1380.00</td>
<td>-0.48%</td>
</tr>
<tr>
<td>2</td>
<td>€284,890</td>
<td>€60.00</td>
<td>0.02%</td>
</tr>
<tr>
<td>3</td>
<td>€283,450</td>
<td>-€1380.00</td>
<td>-0.48%</td>
</tr>
<tr>
<td>4</td>
<td>€283,910</td>
<td>-€920.00</td>
<td>-0.32%</td>
</tr>
<tr>
<td>5</td>
<td>€283,450</td>
<td>-€1380.00</td>
<td>-0.48%</td>
</tr>
</tbody>
</table>

Based on this sensitivity analysis, we can conclude that for the local warehouses it is best to keep the safety stock levels as low as possible and for the safety stock level of the factory warehouse, it is better to use a higher value.
9.3.3 Sensitivity Analysis: Lead Times

The assumed lead times are a bit pessimistic. This is due to the fact that the real lead times are in weeks and the periods in the model are in months. Therefore, we decided to round up the lead times. This caused the lead time from the packaging supplier to the factory warehouse to be assumed to be two months, whereas the real lead time is six weeks. To investigate the impact of this lead time on the results of the model, we performed a sensitivity analysis in which the lead time from the packaging supplier to the factory warehouse is adapted.

Table 9.5 shows that the total costs increase a lot if the lead time from the packaging supplier to the factory warehouse is increased from one to two months.

Table 9.5 Results of the sensitivity analysis for the lead time

<table>
<thead>
<tr>
<th>$L_{N \rightarrow E}$</th>
<th>Total costs</th>
<th>Cost increase in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>€157,639</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>€365,410</td>
<td>131.8%</td>
</tr>
</tbody>
</table>

This can be explained by the fact that, in the case of the larger lead time, the customers are waiting longer before the full packaging arrives. Thus, the customers have more backorders in the case with the larger lead time and thus more backorders costs. In addition to this, due to the longer lead time the factory warehouse orders more new empty packaging materials in the first period, i.e. 38 empty packaging units in the case where the lead time is one month and 73 empty packaging units in the case where the lead time is two months. Thus, the factory warehouse wants to prevent high backorder costs in the case the lead time is larger, and thus, orders more new empty packaging materials in the first period.

Based on the results of this sensitivity analysis, we can conclude that assuming different values for the lead times can have major influences on the total costs.

9.3.4 Sensitivity Analysis: Disposal Costs

For the company, the disposal costs of the empty packaging materials in the local warehouses are neglectable. Therefore, the disposal costs must be as low as possible. Thus, we assumed for the previous analyses that the disposal costs in the local warehouses and the factory warehouse are €10 per empty packaging disposed, i.e. $C_{D,E} = C_{D,S} = 10$. To check if this assumption of the company is correct, we performed a sensitivity analysis for the disposal costs. The impact of increasing and decreasing the assumed disposal costs is investigated during this analysis and the results are reported below.

Table 9.6 shows that the total costs are the least in the case where the disposal costs in the local warehouses and the factory warehouse are €5 per empty packaging disposed. However, this is only a 0.25% decrease compared to the total costs if the disposal costs are zero.

Table 9.6 Results of the sensitivity analysis for the disposal costs

<table>
<thead>
<tr>
<th>$C_{D,E} = C_{D,S}$</th>
<th>Total costs</th>
<th>Cost difference in €</th>
<th>Cost difference in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>€366,930</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>€366,020</td>
<td>-€910.00</td>
<td>-0.25%</td>
</tr>
<tr>
<td>10</td>
<td>€366,530</td>
<td>-€400.00</td>
<td>-0.11%</td>
</tr>
<tr>
<td>20</td>
<td>€368,290</td>
<td>€1360.00</td>
<td>0.37%</td>
</tr>
</tbody>
</table>

In addition to this, changing the disposal costs as presented above does not have an influence on the values of the decision variables. For some periods the values are a bit different, but this is only one empty packaging unit difference and the total numbers over all periods are the same. Only the values for $QB_{d,s}(t)$, the number of empty packaging materials disposed in the local
warehouses, are fluctuating. The values for all periods of this decision variable for the local warehouses in country A, B, C and D are presented in Figure 9.21, Figure 9.20, Figure 9.19, and Figure 9.22, respectively.

**Figure 9.19** Sensitivity analysis disposal costs: empty packaging disposed in the local warehouse of Country A

**Figure 9.20** Sensitivity analysis disposal costs: empty packaging disposed in the local warehouse of Country B

**Figure 9.21** Sensitivity analysis disposal costs: empty packaging disposed in the local warehouse of Country C
Table 9.7 presents an overview of the figures displayed above. The total amount of empty packaging materials disposed in all local warehouses over all periods are summed and presented in the table below. If the disposal costs are zero, the local warehouses dispose the highest amount of empty packaging materials. This can be explained by the objective of the model, which is to minimize the total costs. Thus, if the disposal of empty packaging materials is not accompanied by costs, then it is most logical for the model to dispose relatively more empty packaging materials than when the disposal costs are greater than zero.

Based on the results of this sensitivity analysis, we can conclude that it is not optimal to totally neglect the disposal costs. The cheapest option is to assume that the disposal costs are €5 per empty packaging material disposed.

### 9.3.5 Sensitivity Analysis: Different Customer Demand

To investigate whether the customer demand has an impact on the decisions of the model, we performed a sensitivity analysis. In addition to this, the company is interested in whether there exist demand patterns for which it is most interesting to return or dispose empty packaging materials.

From the usage file, we took three different demand patterns. The first pattern represents a packaging with low demand, i.e. on average ~0.50 empty packaging units per month. The second represents a packaging material with a medium demand, i.e. ~4.00 empty packaging units per month. The last pattern represents a packaging material with high demand, i.e. ~13.00 empty packaging units per month. Note that these averages represent the total of the customer demands. Thus, these averages have to be multiplied with the factors presented in Section 7.4.1 (i.e. 0.30 for country A, B and D, and 0.10 for country C) to get the average demand for each customer. The exact values of the demand per period can be found in Appendix E – Values of the Input Parameters for the Sensitivity Analyses.
Table 9.8 shows the total costs for the demand patterns presented above. As expected, the total costs are the lowest in the case the customer demand is low. In this case, not so much new empty packaging materials have to be ordered, which makes a big difference in costs.

<table>
<thead>
<tr>
<th>$DP_{cs}$</th>
<th>Total costs</th>
<th>Cost difference in €</th>
<th>Cost difference in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>€15,687</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Medium</td>
<td>€82,694</td>
<td>€67,007</td>
<td>427%</td>
</tr>
<tr>
<td>High</td>
<td>€283,450</td>
<td>€267,763</td>
<td>1707%</td>
</tr>
</tbody>
</table>

Due to the differences in the demand per period and the size of the demand, the values of the decision variables differ a lot. Even if the customer demand for a specific empty packaging is low, the cheapest option is to return empty packaging materials from the local warehouses to the factory warehouse. Note: this is in the case of a packaging with a price of €2000.

### 9.4 Conclusion and Discussion

In the present chapter, the results of the case study and the sensitivity analyses are presented and discussed.

For the case study, we compared two different scenarios: Scenario A, which represented the current (As-Is) situation and processes regarding empty packaging in the supply chain of the company, and, Scenario B, which represented the to-be scenario. The results of comparing these two scenarios showed that by using the new process and decision support model developed in Chapter 6 and 7 respectively can decrease the total costs of empty packaging in the supply chain by 7.9% in the case the packaging price is €500.00 and 20.0% in the case the packaging price is €1000.00. In addition to this, the cost of buying new empty packaging materials as well as the number of empty packaging materials disposed can be decreased significantly if the decision-support model is used. The cost savings for the reverse flow of one specific empty packaging material are considerably large. Therefore, we can conclude that using the developed decision support model makes the closed-loop supply chain of the company more efficient and less expensive.

Regarding the five sensitivity analyses conducted on the decision support model, the following things are concluded:

- If the price of the packaging decreases, the total costs regarding empty packaging also decreases. As already mentioned before, this is logically because buying new empty packaging materials is less expensive. Thus, if the factory warehouse orders the same amount of new empty packaging materials, the total costs of buying new empty packaging are lower for a less expensive packaging material.
- If the price of the packaging decreases, more empty packaging materials are disposed, and less empty packaging materials are returned. This implies that if the packaging is more expensive, it is cheaper to return the empty packaging materials than to dispose it and buy the packaging new. The same holds for cheaper empty packaging materials: it is cheaper to dispose the empty packaging materials and buy the empty packaging material new than to return the empty packaging material to the factory warehouse.
- Only the local warehouse in Country D returns empty packaging materials in the case that the price of the packaging is €500; the other three local warehouses do not return any empty packaging materials in this case. Based on this, we can conclude that €500 would be a better threshold value for disposing or returning empty packaging materials.
- Changing the safety stock has almost no impact on the total costs regarding empty packaging materials.
• Assuming different values for the lead times has a major impact on the results of the model, especially on the total costs of empty packaging within the closed-loop supply chain.

• Decreasing or increasing the disposal costs has only a small influence on the total costs of the supply chain regarding empty packaging materials.

• The decision whether to return or dispose an empty packaging material is strongest related to the packaging price of the material.
10 Conclusion and Recommendations

In this chapter, we present the conclusions and recommendations based on the work we did. We recall the main research question of this Master thesis project:

Main Research Question:
*What to do with empty packaging within the different stages of ASML’s supply chain?*

In order to answer this question, first we have created insights in (1) the current processes of handling empty packaging within the local warehouses (Chapter 4 and 5) and (2) the root causes of the empty packaging problem (Chapter 5). Based on these insights, we were able to design a new process for handling empty packaging in the local warehouses (Chapter 6) and we developed a decision support model which help the decision-makers of the company what to do with the empty packaging materials (Chapter 7). In the following sections, the main conclusions of this project are motivated (Section 10.1) and the recommendations for the company are presented (Section 10.2). In Section 10.3, we give some directions for future research and lastly, Section 10.4 presents the academic contribution of this Master thesis project.

10.1 Conclusions

In this section, we motivate the main conclusions of this study. In Chapter 1 - Introduction, we concluded that ASML is facing a problem regarding the decision-making process for empty packaging materials in the local warehouses. It was unsure what to do with the empty packaging materials, i.e. return to the factory warehouse and reuse the packaging or scrap and dispose the packaging. Due to this, the local warehouses are full of unused empty packaging materials. ASML have been used as a case study to research how this problem can be tackled and to improve the decision-making process regarding the empty packaging materials in the local warehouses.

To be able to solve the empty packaging problem and answer the main research question, we first answered the two sub research questions: *What are the root causes of the empty packaging problem* and *What is a suitable decision support model for managing empty packaging?*

The first research question is answered by making the current processes visible and by gathering information about why the local warehouses are facing this empty packaging problem. Regarding the current processes of handling empty packaging in the local warehouses, we could conclude that the current processes are far too complex and consist of too many steps. Additionally, each local warehouse has a different way of working and their focus is on the packaging in combination with the part. To be able to have a return flow of empty packaging, the focus should switch from packaging including a part to packaging as an independent item. As a result, more empty packaging materials could be returned to the factory warehouse and be reused to shipped parts to the customers. Based on these insights, we found the main root causes of the empty packaging problem. The main root causes of the problem are the following:

1. No clear instructions for handling packaging, which results in each local warehouse handling the empty packaging materials in a different way.
2. The empty packaging materials are not traceable in SAP. Due to this, all empty packaging inventory in the local warehouses is not visible in SAP. Some local warehouses try to make the inventory visible with an Excel list.
3. The X-plant status of the empty packaging materials are not up-to-date. With the X-plant status, the local warehouses can check what to do with the packaging material, i.e. return or scrap. However, if this status is not up-to-date wrong decisions can be made and as a result, the local warehouses just keep all packaging materials in inventory.
4. Within the company, there is no ownership for the empty packaging materials. The focus of the company is on the parts, and not on the packaging materials. This is also represented by the fact that there are no KPIs developed for empty packaging.

5. The 3PL employees with the local warehouses do not have knowledge about the packaging. This results in unclear responsibilities. In addition, the 3PL employees are not allowed to make the return/scrap decision.

These five root causes provide the answer of the first sub research question.

In order to answer research question 2, we first have designed a new standardized process for handling empty packaging in the local warehouses, based on the insights gained from the first research question. This new designed process focuses on the empty packaging materials and not on the part to be packed with the packaging material. With this process, the flow of empty packaging in the local warehouses can be handled more efficiently and the employees in the local warehouses know what to do with the empty packaging materials.

For the employees of the reverse operations team, we developed an Excel tool for determining the X-plant status. In the past, the X-plant status for empty packaging materials was based on several doubtful assumptions (e.g. threshold for scrapping parts was used). The new way of determining the X-plant status is based on the cost of buying the packaging new, the demand for the packaging material and whether it is profitable to return the empty packaging material. With this tool, the reverse operations team can easily determine the X-plant status and keep it up-to-date.

The second part of answering research question 2 was to develop a decision support model which is suitable for managing empty packaging in the supply chain of the company under consideration. The mathematical model that forms the basis of the decision support model is a Mixed Integer Linear Programming model which contains a pull inventory control policy. This type of model in combination with the mentioned inventory policy was found most suitable for the company. The decision support model determines how many empty packaging should be returned or disposed in a specific month. Thus, by using the developed decision support model, the company can plan the packaging ahead and prevent that the local warehouses get full of empty packaging materials.

The developed decision support model makes the decision-making regarding empty packaging even more efficient, which is presented in the results of the case study, which show that implementing the developed decision support model in the company can result in large cost savings per month. The monthly cost savings can go up to €2964.64 and a decrease of 20.0% in the total costs over 28 periods can be reached, in case the packaging price is €1000.

With the answers of both sub research questions, we can conclude that we have developed a decision support model that facilitate the decision-making regarding empty packaging in the supply chain of the company. The model suggests, based on the lowest costs, what is optimal to do with the empty packaging in the different stages of the supply chain of ASML. Hence, if the company uses the decision support model, they know what is best to do with the empty packaging materials, i.e. return or dispose the packaging materials.

10.2 Recommendations for the Company

In this section, we motivate our recommendations for the company for the next steps of our work.

New standardized process

Due to time constraints, it was not possible to do a pilot with the new process. Therefore, it is important for the company to first do a pilot. We recommend providing the work instruction of the new process to a couple local warehouses and if this turns out to be a success, implement the new process worldwide.
New way of determining X-plant status

Based on the results of the sensitivity analysis for the packaging price, we recommend changing the threshold of disposing or returning empty packaging from €X to €500.00. The results of this study showed that this is the optimal threshold value. This implies that if the packaging material is cheaper than €500.00, it can be disposed immediately, and the empty packaging need to be bought new. If the packaging material is more expensive than €500, the empty packaging materials should be returned.

Decision support model

The decision support model is now based on a closed-loop supply chain with one factory warehouse, four local warehouses and each local warehouse has one customer. This is a simplified version of the real supply chain of ASML. Therefore, we recommend doing a pilot with the modeled CLSC first and after the pilot, extend the decision support model for multiple factory warehouses, more local warehouses and customers. Furthermore, we recommend exploring the possibilities to determine the real demand input for empty packaging materials and making a forecast for the empty packaging demand. Currently, we used historical usage data as demand input for the decision support model. Thus, this data is not totally accurate because it does not represent the demand for empty packaging materials, but the number of packaging materials used per month. We recommend exploring new ways of determining the actual demand for empty packaging materials. The actual demand and a demand forecast for empty packaging enable the model to plan the empty packaging and will give more accurate advices on what to do with the empty packaging materials in the supply chain.

Empty packaging material

To make the processes regarding empty packaging even more efficient, we recommend using radio frequency identification (RFID) technology for the more expensive packaging materials. RFID is a wireless automatic identification and data capture technology (Demir, 2010). With RFID, the packaging materials can be made visible throughout the whole supply chain, and thus, it is easier to track the exact location of the packaging material. Hence, the structure of SAP regarding packaging materials does not have to change if the RFID technology is used, because with this technique it can be tracked where the packaging material is. Moreover, by using this technique in combination with the developed decision support model, the packaging materials can be at the right place in the supply chain and at the right time in the right quantity. This technology could have added value for the efficiency of the supply chain and therefore, our recommendation to the company is to further explore this technology.

10.3 Directions for Future Research

In this section, we present some opportunities for future research.

The first direction for future research which is suggested by us is the relaxation of the simplifications of the Mixed Integer Linear Programming model. In Chapter 7, we described the mathematical model which forms the basis of the decision support model. For convenience, we made some assumptions and simplifications to develop the most suitable decision support model. However, by relaxing the simplifications the model can be further improved which in the end leads to better decision-making regarding empty packaging. First, we assumed that the packaging supplier always has sufficient packaging materials in stock, however, in the real system this is not always the case. Therefore, an improvement of the model could be to relax this assumption. This will probably have an influence on the safety stock of the factory warehouse. Another assumption made to simplify the model was that the parts to be packed with the packaging material is. Moreover, by using this technique in combination with the developed decision support model, the packaging materials can be at the right place in the supply chain and at the right time in the right quantity. This technology could have added value for the efficiency of the supply chain and therefore, our recommendation to the company is to further explore this technology.

Additionally, we suggest exploring the opportunity of making the model for multiple packaging materials. The decision support model determines for one specific packaging material what the
least expensive option is, i.e. returning or disposing. If the model can be extended to a model with multiple packaging materials, this could make the decision-making faster and more efficient.

Another good opportunity for further research is to investigate the safety stock levels in the local warehouses and the factory warehouse. The safety stock of empty packaging materials is related to the availability of empty packaging materials in the warehouses. Having the right amount of empty packaging materials on stock is very important, e.g. for emergency shipments of a new part to the customer or if a defect part must be returned to the supplier for repair as soon as possible. In these cases, it is good to have some empty packaging materials available in the warehouses. Because the faster parts can be shipped to the right place, the more costs can be saved. Therefore, we suggest that optimizing the safety stock level for empty packaging materials within the local warehouses and the factory warehouse is a great opportunity for future research.

10.4 Academic Contribution
This Master thesis has examined what to do with the empty packaging materials in the local warehouses of the company. In the current state-of-the-art, most studies focused on the comparison which packaging system is economically and environmentally optimal for companies. To the best of our knowledge, a decision support model for a packaging system that combines disposable packaging and returnable packaging has not yet been reported. Hence, the decision support model developed in this research can considered to be a new contribution to the academic literature.
References


Appendix A – Process Flow of Work Instruction 2014

Figure A.1 Process flow of the existing work instruction regarding empty packaging
Appendix B – Packaging Scrap List

This Appendix shows the criteria for the packaging materials that can be scrapped immediately:
1. (Standard) packaging materials which has a new buy value less than €500.00
2. The packaging material is a cardboard box
3. The packaging material is a clean assy:
   a) Plastics foils
   b) Plastic bags
4. Triple wall boxes
5. Standard plastic pallets

Note that most cardboard boxes and clean assys are standard packaging materials of which the new buy value is mostly less than €500.00. The same applies for the triple wall boxes and the plastic pallets.
Appendix C – Values of the Input Parameters of the Internal Validity Test

For the internal validity test performed in Section 8.3.2, the values for the input parameters are presented in Table A.1. Note that the inventory holding cost and transportation cost parameters have the values as presented in Section 7.3.1 and 7.3.2 respectively. The same applies for the lead times: these have the values presented in Section 7.4.2. Note that all numbers used for the internal validity test are fictitious and serve for illustrative purposes only.

Table A.1 Values of the input parameters during the internal validity test

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of empty packaging items returned from customer $c$ to local warehouse $s$ after emptying the packaging material</td>
<td>$\alpha_{c,s}$</td>
<td>0.75</td>
</tr>
<tr>
<td>Backorders for full packaging units at customer $c$ of local warehouse $s$ in period 1</td>
<td>$BP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Backorder cost per full packaging unit missing at customer $c$ of local warehouse $s$</td>
<td>$C_{B,c,s}$</td>
<td>€200 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit in the factory warehouse in Country E</td>
<td>$C_{D,E}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit by warehouse $s$</td>
<td>$C_{D,s}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for buying one unit of an empty packaging material new</td>
<td>$C_N$</td>
<td>€2000</td>
</tr>
<tr>
<td>Cost for cleaning and repairing an empty packaging unit at the factory warehouse in Country E.</td>
<td>$C_{R,E}$</td>
<td>€50 per packaging unit</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the factory warehouse</td>
<td>$IB_{max,E}$</td>
<td>50</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in local warehouse $s$</td>
<td>$IB_{max,s}$</td>
<td>50</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in the factory warehouse in Country E in period $t$. This on-hand inventory is measured at the beginning of period 1</td>
<td>$IB_{E}(1)$</td>
<td>1 ($=SB_{E}(t)$)</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in local warehouse $s$ in period 1</td>
<td>$IB_{s}(1)$</td>
<td>1 ($=SB_{s}(t)$)</td>
</tr>
<tr>
<td>On-hand inventory of full packaging materials (i.e. packaging including a part) at customer $c$ of local warehouse $s$ in period 1</td>
<td>$IP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>On-hand inventory of full packaging materials (i.e. packaging including a part) in local warehouse $s$ in period 1</td>
<td>$IP_{s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Safety stock of empty packaging materials at the factory warehouse in Country E in period $t$</td>
<td>$SB_{E}(t)$</td>
<td>1</td>
</tr>
<tr>
<td>Safety stock of empty packaging materials at local warehouse $s$ in period $t$</td>
<td>$SB_{s}(t)$</td>
<td>1</td>
</tr>
<tr>
<td>Chargeable weight of the packaging material</td>
<td>$W_c$</td>
<td>166.67 kg</td>
</tr>
<tr>
<td>Warehouse space occupied by the empty packaging material</td>
<td>$WS$</td>
<td>1 m²</td>
</tr>
</tbody>
</table>

The demand input for the empty packaging material is presented in Table A.2.
Table A.2 Demand input during the internal validity tests

<table>
<thead>
<tr>
<th>Period</th>
<th>Customer demand $DP_{c,s}(t)$</th>
<th>Period</th>
<th>Customer demand $DP_{c,s}(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td>19</td>
<td>$t = 13$</td>
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<tr>
<td>$t = 2$</td>
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<tr>
<td>$t = 12$</td>
<td>19</td>
<td>$t = 24$</td>
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</tbody>
</table>
Appendix D – Values of the Input Parameters for the Scenario Analysis

For the scenario analysis performed in Section 9.2, the values for the input parameters are presented in Table A.3. Note that the inventory holding cost and transportation cost parameters have the values as presented in Section 7.3.1 and 7.3.2 respectively. The same applies for the lead times: these have the values presented in Section 7.4.2. Note that all numbers used for the scenario analysis are fictitious and serve for illustrative purposes only.

Table A.3 Values of the input parameters used for the scenario analysis

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of empty packaging items returned from customer $c$ to local warehouse $s$ after emptying the packaging material</td>
<td>$\alpha_{c,s}$</td>
<td>0.75</td>
</tr>
<tr>
<td>Backorders for full packaging units at customer $c$ of local warehouse $s$ in period 1</td>
<td>$BP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Backorder cost per full packaging unit missing at customer $c$ of local warehouse $s$</td>
<td>$C_{B,c,s}$</td>
<td>€200 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit in the factory warehouse in Country E</td>
<td>$C_{D,E}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit by warehouse $s$</td>
<td>$C_{D,s}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for buying one unit of an empty packaging material new</td>
<td>$C_N$</td>
<td>€500.00 or €1000.00</td>
</tr>
<tr>
<td>Cost for cleaning and repairing an empty packaging unit at the factory warehouse in Country E.</td>
<td>$C_{R,E}$</td>
<td>€50 per packaging unit</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the factory warehouse</td>
<td>$IB_{max,E}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in local warehouse $s$, where $s =$ country A, B and D</td>
<td>$IB_{max,s}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the local warehouse in Country C</td>
<td>$IB_{max,C}$</td>
<td>25</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in the factory warehouse in Country E in period $t$. This on-hand inventory is measured at the beginning of period 1</td>
<td>$IB_E(t)$</td>
<td>1 ($=SB_E(t)$)</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in local warehouse $s$ in period 1</td>
<td>$IB_s(t)$</td>
<td>1 ($=SB_s(t)$)</td>
</tr>
<tr>
<td>On-hand inventory of full packaging materials (i.e. packaging including a part) at customer $c$ of local warehouse $s$ in period 1</td>
<td>$IP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>On-hand inventory of full packaging materials (i.e. packaging including a part) in local warehouse $s$ in period 1</td>
<td>$IP_s(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Safety stock of empty packaging materials at the factory warehouse in Country E in period $t$</td>
<td>$SB_E(t)$</td>
<td>1</td>
</tr>
<tr>
<td>Safety stock of empty packaging materials at local warehouse $s$ in period $t$</td>
<td>$SB_s(t)$</td>
<td>1</td>
</tr>
<tr>
<td>Chargeable weight of the packaging material</td>
<td>$W_c$</td>
<td>166,67 kg</td>
</tr>
<tr>
<td>Warehouse space occupied by the empty packaging material</td>
<td>$WS$</td>
<td>1 m2</td>
</tr>
</tbody>
</table>

The demand input for the empty packaging material is presented in Table A.4.
Table A.4 Demand input during the scenario analysis

<table>
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<tr>
<th>Period</th>
<th>Customer demand $DP_{c,s}(t)$</th>
<th>Period</th>
<th>Customer demand $DP_{c,s}(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td>19</td>
<td>$t = 15$</td>
<td>9</td>
</tr>
<tr>
<td>$t = 2$</td>
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Appendix E – Values of the Input Parameters for the Sensitivity Analyses

For the scenario analyses performed in Section 9.3.1 to 9.3.5, the values for the input parameters are presented in the following tables. Note that the inventory holding cost and transportation cost parameters have the values as presented in Section 7.3.1 and 7.3.2 respectively. The same applies for the lead times: these have the values presented in Section 7.4.2. Note that all numbers used for the sensitivity analyses are fictitious and serve for illustrative purposes only.

Scenario Analysis Packaging Prices
The values of the input parameters used for the sensitivity analysis of the packaging prices are presented in Table A.5 and Table A.6.

Table A.5 Values of the input parameters during the packaging price sensitivity analysis

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of empty packaging items returned from customer c to local warehouse s</td>
<td>( \alpha_{c,s} )</td>
<td>0.75</td>
</tr>
<tr>
<td>Backorders for full packaging units at customer c of local warehouse s in period 1</td>
<td>( BP_{c,s}(1) )</td>
<td>0</td>
</tr>
<tr>
<td>Backorder cost per full packaging unit missing at customer c of local warehouse s</td>
<td>( C_{B,c,s} )</td>
<td>€200 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit in the factory warehouse</td>
<td>( C_{D,E} )</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit by warehouse s</td>
<td>( C_{D,s} )</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for buying one unit of an empty packaging material new</td>
<td>( C_N )</td>
<td>€100, €500, €750, €1000 and €2000</td>
</tr>
<tr>
<td>Cost for cleaning and repairing an empty packaging unit at the factory warehouse</td>
<td>( C_{R,E} )</td>
<td>€50 per packaging unit</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the factory warehouse</td>
<td>( IB_{max,E} )</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in local warehouse s, where s = country A, B and D</td>
<td>( IB_{max,s} )</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the local warehouse in Country C</td>
<td>( IB_{max,C} )</td>
<td>25</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in the factory warehouse in period t. This on-hand inventory is measured at the beginning of period 1</td>
<td>( IB_{E}(1) )</td>
<td>1 (=( SB_{E}(t) ))</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in local warehouse s in period 1</td>
<td>( IB_{s}(1) )</td>
<td>1 (=( SB_{s}(t) ))</td>
</tr>
<tr>
<td>On-hand inventory of full packaging materials (i.e. packaging including a part) at customer c of local warehouse s in period 1</td>
<td>( IP_{c,s}(1) )</td>
<td>0</td>
</tr>
<tr>
<td>On-hand inventory of full packaging materials (i.e. packaging including a part) in local warehouse s in period 1</td>
<td>( IP_{s}(1) )</td>
<td>0</td>
</tr>
<tr>
<td>Safety stock of empty packaging materials at the factory warehouse in period t</td>
<td>( SB_{E}(t) )</td>
<td>1</td>
</tr>
</tbody>
</table>
Safety stock of empty packaging materials at local warehouse $s$ in period $t$, $SB_s(t)$, 1

Chargeable weight of the packaging material, $W_c$, 166.67 kg

Warehouse space occupied by the empty packaging material, $WS$, 1 m²

The demand input for the empty packaging material used during the sensitivity analysis of the packaging prices is presented in Table A.6.

<table>
<thead>
<tr>
<th>Period</th>
<th>Customer demand $DP_{c,s}(t)$</th>
<th>Period</th>
<th>Customer demand $DP_{c,s}(t)$</th>
</tr>
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<tbody>
<tr>
<td>$t = 1$</td>
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<tr>
<td>$t = 12$</td>
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<td>$t = 24$</td>
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</tbody>
</table>

Sensitivity Analysis Safety Stock Local Warehouses

The values of the input parameters used for the sensitivity analysis of the safety stock of the local warehouses are presented in Table A.7 and Table A.9.

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of empty packaging items returned from customer $c$ to local warehouse $s$ after emptying the packaging material</td>
<td>$\alpha_{c,s}$</td>
<td>0.75</td>
</tr>
<tr>
<td>Backorders for full packaging units at customer $c$ of local warehouse $s$ in period 1</td>
<td>$BP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Backorder cost per full packaging unit missing at customer $c$ of local warehouse $s$</td>
<td>$C_{B,c,s}$</td>
<td>€200 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit in the factory warehouse</td>
<td>$C_{D,E}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit by warehouse $s$</td>
<td>$C_{D,s}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for buying one unit of an empty packaging material new</td>
<td>$C_N$</td>
<td>€1000</td>
</tr>
<tr>
<td>Cost for cleaning and repairing an empty packaging unit at the factory warehouse</td>
<td>$C_{R,E}$</td>
<td>€50 per packaging unit</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the factory warehouse</td>
<td>$IB_{max,E}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in local warehouse $s$, where $s = \text{country A, B and D}$</td>
<td>$IB_{max,s}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the local warehouse in Country C</td>
<td>$IB_{max,C}$</td>
<td>25</td>
</tr>
</tbody>
</table>
On-hand empty packaging inventory in the factory warehouse in period $t$. This on-hand inventory is measured at the beginning of period $1$.

On-hand empty packaging inventory in local warehouse $s$ in period $1$.

On-hand inventory of full packaging materials (i.e. packaging including a part) at customer $c$ of local warehouse $s$ in period $1$.

Safety stock of empty packaging materials at the factory warehouse in period $t$.

Safety stock of empty packaging materials at local warehouse $s$ in period $t$.

Chargeable weight of the packaging material.

Warehouse space occupied by the empty packaging material.

**Sensitivity Analysis Safety Stock Factory Warehouse**

The values of the input parameters used for the sensitivity analysis of the safety stock of the factory warehouse are presented in Table A.8 and Table A.9.

**Table A.8 Values of the input parameters during the sensitivity analysis of the safety stock of the local warehouses**

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of empty packaging items returned from customer $c$ to local warehouse $s$ after emptying the packaging material</td>
<td>$\alpha_{c,s}$</td>
<td>0.75</td>
</tr>
<tr>
<td>Backorders for full packaging units at customer $c$ of local warehouse $s$ in period 1</td>
<td>$BP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Backorder cost per full packaging unit missing at customer $c$ of local warehouse $s$</td>
<td>$C_{B,c,s}$</td>
<td>€200 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit in the factory warehouse</td>
<td>$C_{D,E}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit by warehouse $s$</td>
<td>$C_{D,s}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for buying one unit of an empty packaging material new</td>
<td>$C_N$</td>
<td>€1000</td>
</tr>
<tr>
<td>Cost for cleaning and repairing an empty packaging unit at the factory warehouse.</td>
<td>$C_{R,E}$</td>
<td>€50 per packaging unit</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the factory warehouse</td>
<td>$IB_{max,E}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in local warehouse $s$, where $s$ = country A, B and D</td>
<td>$IB_{max,s}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the local warehouse in Country C</td>
<td>$IB_{max,C}$</td>
<td>25</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in the factory warehouse in period $t$. This on-hand inventory is measured at the beginning of period $1$</td>
<td>$IB_E(1)$</td>
<td>1 (= $SB_E(t)$)</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in local warehouse $s$ in period $1$</td>
<td>$IB_s(1)$</td>
<td>1 (= $SB_s(t)$)</td>
</tr>
</tbody>
</table>

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On-hand inventory of full packaging materials (i.e. packaging including a part) at customer $c$ of local warehouse $s$ in period 1

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-hand inventory of full packaging materials (i.e. packaging including a part) in local warehouse $s$ in period 1</td>
<td>$IP_s(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Safety stock of empty packaging materials at the factory warehouse in period $t$</td>
<td>$SB_E(t)$</td>
<td>0, 1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>Safety stock of empty packaging materials at local warehouse $s$ in period $t$</td>
<td>$SB_s(t)$</td>
<td>1</td>
</tr>
<tr>
<td>Chargeable weight of the packaging material</td>
<td>$W_c$</td>
<td>166.67 kg</td>
</tr>
<tr>
<td>Warehouse space occupied by the empty packaging material</td>
<td>$WS$</td>
<td>1 m2</td>
</tr>
</tbody>
</table>

During the sensitivity analysis of the safety stock levels in the local warehouses and the factory warehouse the same demand patterns is used, which is presented in Table A.9.

Table A.9 Demand input during the sensitivity analysis of the safety stock of the local warehouses and factory warehouse

<table>
<thead>
<tr>
<th>Period $t$</th>
<th>Customer demand $DP_{c,s}(t)$</th>
<th>Period $t$</th>
<th>Customer demand $DP_{c,s}(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td>19</td>
<td>$t = 13$</td>
<td>12</td>
</tr>
<tr>
<td>$t = 2$</td>
<td>13</td>
<td>$t = 14$</td>
<td>11</td>
</tr>
<tr>
<td>$t = 3$</td>
<td>7</td>
<td>$t = 15$</td>
<td>9</td>
</tr>
<tr>
<td>$t = 4$</td>
<td>16</td>
<td>$t = 16$</td>
<td>20</td>
</tr>
<tr>
<td>$t = 5$</td>
<td>10</td>
<td>$t = 17$</td>
<td>20</td>
</tr>
<tr>
<td>$t = 6$</td>
<td>12</td>
<td>$t = 18$</td>
<td>16</td>
</tr>
<tr>
<td>$t = 7$</td>
<td>18</td>
<td>$t = 19$</td>
<td>13</td>
</tr>
<tr>
<td>$t = 8$</td>
<td>10</td>
<td>$t = 20$</td>
<td>10</td>
</tr>
<tr>
<td>$t = 9$</td>
<td>11</td>
<td>$t = 21$</td>
<td>17</td>
</tr>
<tr>
<td>$t = 10$</td>
<td>10</td>
<td>$t = 22$</td>
<td>11</td>
</tr>
<tr>
<td>$t = 11$</td>
<td>9</td>
<td>$t = 23$</td>
<td>7</td>
</tr>
<tr>
<td>$t = 12$</td>
<td>19</td>
<td>$t = 24$</td>
<td>17</td>
</tr>
</tbody>
</table>

Sensitivity Analysis Lead Times

The values of the input parameters used for the sensitivity analysis lead times are presented in Table A.10. During this sensitivity analysis the same demand pattern as the previous sensitivity analyses is used, which is presented in Table A.9.

Table A.10 Values of the input parameters during the sensitivity analysis of the lead times

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of empty packaging items returned from customer $c$ to local warehouse $s$ after emptying the packaging material</td>
<td>$\alpha_{c,s}$</td>
<td>0.75</td>
</tr>
<tr>
<td>Backorders for full packaging units at customer $c$ of local warehouse $s$ in period 1</td>
<td>$BP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Backorder cost per full packaging unit missing at customer $c$ of local warehouse $s$</td>
<td>$C_{B,c,s}$</td>
<td>€200 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit in the factory warehouse</td>
<td>$C_{D,E}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit by warehouse $s$</td>
<td>$C_{D,s}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for buying one unit of an empty packaging material new</td>
<td>$C_N$</td>
<td>€2000</td>
</tr>
</tbody>
</table>
Cost for cleaning and repairing an empty packaging unit at the factory warehouse. $C_{R,E}$ €50 per packaging unit

Maximum storage space for empty packaging materials in the factory warehouse $IB_{max,E}$ 75

Maximum storage space for empty packaging materials in local warehouse $s$, where $s = \text{country A, B and D}$ $IB_{max,s}$ 75

Maximum storage space for empty packaging materials in the local warehouse in Country C $IB_{max,C}$ 75

On-hand empty packaging inventory in the factory warehouse in period $t$. This on-hand inventory is measured at the beginning of period 1 $IB_E(1)$ 1 ($=SB_E(t)$)

On-hand empty packaging inventory in local warehouse $s$ in period 1 $IB_s(1)$ 1 ($=SB_s(t)$)

On-hand inventory of full packaging materials (i.e. packaging including a part) at customer $c$ of local warehouse $s$ in period 1 $IP_{c,s}(1)$ 0

On-hand inventory of full packaging materials (i.e. packaging including a part) in local warehouse $s$ in period 1 $IP_s(1)$ 0

Safety stock of empty packaging materials at the factory warehouse in period $t$ $SB_E(t)$ 1

Safety stock of empty packaging materials at local warehouse $s$ in period $t$ $SB_s(t)$ 1

Chargeable weight of the packaging material $W_c$ 166,67 kg

Warehouse space occupied by the empty packaging material $WS$ 1 m²

**Sensitivity Analysis Disposal Costs**

The values of the input parameters used for the sensitivity analysis of the lead times are presented in Table A.11. During this sensitivity analysis the same demand pattern as the previous sensitivity analyses is used, which is presented in Table A.9.

**Table A.11 Values of the input parameters during the sensitivity analysis of the disposal costs**

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of empty packaging items returned from customer $c$ to local warehouse $s$ after emptying the packaging material</td>
<td>$\alpha_{c,s}$</td>
<td>0.75</td>
</tr>
<tr>
<td>Backorders for full packaging units at customer $c$ of local warehouse $s$ in period 1</td>
<td>$BP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Backorder cost per full packaging unit missing at customer $c$ of local warehouse $s$</td>
<td>$C_{B,c,s}$</td>
<td>€200 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit in the factory warehouse</td>
<td>$C_{D,E}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit by warehouse $s$</td>
<td>$C_{D,s}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for buying one unit of an empty packaging material new</td>
<td>$C_N$</td>
<td>€2000</td>
</tr>
<tr>
<td>Cost for cleaning and repairing an empty packaging unit at the factory warehouse</td>
<td>$C_{R,E}$</td>
<td>€50 per packaging unit</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the factory warehouse</td>
<td>$IB_{max,E}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in local warehouse $s$, where $s = \text{country A, B and D}$</td>
<td>$IB_{max,s}$</td>
<td>75</td>
</tr>
</tbody>
</table>
Maximum storage space for empty packaging materials in the local warehouse in Country C $IB_{max,C}$ 25

On-hand empty packaging inventory in the factory warehouse in period $t$. This on-hand inventory is measured at the beginning of period 1 $IB_E(t)$ 1 ($=SB_E(t)$)

On-hand empty packaging inventory in local warehouse $s$ in period 1 $IB_s(t)$ 1 ($=SB_s(t)$)

On-hand inventory of full packaging materials (i.e. packaging including a part) at customer $c$ of local warehouse $s$ in period 1 $IP_{c,s}(1)$ 0

On-hand inventory of full packaging materials (i.e. packaging including a part) in local warehouse $s$ in period 1 $IP_s(1)$ 0

Safety stock of empty packaging materials at the factory warehouse in period $t$ $SB_E(t)$ 1

Safety stock of empty packaging materials at local warehouse $s$ in period $t$ $SB_s(t)$ 1

On-hand inventory of full packaging materials (i.e. packaging including a part) at customer $c$ of local warehouse $s$ in period 1 $IP_{c,s}(1)$ 0

Safety stock of empty packaging materials at local warehouse $s$ in period $t$ $SB_s(t)$ 1

Chargeable weight of the packaging material $W_c$ 166.67 kg

Warehouse space occupied by the empty packaging material $WS$ 1 m²

### Sensitivity Analysis Customer Demand

The values of the input parameters used for the sensitivity analysis of the customer demand are presented in Table A.12.

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of empty packaging items returned from customer $c$ to local warehouse $s$ after emptying the packaging material</td>
<td>$\alpha_{c,s}$</td>
<td>0.75</td>
</tr>
<tr>
<td>Backorders for full packaging units at customer $c$ of local warehouse $s$ in period 1</td>
<td>$BP_{c,s}(1)$</td>
<td>0</td>
</tr>
<tr>
<td>Backorder cost per full packaging unit missing at customer $c$ of local warehouse $s$</td>
<td>$C_{B,c,s}$</td>
<td>€200 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit in the factory warehouse</td>
<td>$C_{D,E}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for disposing one packaging unit by warehouse $s$</td>
<td>$C_{D,s}$</td>
<td>€10 per packaging unit/period</td>
</tr>
<tr>
<td>Cost for buying one unit of an empty packaging material new</td>
<td>$C_N$</td>
<td>€1000</td>
</tr>
<tr>
<td>Cost for cleaning and repairing an empty packaging unit at the factory warehouse</td>
<td>$C_{R,E}$</td>
<td>€50 per packaging unit</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the factory warehouse</td>
<td>$IB_{max,E}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in local warehouse $s$, where $s$ = country A, B and D</td>
<td>$IB_{max,s}$</td>
<td>75</td>
</tr>
<tr>
<td>Maximum storage space for empty packaging materials in the local warehouse in Country C</td>
<td>$IB_{max,EU}$</td>
<td>25</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in the factory warehouse in period $t$. This on-hand inventory is measured at the beginning of period 1</td>
<td>$IB_E(1)$</td>
<td>1 ($=SB_E(t)$)</td>
</tr>
<tr>
<td>On-hand empty packaging inventory in local warehouse $s$ in period 1</td>
<td>$IB_s(1)$</td>
<td>1 ($=SB_s(t)$)</td>
</tr>
</tbody>
</table>
On-hand inventory of full packaging materials (i.e. packaging including a part) at customer $c$ of local warehouse $s$ in period $1$ \( IP_{c,s}(1) \) 0

On-hand inventory of full packaging materials (i.e. packaging including a part) in local warehouse $s$ in period $1$ \( IP_s(1) \) 0

Safety stock of empty packaging materials at the factory warehouse in period $t$ \( SB_E(t) \) 1

Safety stock of empty packaging materials at local warehouse $s$ in period $t$ \( SB_s(t) \) 1

Chargeable weight of the packaging material \( W_c \) 166.67 kg

Warehouse space occupied by the empty packaging material \( WS \) 1 m²

The demand patterns used for the sensitivity analysis of the customer demand is presented in Table A.13.

Table A.13 Input values for the different demand scenarios

<table>
<thead>
<tr>
<th>Period ( t )</th>
<th>Low ( DP_{c,s}(t) )</th>
<th>Medium ( DP_{c,s}(t) )</th>
<th>High ( DP_{c,s}(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t = 1 )</td>
<td>2</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>( t = 2 )</td>
<td>0</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>( t = 3 )</td>
<td>0</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>( t = 4 )</td>
<td>1</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>( t = 5 )</td>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>( t = 6 )</td>
<td>1</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>( t = 7 )</td>
<td>1</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>( t = 8 )</td>
<td>0</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>( t = 9 )</td>
<td>1</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>( t = 10 )</td>
<td>2</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>( t = 11 )</td>
<td>0</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>( t = 12 )</td>
<td>0</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>( t = 13 )</td>
<td>1</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>( t = 14 )</td>
<td>0</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>( t = 15 )</td>
<td>0</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>( t = 16 )</td>
<td>0</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>( t = 17 )</td>
<td>0</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>( t = 18 )</td>
<td>2</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>( t = 19 )</td>
<td>0</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>( t = 20 )</td>
<td>0</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>( t = 21 )</td>
<td>0</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>( t = 22 )</td>
<td>1</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>( t = 23 )</td>
<td>1</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>( t = 24 )</td>
<td>2</td>
<td>4</td>
<td>17</td>
</tr>
</tbody>
</table>

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