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Managing the reverse supply chain by outsourcing reconditioning activities to a Repair Captain

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Managing the reverse supply chain by outsourcing reconditioning activities to a Repair Captain

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A Master Thesis implemented at an electronics company

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Preface

This master thesis is conducted at a company to complete the master Operations Management and Logistics at Eindhoven University of Technology. Due to confidentiality reasons, the company remains anonymous and is called 'The Company'. This graduation project marks the end of my study, which I enjoyed. I would like to to show my gratitude to the people that supported me during this project.

First of all, I would like to thank my university professors Sonja Rohmer and Tarkan Tan for all the support and flexibility throughout the research. Additionally, I would like to thank PhD student Gizem Mullaoglu as well. All of you provided me with good feedback and you always shared your opinions with me. The bi-weekly supply chain students meetings were very much appreciated.

Moreover, I would like thank my company supervisors for their involvement and continuous feedback. This was especially valuable when working from home during covid-times. You made me feel welcome at the company and connected me with the right people. You always made some time available in your agenda's.

I would also like to thank my family and close friends for their support. I have met friends for life during my studies and I enjoyed some distraction with you. I also want to thank you for the good talks when needed. I also would like to thank my parents for their unconditional support and for encouraging me to follow my own path. Lastly, I would like to thank Maarten. I appreciate that you were always there for me, listening to all my research stories and making me comfortable during the stressful times. You made our 'home-office' a great place to end my studies.

Sifa van Zutphen, August 2021

Abstract

Design of the reverse supply chains, or more broadly closed-loop supply chain (CLSC) design has been the interest of researchers for a couple of decades now (see e.g.,Fleischmann et al. (1997), Inderfurth et al. (2001), Guide Jr et al. (2003), Savaskan and Van Wassenhove (2006)). However, companies still experience some challenges when implementing or improving the reverse supply chain these days. This master thesis provides a literature review on reverse supply chain management and challenges. Also the strategic decision-making in reverse supply chains is discussed. A new concept is introduced, namely the 'Repair Captainship'. This refers to the situation where reconditioning activities, such as repair and remanufacture operations, take place at a so-called Repair Captain. This captain is a firms' current supplier or other third-party, capable of reconditioning products that were not necessarily originally manufactured by the repair captain. Specifically the opportunities and limitations of outsourcing reconditioning activities to a Repair Capatin is investigated by means of a multi-criteria decision (MCDM) making model. Furthermore, possible economic and environmental implications of a Repair Captainship are modeled by means of an MCDM and Monte Carlo simulation. Lastly, supplier selection criteria are discussed to decide on the most suitable Repair Captain. Overall, several criteria are playing a role in the strategic decision-making whether to outsource reconditioning activities to a Repair Captain or not. Depending on performance assumptions, the MCDM model allows to compare several outsourcing strategies. The Repair Captainship has a positive influence on a firms' environmental footprint and can compete with OEMs' reconditioning costs, when the Captains' repair yield is increased.

Keywords: Reverse supply chain management, Repair Captainship, Repair Captain, CLSC, Outsourcing, MCDM, AHP, Monte Carlo simulation, reconditioning, supplier selection

Executive Summary

This master thesis provides insights on how to manage the reverse supply chain and includes a company implementation.. Due to confidentiality reasons, the company remains anonymous and is called 'The Company'. The main goal of this research is to investigate the possibility to outsource reconditioning activities to a so-called Repair Captain instead of to the original equipment manufacturers (OEMs). This can be interesting when OEMs have a limited global footprint or when they are less flexible to recondition closer to firms' customers. This Repair Captain would recondition products that were not necessarily originally manufactured by the Captain. To analyze the possibilities of this Repair Captainship, first the opportunities and limitations of applying this strategy are investigated. Afterwards, possible economic and environmental implications are analyzed. The concept is new in supply chain management and can be relevant for several firms in different industries.

Problem definition
This research addresses the problem that The Company experiences. The Company is outsourcing product reconditioning activities to its OEMs for the last years. However, The Company is doubting whether this reconditioning strategy is the most optimal reconditioning strategy for the upcoming years. The Company has a global footprint with warehouses, offices and customers all over the world. Most customers are located in Asia, whereas most of the OEMs are located in and around the Netherlands. The Company aims to facilitate the reconditioning activities close to the customers, but this is difficult with the OEMs being located in another continent. This makes one wonder whether assigning a firm as Repair Captain, who would recondition (most of) the returns locally, could be a good way to go. Therefore the following main research question is posed:

How could a firm determine whether it is beneficial to manage the reverse supply chain with a Repair Captainship strategy?

This question is split into the following sub-research questions:

1. *How are reverse supply chains managed, in terms of challenges and applied reconditioning strategies in the capital goods industry, according to literature?*
2. *How does the reverse supply chain look like in terms of the product return flow and challenges?*
3. *How to determine the opportunities and limitations of applying a Repair Captainship?*
4. *What are criteria, considering related risks, to decide on a suitable Repair Captain?*
5. *How to model the economic and environmental implications of a Repair Captainship strategy?*

Methodology
To answer the main research question and sub-research questions, two multi-criteria decision-making (MCDM) models were developed. Prior to the development of those models, a literature search was conducted to understand how reverse supply chains are managed. Moreover, semi-structured interviews were conducted to understand The Company's current reverse supply chain. After the interviews, the first MCDM model was developed, focusing on the opportunities and limitations of a Repair Captainship. The model enables to rank several products or product categories depending on the opportunities and limitations to outsource the reconditioning to a Repair Captain. The Analytic Hierarchy Process (AHP) method was used to determine criteria weights. Also a literature search was conducted to depict important Repair Captain selection criteria and related risks. The second MCDM model was built to analyze the economic and environmental implications of a Repair Captainship. This model was based on historical data and Monte Carlo

simulations. These Monte Carlo simulations allowed to incorporate uncertainty in the decision-making.

Results
Overall, the research results showed that product design and whether reuse is seen as core competence or not, appear to have a large influence on the selection of the reconditioning strategy. Moreover, six main challenges in the reverse supply chain are found from literature. These are variability (in demand, quantity, timing and volume of returned products), legislation, disposition decisions, transparency, coordination and awareness in the reverse supply chain. During interviews, certain challenges arose as well. Afterwards, the first MCDM model was developed. This model provides 18 criteria that influence the opportunity to outsource reconditioning activities to a Repair Captain. This MCDM is shown in Figure 0.1. The technical criteria appear to be highly important. Especially product design complexity appears to have a large influence on the opportunity to outsource reconditioning activities.

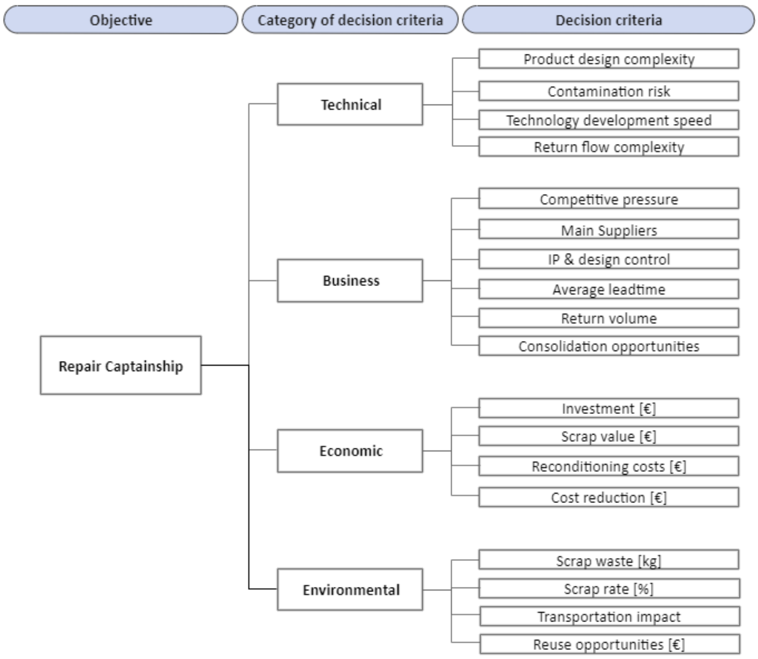

Figure 0.1: The MCDM structure of the product category selection for a Repair Captainship

After modeling the opportunities and limitations, also some attention is given on the selection of a Captain. The geographical location of a firm, compliance to protect IP & design, meeting delivery agreements and technical (repair) capabilities are the most important Repair Captain selection criteria. Besides these criteria, also some risks should be considered, namely operational risks, regulatory risks and political risks. Then, the second MCDM model compares the current reconditioning strategy (reconditioning at the OEMs) with two alternative Repair Captainships: one Repair Captain located in Korea, and one Repair Captain with repair facilities in Korea & Taiwan. The main economic indicator in the model is the average reconditioning cost per reconditioned product. This indicator includes transportation & duty costs, hidden costs and possible investment costs that a Captain could translate in the reconditioning price. Environmental indicators are the scrap rate among processed returns, scrap waste among all returns and the carbon emissions caused by transportation. Several scenario's were compared. First a base scenario was created for the Repair Captain, where assumptions were made based on the opinions of relevant The Company experts and scientific insights. Based on this base scenario, several other scenario's are created to reflect the economic and environmental implications of a Repair Captainship. Preference for a strategy depends on the given weight to economic and environmental implications. The MCDM allows to compare the strategies, where the strategy with the highest score is the optimal strategy. The resulting scores for the alternatives in the base scenario are shown in Figure 0.2.

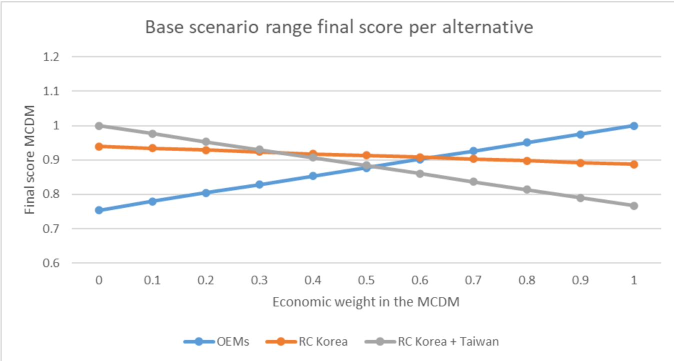

Figure 0.2: Final score of the three strategies in the base scenario

Conclusion and recommendations
The second MCDM model shows that the repair yield of a Repair Captain and the related transportation costs appear to influence the outsourcing decision-making the most. These costs appear to influence the decision-making more than the reconditioning costs of a potential Repair Captain or additional investments. In addition, by answering all five research questions, a firm can determine whether there is the opportunity to outsource reconditioning activities to a Repair Captain or not. Besides, two general recommendations a The Company specific recommendation are provided:

- *Use the provided flowchart to determine the long-term reconditioning strategy with regards to a Repair Captainship*
  If a company decides not to be involved with reconditioning, it will be difficult to regain back the aftermarket in the future. In the end, a long-term reconditioning strategy is also required to determine whether a Repair Captainship is beneficial at all. A flowchart (see Figure 8.1) was developed to support firms in the decision-making, whether to outsource reconditioning activities to the OEMs or to a Repair Captain.

- *Include additional environmental indicators to evaluate a reconditioning strategy*
  The environmental indicators are mainly focused on the scrap rate and waste and on CO_2 emissions caused by transportation. However, there are also other sources for emissions. The energy consumption could be included in the model in terms of carbon emissions. The difference in energy consumption (energy savings) between manufacturing and remanufacturing is about 85 %. Thus, it would be interesting to include these in the (environmental) performance evaluation of a Repair Captain and OEMs.

- *Consider to apply a Repair Captainship strategy and increase the Captains' repair yield*
  The Company should think about what it would like to achieve with regards to the reconditioning performance in the upcoming years. This would enable to balance economic and environmental implications. The Company has set ambitious sustainability targets, namely cutting the amount of waste per revenue by 50 % and working towards zero carbon emissions across all operations. Following these targets, it can be concluded that a Repair Captainship significantly lowers the environmental impact of The Company. The Captainship is expected to decrease the CO_2 emissions caused by transportation by 50 % to 60 %, depending on the implementation. In addition, it is recommended that The Company collaborates with the Repair Captain to improve the repair yield. This will make the Repair Captainship also from economic point of view the preferred reconditioning strategy.

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List of Abbreviations

Abbreviation	Description
OEM	Original equipment manufacturer
CLSC	Closed-Loop Supply Chain
AHP	Analytic Hierarchy Process
RL	Reverse logistics
3PL	Third-party logistics service provider
ANP	Analytic network process
RBV	Resource-based view
BSC	Balanced-scorecard
MCDM	Mutli-criteria decision-making
SAW	Simple additive weighted
LCA	Life cycle assesment
SPFT	Strategic Product family teams
IP	Intellectual property
R&D	Research and development
GHG	Greenhouse Gas Protocol
NTM	Network for transport and environment
MSE	Mean square error
MAPE	Measurement absolute percentage error
RMSE	Root mean square error
NOK	Not okay
WACC	Weighted average cost of capital
ROI	Return-on investment
RC	Repair Captain
EPM	Emission and pollution minimization
DES	Double exponential smoothing
BWM	Best-worst methodology
HW	Holt-Winters
RC	Repair Captain

1 Introduction

This chapter introduces the research topic. This research provides general scientific insights on a Repair Captainship and includes a company implementation as well. The company remains anonymous due to confidentially reasons. The names and data in this research are possibly adjusted. The electronics company will be called "The Company" in the this research. More about the company implementation is provided in Chapter 2.
First, the research motivation is provided to understand the practical and scientific relevance of this research. Second, the problem statement is provided. This problem statement is based on the management of reconditioning activities of "The Company". Though, the type of challenges that "The Company" experiences, could be generalized to other firms as well. Afterwards the research aim and thesis outline are discussed.

1.1 Motivation

Stock et al. (2010) identified some research opportunities in supply chain management. According to Stock et al. (2010), often in supply chains there appears to be a 'captain'. This captain is leading in eliminating waste and supports the management of a supply chain, though supply chain management researchers have not investigated this in further detail yet. In general, researchers focusing on conventional supply chain management might be hesitant to investigate new concepts (Guide Jr et al., 2003). In contrast, this master thesis research does address this 'captain' by analyzing the possibility of consolidating reconditioning activities at a Repair Captain.

This Repair Captainship strategy refers to outsourcing reconditioning activities to other third parties than the OEMs. Those other third parties could be current suppliers as well as any other external parties. These Repair Captains would be capable of reconditioning products that are not originally manufactured by themselves. This way of managing the repair/remanufacturing operations seems to have some similarities with the concept of 'category captainship', which has mainly been applied in the retail industry (Kurtuluş and Toktay, 2008). It also has some similarities with the concept of a 'channel captain', which has its origin in marketing management (Smith, 2006). Therefore, out of convenience, this new concept is called a "Repair Captainship".

Besides addressing a research opportunity in supply chain management, there are also other scientific and practical reasons for this research. First of all, it provides practical guidance. There are several actions and decisions to make to properly manage the reverse supply chain. Firms experience many challenges with regards to managing the reverse supply chain nowadays. Coordinating the reverse supply chain and deciding what to do with returned products appears to be one of those challenges (Gupta, 2013). In addition, Lau and Wang (2009) mentioned in their research that firms experience difficulties in selecting the appropriate parties for the reverse supply chain activities.

Second, investigating the economic and environmental implications of a Repair Captainship strategy provides practical guidance for firms and also result in new scientific insights. Most scientific contributions on the reverse supply chain did not focus on both the economical (performance) aspects and environmental (performance) aspects. Environmental aspects could be reducing waste or reducing carbon emissions caused by transportation. The scientific papers that do include both, are often relatively new (less than five years old) and the number of papers is still limited (Shaharudin et al., 2017; Sangwan, 2017; Kongar, 2004).

Third, this research will provide guidance in how to apply a Repair Captainship by providing selection criteria, to decide on the most suitable Repair Captains. The supplier selection criteria focus on criteria that are important for reconditioning activities. Now, most scientific papers that provide selection criteria do not consider current suppliers as possible captains for reconditioning (Gupta, 2013; Amin and Zhang, 2012).

Fourth, this research provides new scientific and practical insights on the position of suppliers in the reverse supply chain. Most scientific papers that focus on outsourcing reverse supply chain activities only consider the OEMs, using third party logistics service providers or another distribution partner for the execution of reconditioning activities (Shaharudin et al., 2014; Flapper et al., 2005b; Aghazadeh, 2003; Sink and Langley Jr, 1997).

1.2 Problem statement

The Company's strategy is to increase reconditioning and to enable local reconditioning, closer to its customers. However, the reconditioning of The Company's used service parts is outsourced to the OEMs in about 95% of the cases. These OEMs are mainly located in and around the Netherlands, whereas its largest customers are located in Asia. Very occasionally reconditioning is also done in-house. In-house reconditioning is then done at The Company's local repair centers in Korea and Taiwan. The number of defects that are reconditioned at the local repair centers will also not increase significantly in the upcoming five years, e.g. due to capacity and reconditioning capability constraints. Nonetheless The Company desires to increase the reconditioning and to increase local reconditioning. Preferably The Company would like their current suppliers, who are also located in Asia, to execute more reconditioning activities close to The Company's customers in Asia. But due to the low volumes, variability in the return volume and the investment requirements in tooling and test equipment, the current suppliers are not supporting reconditioning in Asia. This makes The Company wonder whether it would be feasible to consolidate certain product returns to one current supplier or other third-party. There is some variation in the (reconditioning) maturity of the OEMs and this makes The Company wonder whether some of the current suppliers could be leading in reconditioning product returns or if The Company could make a partnership with another third-party. For example certain electronic products, are already transferred between suppliers. So these suppliers are already becoming more mature and capable of reconditioning other products than manufactured by themselves.
Hence, this makes one wonder whether it would make sense, considering economic and environmental implications, to use certain suppliers or other third-parties for reconditioning activities as a Repair Captain. Nevertheless, The Company does not know what the impact of this specific reconditioning strategy is on the performance, in terms of economics and circular implications, of their reverse supply chains. Therefore they do not know whether they must proceed with the current reconditioning strategy for their SPFTs and product categories, or whether it would be reasonable to change their current strategy. This problem arises as The Company has set up a couple of sustainability targets for 2025 and they are figuring out how to meet these targets. One of these targets is to cut the amount of waste per revenue by 50% compared to 2019, by working closely with customers and suppliers, and they aim for zero carbon emissions across all operations.

1.3 Research aim

This research aims to answer the following main research question: *How could a firm determine whether it is beneficial to manage the reverse supply chain with a Repair Captainship strategy?* Therefore to meet the aim, a general understanding of the reverse supply chain is needed and current challenges are investigated. Besides, the opportunities and limitations to apply a Repair Captainship are identified. Lastly, the economic and environmental implications of a Repair Captainship are analyzed. More specifically, the impact of a Repair Captainship strategy is analyzed in terms of economics, risks and circular implications. Next, this research also aims to give direction on how to apply this strategy by providing selection criteria for a Repair Captain. Overall, this research aims to provide general recommendations with regards to the management of the reverse supply chain and to provide scientific insights on how to model the economic and environmental implications of a Repair Captainship. These recommendations could then be use full to The Company and other firms.

1.4 Thesis outline

This section discusses how this research is structured. Chapter 2 provides the research design which discusses the project scope, the research questions and briefly discusses the applied methodologies. Chapter 3 provides a theoretical background on reverse supply chain management, providing scientific insights on how other firms are managing the revers supply chain activities. Next, chapter 4, discusses the current return flow of defects, the current challenges and illustrates the return flow with a Repair Captain. This information is gathered via the company implementation. Chapter 5 discusses the opportunities and limitations of applying a Repair Captainship. During the company implementation, these opportunities and limitations are modeled for several type of product categories. This leads to the creation of a model that enables to rank product categories, based on the opportunities and limitations to apply a Repair Captainship. Then, chapter 6 provides a model that shows the economic and environmental implications of a Repair Captainship. Several possible Repair Captainship scenario's are compared against each other. Chapter 7 provides some directions on how to apply a Repair Captainship, also considering possible risks. Chapter 8 discusses the general conclusions of this research, including the recommendations and limitations.

2 Research Design

This chapter will first define a Repair Captain and briefly discuss reasons to apply a Repair Captainship strategy. Second, the project scope is provided to understand what is in and out of scope in this research. Third, the research questions and applied methodologies are discussed. Lastly, the company implementation is discussed.

2.1 Definition of a Repair Captain

A Repair Captain refers to a current supplier or other third-party who is capable of reconditioning products they originally manufactured themselves, but also to recondition products that were manufactured by others. This has benefits, risks and economic and circular implications. The repair captainship remains a new type of concept and scientific insights on the topic are limited. Though, Govindan et al. (2019) discussed some reasons for a firm to outsource reconditioning activities, namely:

- The geographical locations of a firm, e.g. if a firm is located close to The Company's customers and thus transportation costs might be decreased.
- The outstanding reconditioning capabilities of a firm, e.g. due to technology expertise, automated processes, usage of new innovative technologies, etcetera.
- The opportunity to consolidate more volume to make reconditioning more interesting (if volume is low, perhaps relatively more difficult and costly to recondition), e.g. perhaps similar products require similar tooling and expertise or when a firm is already manufacturing several type of products
- A firms' service capability, referring to the ability to provide additional services and its ability to be flexible in its attitude towards market changes.

Possibly the above mentioned reasons, could also be reasons for a firm to outsource reconditioning activities to a Repair Captain as well. Managing the reverse supply chain by outsourcing the reconditioning to a Repair Captain is also often called a 'Repair Captainship' in the remaining of this research.

2.2 Project scope

To understand the scope of this project, first the stages in the reverse supply chain are briefly discussed. The reverse supply chain consists of a couple of steps from acquiring returned or used products, transporting the used products, investigating what to do with the returned products (e.g., deciding to recondition or to scrap, etc.), to reconditioning the product (regain product value by means of e.g. repair, remanufacture, refurbishing) and placing the product back into the market (Guide Jr and Van Wassenhove, 2002). This research will investigate the economic and environmental implications that the new concept of a Repair Captainship can have on a certain part of the reverse supply chain. The focus lays on the reverse supply chain stages from 'Reverse logistics' until 'Reconditioning'. These stages are shown in Figure 2.1. The stages in scope are delineated.

Figure 2.1: The reverse supply chain stages, based on Guide Jr and Van Wassenhove (2002)

The Repair Captainship is, in terms of the reverse supply chain stages, a new reconditioning strategy, where reconditioning (e.g., repair/remanufacturing) is done at a certain Repair Captain. The Repair Captains refer to external third-parties or current suppliers who would be capable of reconditioning products from other manufacturers. This strategy would imply that a firm could outsource the reconditioning of products or product categories to a Repair Captain. Therefore, the reconditioning stage will directly be affected by the Repair Captainship strategy, but this could also have implications on the reverse logistics (transportation to the Repair Captain) and the inspection decision (scrap or not). Note that the collection of the used service parts and the remarketing of the used service parts are left out of scope. Though, to analyze the reverse supply chain it will be important to have some understanding of all these stages, including the stages that are left out of scope, before focusing only on a certain part of the chain. Note that with regards to the reconditioning options also recycling is left out. The focus lays mainly on reconditioning by repair or repair and upgrade activities.

2.3 Research questions and methodology

The research will follow the problem-solving methodology that is mentioned by Van Aken and Berends (2018). Their problem-solving cycle contains the following steps: identifying and defining the problem, analyzing the problem, identifying possible solutions, create possible solution designs, implementing the solution designs and evaluating the solution designs. Identification of the problem up to analyzing the problem is mainly done in the first part of this thesis, in chapter 3 and 4. Then, from chapter 5 to 7 possible solution directions and implementations are provided. Then, chapter 8 discusses the main conclusions. The main research question is stated as follows:

How could a firm determine whether it is beneficial to manage the reverse supply chain with a Repair Captainship strategy?

This main research question is answered by answering the sub-research question 1 to 5

1. *How are reverse supply chains managed, in terms of challenges and applied reconditioning strategies in the capital goods industry, according to literature?*
2. *How does the reverse supply chain look like in terms of the product return flow and challenges?*
3. *How to determine the opportunities and limitations of applying a Repair Captainship?*
4. *What are criteria, considering related risks, to decide on a suitable Repair Captain?*
5. *How to model the economic and environmental implications of a Repair Captainship strategy?*

The applied methodology to answer the sub-research questions is discussed per chapter. Chapter 3 answers sub-research question 1 and it is answered by means of a literature study. Chapter 4 answers sub-research question 2 and it is answered by means of open-ended interviews with The Company's experts involved in the reverse supply chain. Chapter 5 answers sub-research question 3 and it is answered by creating a multi-criteria decision-making (MCDM) model and applying the analytical hierarchy process (AHP). Chapter 6 answers research question 4 and the research question is answered by open-ended interviews, field notes and a literature search on supplier selection and risks. Lastly, Chapter 7 answers research question 5 and it is answered by creating a multi-criteria decision-making (MCDM) model, Monte Carlo simulations and scenario analysis. In each chapter the methodologies are explained in further detail.

2.4 Company implementation

This research aims to have both scientific and practical relevance as discussed in Section 1.1. Therefore, the scientific findings are implemented in a large electronics company. This company implementation allows to provide practical insights and to compare the scientific results with practical expectations. To answer sub-research question 2 to 5, scientific findings are implemented at The Company. As mentioned earlier, the company remains anonymous. Though some contextual background is provided. First the company is introduced. Afterwards, the company stakeholders are discussed.

2.4.1 Company description

The Company is a large electronics company that provides electronic machines to its customers. The Company is focused on assembling electronic systems. They order their electronics from other manufacturers, so-called original equipment manufacturers (OEMs). The company is located in multiple countries and its headquarters are in the Netherlands. The Company has local warehouses close to their customers. These warehouses keep electronic parts on-stock. The downtime costs of the electronic machines are very costly. This explains the need for local warehouses close by the customers. The global warehouses are in the Netherlands, the United States and in Taiwan. The Company has divided their product portfolio in several strategic families of service parts (SPFTs). The SPFTs represent several product categories, like PCBA's, Racks & Cabinets, Cables and more.

2.4.2 Company stakeholders

The company stakeholders involved in the reverse supply chain represent two departments within The Company. These are the Sourcing & Procurement department and the Reuse department. The Sourcing & Procurement department focuses on implementing the sourcing strategy, preparing make/buy decisions, driving strategy development, guiding sourcing decisions and scouting of technologies, suppliers and innovation. Then the Reuse department. This department consists of people with different backgrounds and experiences, coming from different departments. They are working closely together and their mission is as follows: *"Drive and own re-use of parts, tools & packaging materials to accelerate learning, reduce costs and eliminate waste, collectively contributing to The Company's circular economy & sustainability goals"*. Next to this, this department aims to:

- organize, deploy and execute reuse policies
- be responsible for re-use targets, both short and long term targets
- ensure that re-use is embedded in The Company and to run the re-use business

One of the company supervisors is part of the Reuse department and has a background in sourcing & procurement. The other supervisor is part of the sourcing & procurement department. This research will be of value for both of the previously mentioned departments.

3 Theoretical background of reverse supply chain management

This chapter provides theoretical background on reverse supply chain management. First the definition of a reverse supply chain, its relation with the closed-loop supply chain (CLSC) and its challenges are discussed. Second, scientific insights are given on the management of the reverse supply chain by other firms in the capital goods industry. Third, a framework is presented that shows the interaction between product design and whether reconditioning is seen as core competency or not. Besides, three CLCS strategies are discussed. Lastly, a short discussion is provided that concludes this chapter. This literature review answers sub-research question 1:

How are reverse supply chains managed, in terms of challenges and applied reconditioning strategies in the capital goods industry, according to literature?

3.1 Definition of reverse supply chains

This section discusses the definition of reverse supply chains and the concept of a CLCS. According to the content analysis of reverse logistics issues created by De Brito and Dekker (2004) the concept of reverse supply chains is already known for a couple of years now. However, the concept is still relatively new and therefore the concept is mentioned in several ways, such as Reversed Logistics, Return flow and Return logistics (De Brito and Dekker, 2004). Some of these definitions are provided in section.

In the nineties, the Council of Logistics Management defined and discussed the term Revere Logistics (RL). This is done by Stock (1992). Stock (1992) takes a broad perspective on the role of logistics on handling issues such as waste pollution and resource scarcity. Next to recycling, reconditioning and source reduction are part of RL. By the end of the nineties, Rogers and Tibben-Lembke (1998) presented a book that provides an overview and introduction to RL. Their definition takes, similar to the work of Stock (1992), a broader perspective on the logistic activities to recover the value of products. Rogers and Tibben-Lembke (1998) define RL as follows: *"The process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal"*.

In the twenty-first century, Guide Jr and Van Wassenhove (2002) also mention the concept of RL, but according to them RL are activities that are part of reverse supply chains. They refer to reverse supply chains as series of activities that are required to retrieve products from a customer to either recover value or to dispose these products. Their research mentions that there are several activities or stages of which a reverse supply chain consists. According to them the first stage is 'product acquisition' and this includes activities related to retrieving the used product. The reverse supply chain ends with the fifth stage, 'distribution and sales', that includes activities related to the re-positioning of the recovered product in the market. The second stage of the reverse supply chain is then called 'RL' (Guide Jr and Van Wassenhove, 2002). In comparison to previous mentioned research (see Stock (1992); Rogers and Tibben-Lembke (1998)), they refer to RL as the transportation of products to inspection facilities, before the inspection, sorting and disposition of products takes place. Thus, Guide Jr and Van Wassenhove (2002) define RL less broadly and present the broader picture by means of the reverse supply chain instead. While analyzing this, the definition given by Rogers and Tibben-Lembke (1998) of RL seems to be more similar to Guide Jr and Van Wassenhove (2002) their definition of reverse supply chains.

Later, the research of Prahinski and Kocabasoglu (2006) also provides a definition of RL given by, among others, Rogers and Tibben-Lembke (1998) and Stock (1992), that is quite similar to their definition of reverse supply chains. Thus, as already mentioned, definitions of RL and reverse

supply chains might overlap or refer to the same (De Brito and Dekker, 2004).
When talking about the reverse supply chain also the concept of the closed-loop supply chain (CLSC) is often mentioned. The CLSC considers simultaneously the forward or traditional supply chain and the reverse supply chain (Govindan et al., 2015). According to Govindan et al. (2015) the reverse supply chain starts from the end-users and aims to manage or extend the end-of-life (EOL) of a product through different decisions. This CLSC, network of forward and reverse supply chain, is also visualized by (Flapper et al., 2005b). This visualization of the forward and reverse supply chain is shown in Figure 3.1.

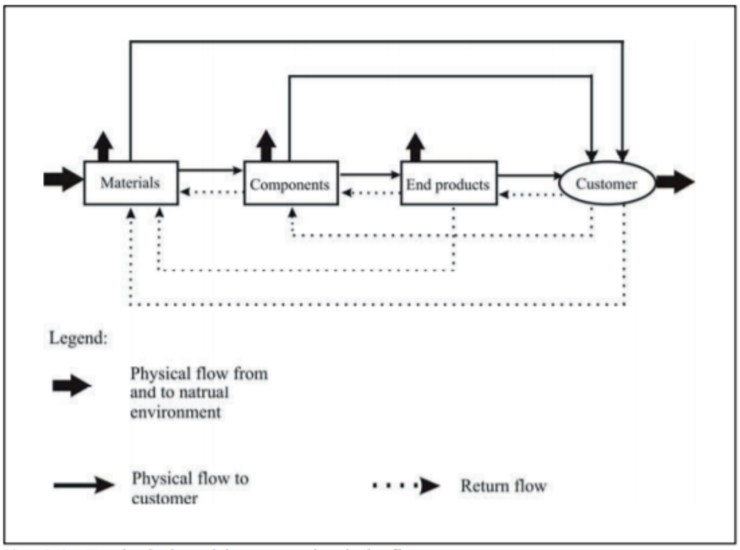


Figure 3.1: Visualization of the closed-loop supply chain by Flapper et al. (2005b)

3.2 Challenges in reverse supply chains

This subsection discusses the scientific papers that provide insights on the challenges of reverse supply chains. First a short discussion is given on the insights of the scientific papers. Second the challenges are shortly described and Table 3.1 shows per paper which challenges are mentioned.
Gupta (2013) classified the challenges of reverse supply chains into five categories, namely: returns related; process, recovery, and technology related; network design and coordination related; regulatory and sustainability related; and cost-benefit related. The most challenging challenges are briefly discussed here. One of them is the unpredictability and variability in supply and demand in reverse supply chains. Apparently firms face this as greatest challenge; to predict and control the quantity, quality and timing of the returned products. Besides, coordinating both the forward and reverse supply chain and the disposition task (what to do with the returned products) are major challenges. Next, traceability through the reverse supply chain appears to be important to control risks and create transparency, but this remains challenging. To create transparency, information technology infrastructure is required to trace product returns through the supply chain. Legislation also appears to have impact on the reverse supply chain as it could lead to increased interest in reverse supply chain activities. Here, legislation refers to enforcing that firms take back products or materials to recover its value. Though the lack of legislation also appears to be a barrier to reverse supply chains in some countries. Lastly, awareness appears one of the biggest challenges. There can be a lack of internal (by the top management) and external (by possible consumers) awareness for the need for reverse supply chains (Gupta, 2013).
In the late nineties, the work of Thierry et al. (1995) and Rogers and Tibben-Lembke (1998) already mentioned all these challenges mentioned by Gupta (2013). Gupta (2013) also used the work of Thierry et al. (1995) and Rogers and Tibben-Lembke (1998) as sources. The challenges

identified by Rogers and Tibben-Lembke (1998) were based on practical insights of 300 research respondents, such as suppliers, customers and competitors of a third-party logistics service provider specialized in RL. Also scientific researchers and the RL Executive Council took part in the research. Thierry et al. (1995) also included practical insights in their research by means of a case study at a multinational copier manufacturer. Thus the challenges were based on both scientific and practical perspective. However, the practical insights are from the late nineties. Perhaps firms are experiencing new challenges these days. Fleischmann et al. (1997) refers to variability and uncertainty in the reverse supply chain, disposition task and coordination problem in a similar manner as mentioned by Gupta (2013). This is not strange as Gupta (2013) also uses the work of Fleischmann et al. (1997) as source.
Next, the work of Guide Jr et al. (2003) mentions the challenges of variability, legislation and coordination. Abbey and Guide Jr (2018) mention the same challenges, which could be explained by the fact that both papers are partially written by the same author. In comparison to the other papers, Guide Jr et al. (2003) also mention future challenges such as increased global competition among firms and shorter product life cycles. Where Gupta (2013) mentions the lack of legislation as a challenge, Abbey and Guide Jr (2018); Guide Jr et al. (2003) mention that legislative pressures make it difficult to configure a reverse supply chain. The legislative pressures can lead to increased costs and even increased environmental impact. So, on the one hand, there can be a lack of legislative pressure, but on the other hand managing the reverse supply chain in such a way that it meets the legislative pressure can be challenging as well.
Lastly, also Souza (2013) mentions challenges of the reverse supply chain. This research makes the distinction between strategic, tactical, and operational issues or challenges. This is different compared to the classification that Gupta (2013) made. Though, when referring to for example the tactical issues, Souza (2013) determines that most of the tactical issues are related to product acquisition, returns and disposition. This is similar to the challenges that are classified as return related by Gupta (2013), only Souza (2013) emphasises more on the tactical character of these issues. Also, in contrast to the other papers mentioning legislation as a challenge, Souza (2013) refers to specific 'take-back' legislation. According to Souza (2013), take-back legislation holds manufacturers both financially and physically responsible for collecting used products at the end of their life cycle, and to dispose these products in an environmentally friendly way. With regards to variability and disposition the challenges are similarly described as described by Gupta (2013).
Now that the main challenges are discussed in this section, these are also briefly summarized and Table 4.1 indicates to which challenges each paper refers.

- Variability: Uncertainty in quantity, quality, timing and volume of product returns are often unknown and hard to influence resulting in variability.
- Legislation: Legislative pressures or the lack of legislative rules and laws supporting the reverse supply chain activities.
- Disposition: Deciding on the appropriate disposition strategy when items or components are returned by (end) customers and in which quantities they arrive.
- Transparency: Information technology infrastructure is important to get accurate insights on the number of returned products and time and to trace products in the reverse supply chain.
- Coordination: Coordinating two markets simultaneously (forward and reverse supply chain).
- Awareness: Lack of awareness for the need for Reverse supply chains by the public or management.

Table 3.1: Overview challenges in reverse supply chains

	Variability	Legislation	Disposition	Transparancy	Coordination	Awareness
Gupta (2013)	*	*	*	*	*	*
Guide Jr et al. (2003)	*	*			*	
Abbey and Guide Jr (2018)	*	*			*	
Fleischmann et al. (1997)	*		*		*	
Thierry et al. (1995)	*	*	*	*	*	*
Rogers and Tibben-Lembke (1998)	*	*	*	*	*	*
Souza (2013)	*	*	*			

3.3 Reverse supply chain management in the capital goods industry

This section discusses the main characteristics and practices applied within the capital goods industry. The focus lays on the aerospace, automotive and healthcare industry. Per industry first the main characteristics of the aftermarket are discussed. Phelan et al. (2000) define aftermarket support as follows: *"Aftermarket support refers to activities associated with products (e.g. spare parts) and services (e.g. engine overhauls) after initial sale of a product."*. Besides, a strategic framework is shown and discussed that can support firms in their reverse supply chain management decisions. Note that this investigation of industry practices in the capital goods industry is conducted in collaboration with Martha Maldonado Murillo (master student Operations Management & Logistics at the TU/e and also a graduate intern at The Company). Separate thesis reports are written, but the scientific sources are similar.

3.3.1 Aerospace

The aerospace or aircraft industry is characterized by a couple of things. First of all, this industry is led by a few firms or remaining giants as mentioned by Pattillo (2001) about the US aircraft industry. Second, the aerospace industry is highly regulated and good safety and performance are the main concerns. This could hold back aircraft manufacturers to apply recovery processes, such as remanufacturing (Hashemi et al., 2014). Though on the other hand, Hashemi et al. (2014, 2016) state that the aerospace industry also experiences high prices for raw materials and has low tolerance for manufactured components that cause relatively many defects, making it more interesting to remanufacture certain components. According to Hashemi et al. (2014), some components may even have longer life cycles after remanufacturing and this is among others the case for remanufactured landing gear tires. Besides, Lorentz et al. (2011) mention that the life cycle of products in the aerospace sector are long, leading to more opportunities in the after-sales market. Specifically the aerospace aftermarket is also characterized by a large number of service parts and customers worldwide, low failure rates and very tight response times. There are also several service centers around the globe and each part has a base stock policy at each warehouse. The response time is often kept low and under a certain threshold, to control the service quality (Lorentz et al., 2011).
The strategic option for repair and remanufacturing that airlines can make is either to perform the repairs in-house (having own repair facilities and personnel) or to outsource the repairs to third parties (Drury et al., 2010). According to Drury et al. (2010), a report by the Federal Aviation Administration (2003) indicated that the outsourced maintenance by major airlines in the United States increased from 37% in 1996 to 47% in 2003. The maintenance was outsourced to both foreign and domestic repair facilities. Also McFadden and Worrells (2012) discuss this evolution

in their research. In the past, airlines had their own repair or maintenance facilities, but now the competitive pressure has increased. Airlines have to offer lower prices and at the same time low cost maintenance is preferred. To decrease the costs, outsourcing of the repair services has increased (McFadden and Worrells, 2012).

3.3.2 Healthcare

The healthcare industry is an important and competitive industry, where people's lifes are at stake. This industry also has direct and indirect effects on the economy and politics. The health care expenditure increased drastically (with about 60 percent) globally over the years (Komenkul and Kiranand, 2017). Thus, implementation of reverse supply chain activities by this industry can be of large impact. It could reduce prices in the healthcare industry and these savings could enable to save more lives (Yazdi et al., 2020). Also important to know is that most supply of and demand for used medical equipment are in Western Europe, the USA and Japan (Jensen et al., 2019). According to Jensen et al. (2019), medical devices experience fast technological innovation, which leads to frequent replacements of systems. This results in a large number of pre-owned equipment that return on the medical device market.
With regards to Philips Healthcare Refurbished Systems, a large number of used medical devices is either remanufactured by the original equipment manufacturer (OEM) or it is bought by third party brokers. When medical devices are sent back to Philips RS for remanufacturing, then also their OEMs are involved, because they have the appropriate knowledge of the technology and they have the process capacities. So multiple times certain parts of the used medical devices are transferred between the supplier of the medical devices and their OEMs in this case (Jensen et al., 2019).

3.3.3 Automotive

Similar to the aerospace industry, also the automotive industry is characterized by multiple service parts and customers (Lorentz et al., 2011). Parts have low failure rates and due to the value of materials as steel and other components the automobile industry is relatively advanced in recycling (Subramoniam et al., 2009). Bedsides, the growing awareness for sustainability is one of the reasons that the automotive industry is also focused on practices such as remanufacturing (Subramoniam et al., 2009). The automobile industry consists of the OEMs that are mainly focused on the vehicle assembly and marketing, but most automobile dealers are also offering certain repair services. There is also an aftermarket, which is mainly focused on offering repair services. These could be all kinds of independent parties, such as remanufacturers and gas stations. In the automotive industry the intent is to offer these repair services on several locations and in several businesses (Daugherty et al., 2003). This industry has applied a couple of interesting things that improve their repair services.
First of all, large car-manufacturers such as Volvo, Saab and BMW redesigned their cars in such a manner that components could be dismantled more efficiently (Kumar and Putnam, 2008). Second, car-manufacturer Mercedes-Benz offers their customers the opportunity to replace broken engines by remanufactured engines during a period of 20 years. These remanufactured engines meet the same quality requirements as the new ones and they are cheaper. Mercedes-Benz does this also for other parts such as water-pumps Flapper et al. (2005a). Third, Toyota increases their supply chain management gains by continuously investing in their suppliers (Crook and Combs, 2007). Lastly, the automotive aftermarket experiences third party involvement for quite some time now. Some firms, such as Ford, have tried to focus more on aftermarket support as well, but the third parties have already strong control on the aftermarket. It appears difficult to enter this market, when several third parties have control on the product collection in the aftermarket Abbey and Guide (2017). Auto-manufacturer Renault even chooses to make use of independent third parties to meet their circularity objectives. After all, the European Union is leading in implementing different regulations targeting producers to take their responsibilities, such as the End-of-Life Vehicles Directive (ELV). Sometimes car-manufacturers are forced to cooperate with

end-of-life third parties to meet their reuse targets (Kumar and Putnam, 2008).

3.4 A strategic framework for reverse supply chain management

The several industries such as the automotive, healthcare and aerospace industry all have their own characteristics and different ways of improving their aftermarket support. Where the automotive industry is faced with regulations due to sustainability awareness, the healthcare and aerospace industry are more focused on repair activities to reduce costs. Though in the strategic decision-making, managers should also consider the lifetime of products Abbey and Guide (2017). Even if the goal is to minimize waste and focus more on CLCS operations, there will always be some waste. Some parts have only multiple lifecycles or just one single lifetime. Therefore, designing for multiple lifecycles can have many positive effects, such as improving the CLSC operations by easier repairability and reduced returns or failure rates (Abbey and Guide, 2017). This interaction between the design of products and CLSC operations as core competencies seems to affect the reconditioning strategy. This product design appears to have influence on the product acquisition management, on the reuse management, RL and on the nature of the aftermarket. Furthermore, design has influence on the reuse opportunities of products, but also on part and component level. This interaction between design and reuse is illustrated in a framework created by Abbey and Guide (2017) in Figure 3.2.

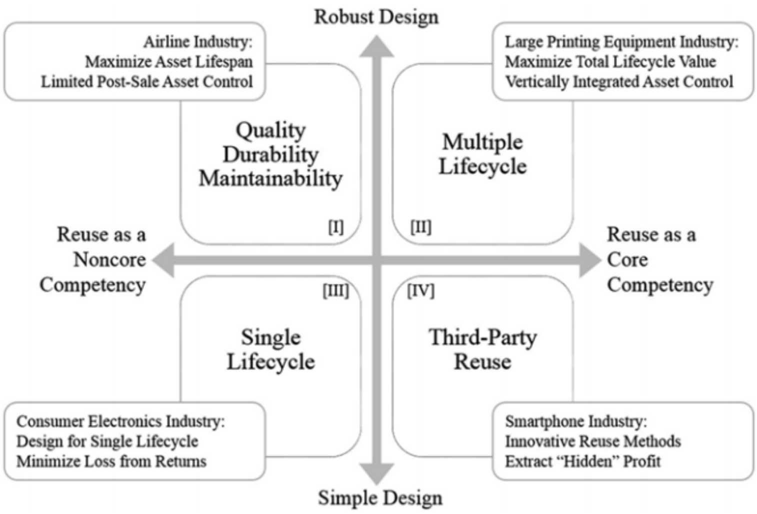


Figure 3.2: Design and core competencies framework for reuse established by Abbey and Guide (2017)

As shown in 3.2, the strategic framework developed by Abbey and Guide (2017) is split into 4 quadrants. The first quadrant focuses on high-value, business-to-business products. The OEMs sell products, but the aftermarket support for these products tends to be limited. The firms in this quadrant have reuse as a noncore competency and the products have a robust design. The second quadrant focuses on high-value business-to-business products as well. In contrast to the first quadrant, OEMs are designing the products for multiple lifecycles. This quadrant has tight control on its products and reuse is perceived as a core competency. In the third quadrant OEMs focus on high-value products that are built for a single life cycle only. The firms maximize profits by simple designs and they aim to prevent any product returns. Nevertheless, this strategy results in large waste streams and due to legislative pressure also these firms could be forced to focus on product, component or material returns. Then, the fourth quadrant shows how OEMs can lose profits to third parties. The OEMs could lack interest to focus on reuse, which leads to third parties entering the aftermarket. The OEM perceives reuse as non-core competence and this leads to competition in the market (Abbey and Guide, 2017).

3.5 Vertically, hybrid and outsourced closed loop supply chains

Next to the presented framework (Figure 3.2), Abbey and Guide (2017) also discussed three ways of managing the CLSCs. They vary from complete outsourcing to pure in-house reconditioning of activities. First there is the vertically integrated CLSC strategy, implying that the firm has complete control over the forward and reverse supply chain. Second, there is the outsourcing CLSC strategy. In general, if a firm is not manufacturing, remanufacturing is also not done easily. The firm will then cooperate with another third party who would be responsible for the remanufacturing. The OEM has then minimal control on the remanufacturing operations, for example by providing performance specifications only. The fully outsourced CLSC performance is only in a few cases performing similar to the vertically integrated and hybrid CLSC. The hybrid CLSC focuses on the core competences of a firm. Depending on its core competences the firm can decide to outsource certain reconditioning activities or not. Certain products are reconditioned internally, whereas the less complex products or less profitable products are reconditioned externally. Though, the firm should keep in mind that current core competencies could change. This hybrid strategy is most often applied and balances outsourcing and in house reconditioning. Overall, there is not one strategy that is the best. There are multiple trade-offs and aspects to take into consideration when choosing the desired reconditioning strategy (Abbey and Guide, 2017). The trade-offs and aspects to consider for a Repair Captainship are discussed in Chapter 5.

3.6 Discussion: reverse supply chains in the capital goods industry

This chapter started with the question: *How are reverse supply chains managed, in terms of challenges and applied reconditioning strategies in the capital goods industry, according to literature?* The answer on this question appears not to be one single answer. Per industry the type of products may differ. Based on the framework of Abbey and Guide (2017) the conclusion can be made that how a firm designs its products and the level of control that a firm exercises on reuse are influencing the management of the reverse supply chain. In the aerospace industry, aircraft manufacturers are not interested in providing aftermarket support. There, third parties are providing the support. Also in the automotive industry, third parties are playing an important role. Certain firms are choosing to cooperate with other third parties to meet sustainability targets and legislative pressure, whereas others would prefer to gain back the aftermarket. Next, there are also firms that are trying to keep the CLSC vertically integrated. Though it should be kept in mind that even in a vertically integrated supply chain still some parts or sources are sourced externally Abbey and Guide (2017). The hybrid CLSC appears to be applied most often and properly balancing insourced and outsourced activities is crucial (Abbey and Guide, 2017). Thus, depending on the interaction between product design and reuse as core competency or not, the reverse supply chain is managed differently. Overall, answering this research question allows to compare scientific findings with practical insights in the upcoming chapters.

4 The reverse supply chain

This chapter discusses the reverse supply chain, to have an understanding of the current processes and challenges. A scientific introduction to the concept of a reverse supply chain is already discussed in Chapter 3, therefore this chapter will not repeat that information. This chapter provides the company implementation of the return flow understanding. First the applied research methodology is discussed to represent the return flow and to understand challenges that a firm can experience in its return flow. Second, the methodology is applied at The Company. So, The Company's current return flow of products is discussed and visually represented. This return flow focuses only on products that failed at The Company's customers and not in one of their factories. A detailed and a short version of the return flow are presented in Figure 4.1 and 4.2. Third, current challenges in The Company's return flow are discussed. Lastly, potential changes in the return flow are discussed in case that a Repair Captainship would be applied. In conclusion, this chapter answers sub-research question 2:

How does the reverse supply chain look like in terms of the product return flow and challenges?

4.1 Methodology

To identify and visualize a firm's reverse supply chain, in-depth interviews are conducted and field notes are made at The Company. These are qualitative data collection methods that aim to discover the property of objects, people and events (Van Aken and Berends, 2018). During the open-ended interviews the interviewer can ask follow-up questions to obtain a better understanding of the answers of a respondent. Questions are prepared beforehand, but there is also some flexibility. Interview questions that are raised spontaneously can be asked during the interview as well (Legard et al., 2003). The open-ended interviews required to prepare interview questions and to determine the required interview respondents. The main experts involved in the reverse supply chain decision-making were selected. These were experts from the Reuse department involved in the logistics and in-house local repair centers, the company supervisors and a The Company expert who is involved in optimizing The Company's return flow. Transcripts of the interviews were made in collaboration with Martha Maldonado Murillo (master student Operations Management & Logistics at the TU/e and also graduate intern for The Company). Together, the main conclusions were extracted and discussed with the interview respondents and other experts within The Company to validate the conclusions. Then, the field notes. Field notes are useful to construct descriptions of a study context, gathering, interview or any focus group (Phillippi and Lauderdale, 2018). Notes were made after two to three important gatherings focusing on the efficiency of the return flow. Experts from several departments were involved in the discussions regarding inefficiencies in the reverse supply chain. The collection of the field notes required some preparation by preparing questions and hypothesis. Based on talks and interviews with The Company experts, a hypothesis could be: "There is a large backlog of defect products, due to the lack of standardized reconditioning agreements or proper forecasts of reconditioning demand". During the meetings, notes were made related to these hypotheses to evaluate the expectations, or to discover new challenges in the reverse supply chain. Any conclusions from the interviews and field notes were always evaluated with The Company experts.

4.2 The Company's current return flow of field service defects

To obtain an understanding of The Company's current return flow, several experts were consulted. The Company's return flow is visualized in Figure 4.1. This figure is created in collaboration with Martha Maldonado Murillo (master student Operations Management & Logistics at the TU/e and also graduate intern for The Company). Besides, the return flow is discussed in further detail below.

4.2.1 A detailed representation of The Company's return flow

Whenever there is a system failure at the customer, a field service engineer from The Company will visit the customer. So, mainly breakdown corrective maintenance is done, implying that a defect product is only removed when it has failed (Arts, 2014). The engineer will make a diagnosis of the problem, take the defects out of the machines in the customers cleanroom and replace these defects. This is done as fast as possible, while downtime (time that the machines are not running) can be very costly for capital electronic assets. These defect products are usually entire electronic modules or sub-modules. Thus, sometimes these modules can include components that are not broken at all, but due to limited resources to repair the specific broken components in the cleanrooms, also some well-functioning components will be taken out. Then the defect products are directly packaged in the cleanroom, to prevent any contamination of the service parts. Next to this, customers want to prevent that any internal information about their electronic systems become public, therefore some IP/security checks are done after which the defect products are transported to a The Company's local warehouse nearby. There a first triage procedure takes place. This is fully automated, where a computer system decides to recondition the used service parts or not. The algorithm behind the triage decision is based on certain thresholds (original costs versus transportation costs, whether there is demand for the service parts etcetera.). Usually there is no physical test of the condition of the service parts and the processing decision is based on the computer algorithm. When the triage decides to recondition the value of defects, the defects are sent from the local warehouses to one of The Company's global warehouses, also called central warehouses. The defect products are usually sent to the global warehouse which is located closest to the reconditioning location (e.g. to the OEMs or The Company's in-house repair facilities). As most of the OEMs are located in and around the Netherlands, about 80 % of the returned defects are sent for reconditioning via the central warehouse in the Netherlands. The remaining 20 % is sent via the global warehouses in the United States and Taiwan. When the defect products are booked and received by the central warehouse, the defects are sent to the OEMs for diagnosis and inspection. These service parts are sent to the OEMs in 95 % of the cases. For a limited part of the product portfolio, products are reconditioned at an in-house facility. After the inspection is executed by the OEMs, The Company and the OEMs discuss the reconditioning terms (e.g. costs of the reconditioning, duration and the number of defects that can be repaired). This, so-called root cause analysis of the defect takes approximately 21 days. When The Company agrees to the terms of the The Company, the OEM will start the reconditioning process (actual reconditioning of the service part and packaging of the parts), taking on average a couple of days. After that, the OEM notifies The Company that the service parts are reconditioned. The Company will then collect the reconditioned products at the OEMs facilities. From there, the products are sent back, via the central warehouse, to the local warehouses again.

In addition, all the transportation of the defects and reconditioned products is executed by 3PLs. The transportation between the customers and local warehouses is usually done via road. The transportation between the local warehouses and global warehouses is usually done via air freight, as international transportation is required. The defects are not transported individually. In general, the defects are only sent from local warehouses to the central warehouses when an entire container or other size transportation box is filled. Thus this would imply that if a defect comes in at time $t = 0$, the defect will wait in the defect inventory until the container is full at time T, which equals the total waiting time until a container is filled. This waiting time can go up to 90 days for a defect that enters the defect inventory as first. Next, the lead time from the moment that a defect product is taken out of the customers' system until the defect product is reconditioned succesfully takes on average 119 days. As mentioned, already quite some time could be spent waiting in defect inventory at the local warehouses. Then, there is some transportation time. When arrived at the central warehouses, there is also some waiting time as the OEMs and The Company have to align on the reconditioning costs and other agreements. Afterwards The Company has to make sure that the reconditioned products are collected. Lastly, all the product disposition or scrap is executed by external 3PLs specialized in waste management.

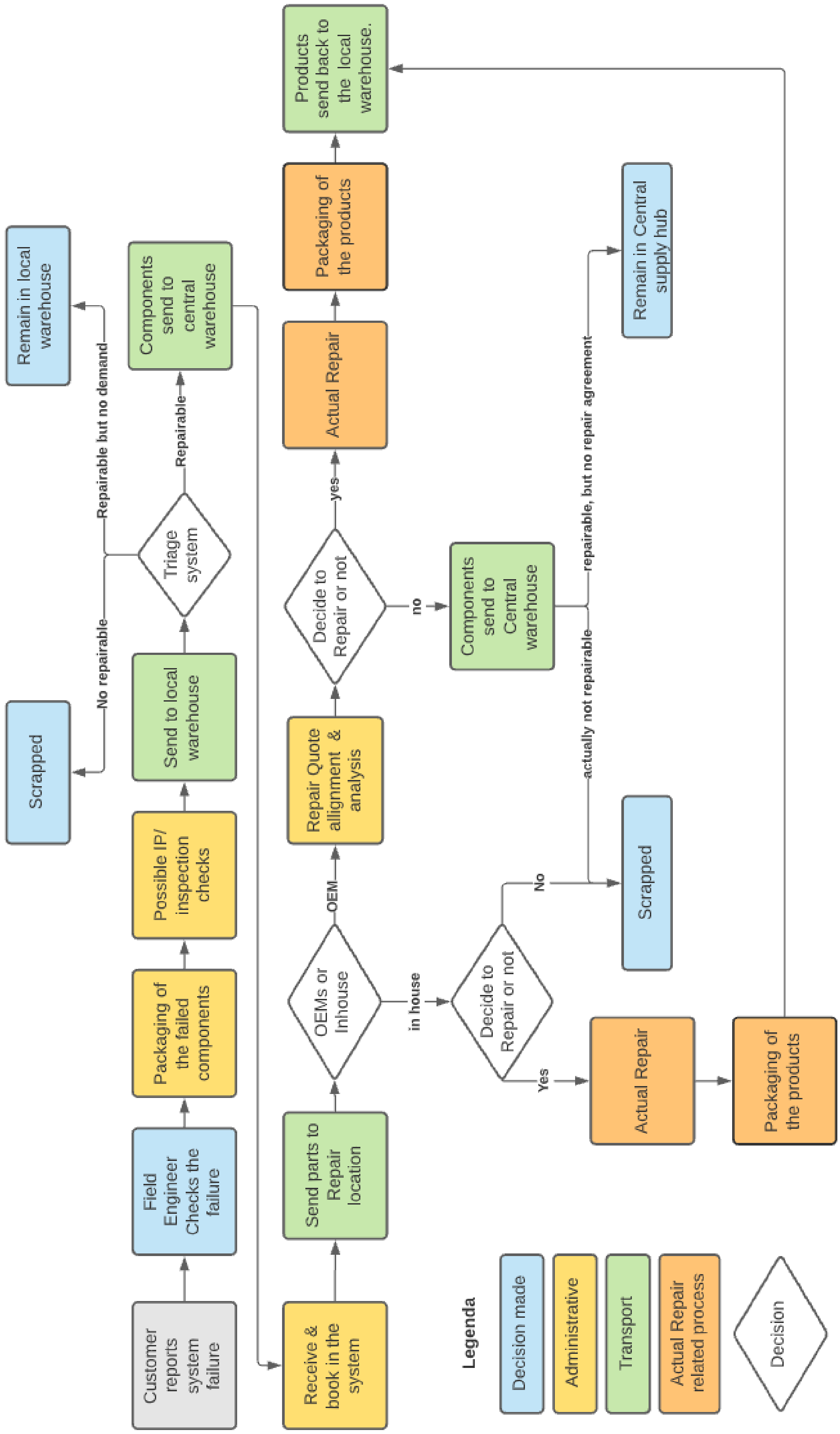


Figure 4.1: A detailed visualization of the return flow

4.2.2 A short representation of the return flow

The return flow is also visualized in less detail, in Figure 4.2. As you can see, the defects are sent from the customer to the nearest local warehouse. Then from the local warehouse to the central warehouse, which is closest to the OEMs or other reconditioning location. Within the return flow, parts can be either scrapped via the local warehouses or via the central warehouses. Then, when a product is successfully reconditioned, the products are sent back into the flow. Thus, the reconditioned parts are sent from the reconditioning location back to the nearest central warehouse. From the central warehouse the parts are sent to be kept on stock to the desired local warehouses (e.g. where there is demand for the specific parts). Specifically in the context of The Company, this research focuses on the reverse logistics, after the defects are collected by the field service engineer, until the defects are reconditioned and sent back to the local warehouses. So how the used service parts are collected and how the remarketing (replacement of the service parts at customers) is done, is left out of scope. Now that the return flow is explained, current challenges in the reverse supply chain can be discussed.

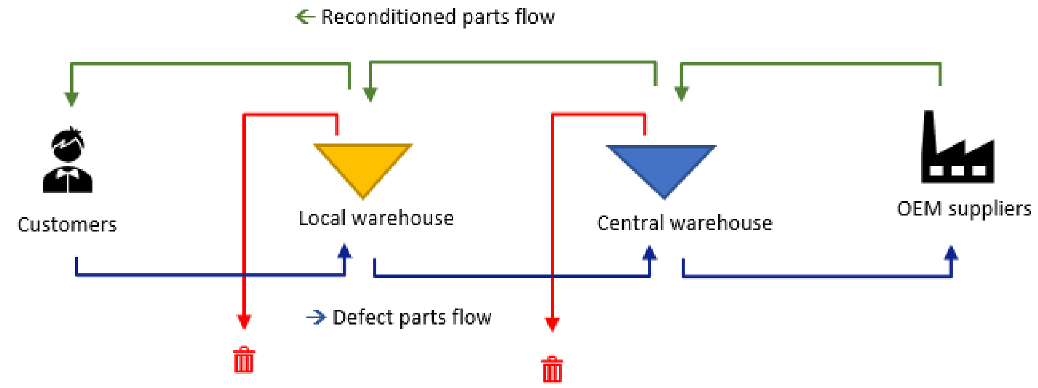


Figure 4.2: The return flow

4.3 Current challenges in the reverse supply chain

This section summarizes a couple of main challenges that The Company experiences in the reverse supply chain. These are challenges that The Company's experts, such as supply chain managers and people from the Reuse department, experience. Besides, these challenges are also related to challenges mentioned in Chapter 3. Thus, The Company is experiencing similar challenges as other firms experience in the reverse supply chain. The five main challenges are as follows:

Challenge 1: No physical analysis of the 'defects' at the local warehouses
The first challenge is that The Company is not able to do a first analysis when the defect products are arriving at the local warehouses. A first analysis would require to have skilled repair technicians that can analyse the products and this would also require to have cleanrooms (to prevent product contamination) in the local warehouses. Often both of these requirements are not met in the local warehouses. Defect products are then sent via the central warehouses to the suppliers without even taking the products out of the package. Then, sometimes suppliers can discover that certain products were not even defect at all. Thus, in hindsight the defects have been transported to other locations for no reason. This leads to unnecessary transportation and analysis costs. Besides, these products could already be put on stock again. Moreover, this also leads to unnecessary CO_2 emissions caused by transportation.

Challenge 2: Contamination risks caused by wrong packaging and issues during transportation
The second challenge in this reverse supply chain is the appropriate packaging of the products and the additional challenge that is caused due to contamination risks. If certain products are not properly packaged, then OEMs might be hesitant to repair these products. They do not want to take the risk that these defects could contaminate their cleanrooms. That could be too costly for them. Therefore whenever there are any doubts about the packaging of the products, it is already becoming more complicated to repair these products. Besides, wrong packaging can lead to damaged products. So, the probability is high that products are scrapped if they are not packaged properly. Mainly because no one dares to use these products again, to prevent contamination.

Challenge 3: No standardized reconditioning agreements or contracts
Third, the lack of reconditioning agreements with the OEMs. When reconditioning is done at the OEM, the transparency during the reconditioning activities differs per OEM. Sometimes The Company is informed on the several processes a service part will undergo at the OEM during reconditioning and on the state of the service parts during reconditioning, whereas for other OEMs The Company is only informed on the total reconditioning time and costs. Often there is no reconditioning contract in place with the OEMs. Therefore, The Company has to negotiate with the OEMs to align on the reconditioning terms every time that used parts need to be reconditioned. The OEMs are supposed to make estimations on the costs and duration of the repair processes even before actually analysing these products. This makes it difficult for the OEMs to make fast and reliable estimations. Moreover, The Company does not provide its OEMs with forecasts for the anticipated repair flow and the OEMs are not asked to reserve any capacity for The Company's return flow. The reason for this lays in the variability that The Company experiences in the return flow. In Chapter 3 variability is also mentioned as one of the main challenges in the reverse supply chain according to scientific research.

Challenge 4: Long lead times
The fifth challenge is the long lead time of the defects, from defect until the defect is reconditioned. There are certain inefficiencies in the return flow that cause the throughput times to be larger than expected. This challenge is related to the coordination challenge, as discussed in Chapter 3 (Section 3.2). The analysis of the defects and alignment on the costs are expected to take on average 21 days. Besides, the transportation of the products from one local warehouse to central warehouses should not take more than 1 week. Still, on average from notification of a defect until the product is reconditioned succesfully could take 119 days. The actual repair process takes about 35 days (analysis and repair). This is relatively fast, even though there is no incentive for suppliers to deliver a repair quickly. Apparently about 75 percent of the throughput time is spent before the actual repair. Namely, defects are awaiting to be shipped until enough defects are collected to fill an entire container. The products could even wait up to 90 days to be sent for reconditioning. These long lead times and the third challenge lead to a large backlog of products that need to wait before reconditioning. This backlog has impact on for example the inventory holding costs. The research was unable to quantify this, but this would be a good opportunity for future research.

Challenge 5: Gaps and differences in data definitions
Then, the last challenge. This is related to the transparency in the reverse supply chain as already discussed in Chapter 3 (Section 3.2). Different The Company experts can have different definitions for concepts like repair yield and repair lead time. Some people would say that the repair lead time is the lead time where the product is actually being repaired at the OEMs, whereas others would say that the repair lead time is from defect notification until value recovery of the product. For every data dashboard or information system it is very important to understand what the data represents. Also the amount of defects that are not yet reconditioned or scrapped is large according to the information systems. These products are supposed to be stored somewhere in the local, but especially in the central warehouses. The question remains if these products are truly physically there or whether the data from the information systems are not completely up-to-date.

4.4 Return flow implications with a Repair Captain

This section discusses how a Repair Captainship could reduce some of the challenges mentioned in Section 4.3. First, if the Repair Captain is located close to the customer, the waiting time before analysis would be reduced. The defects could directly be sent from local warehouse to the Repair Captain. Then, the unrepairable products or products that were not even defect at all are not unnecessarily transported from one side of the earth to the other side. Second, the contamination risks and possible wrong packaging would remain the same. However defects caused during transportation might be reduced as the defects will have shorter transportation times and less transportation moments. Third, if a Repair Captain would be assigned, automatically reconditioning contracts or agreements would be required. The Captain will reserve capacity for the defects, because that would be the main purpose of the Repair Captain for The Company. Fourth, certain inefficiencies would be reduced as The Company would make some standardized reconditioning agreements with the Repair Captain. Lastly, the gaps and differences in the information systems. This challenge is not necessarily reduced by applying a Repair Captainship. Though The Company should keep this in mind when transferring products from the local warehouses to the Repair Captain. Overall, the return flow with a Repair Captain would be different compared to the current return flow, where products are sent back to the OEMs. Preferably the Repair Captain will operate locally, so that defects could be transported from local warehouses directly to the Repair Captain. The return flow under a Repair Captainship is shown in Figure 4.3.

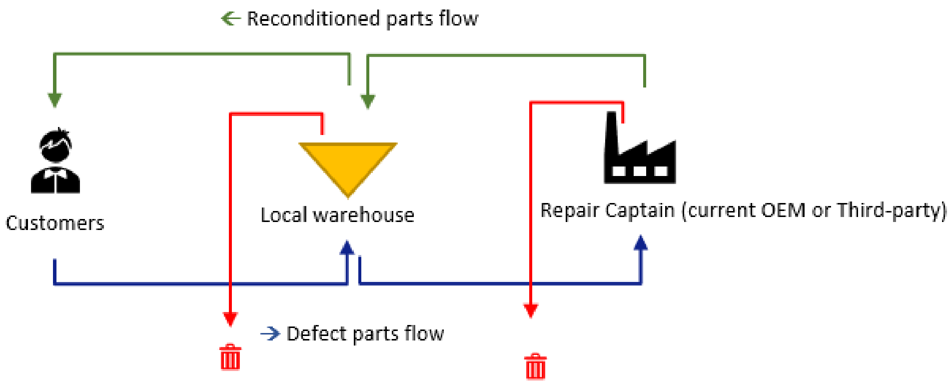


Figure 4.3: The return flow of defects under a Repair Captainship

4.5 Discussion: the reverse supply chain

The chapter started with the question: *How does the reverse supply chain look like in terms of the product return flow and challenges?* The first challenge is that there is no first physical analysis of the products before sending them to the OEMs for potential reconditioning. The second challenge is the risk of contamination of returned products due to wrong packaging and issues during transportation. Third, there are no standardized reconditioning agreements or contracts with the OEMs. These are caused by the variability in the reverse supply chain (see Chapter 3). The fourth challenge is that the overall lead time for reconditioning is long. The last challenge is the gap and difference in data definitions among employees and information systems. These five challenge are related to the the common challenges in the reverse supply chain (see Chapter 3). Overall, The Company experiences similar challenges as other firms experience in the reverse supply chain. This chapter helps to answer the main research question, while it discussed the current management of the reverse supply chain. To understand if a new reconditioning strategy would be beneficial, it is important to understand the current context first. The context is clear now. So the research will proceed by investigating the opportunities and limitations to apply a Repair Captainship in Chapter 5.

5 Modeling the product category selection for a Repair Captainship

This chapter aims to asses the opportunities and limitations to of outsourcing reconditioning activities to a Repair Captain. This is assessed for several product categories at The Company. Different technical, business, economical and environmental characteristics could determine whether outsourcing reconditioning to a Repair Captain could be feasible or whether the opportunities are less or even limited. The scientific insights on how to decide to fully or partially outsource reverse supply chain activities are limited, but discussed in among others the work of Cheng and Lee (2010); Ordoobadi (2009). In addition, Agrawal et al. (2016) considers environmental sustainability concerns, where others tend to focus economical aspects only. Similarly, this research includes both the economical and environmental aspects. This part of the research contributes to the strategic decision-making in reverse supply chains, by providing insights on how to decide to outsource reconditioning activities to a repair captain or not. This leads to the development of a multi-criteria decision-making (MCDM) model which explores the opportunities and limitations of outsourcing reconditioning activities to a repair captain. This model is implemented at The Company, but this model could be useful for other firms as well. There are various types of MCDM approaches, such as TOPSIS and Analytic hierarchy process (AHP) that can be applied for this type of research (Agrawal et al., 2016). This last one, AHP has been applied in this research. This Chapter starts with a short introduction first. Second, a literature review is provided which discusses the applied methodologies in the outsourcing decision and the the relevant decision criteria. Third, the methodology is discussed. Fourth, the analysis is provided. Lastly, a sensitivity analysis is conducted. In summary, this chapter provides the answer on sub-research question 3:

How to determine the opportunities and limitations of applying a Repair Captainship?

5.1 Introduction

The topic of outsourcing has been researched multiple times over the years (Varadarajan, 2009; Weidenbaum, 2005). According to Agrawal et al. (2016) outsourcing could be defined as "acquiring services from external providers". It can also be defined as "outside resource using" (Arnold, 2000). These concepts could be explained in further detail as follows:

- 'outside' refers to the creation of value outside of the company;
- there is a strategic perspective on external resources. Firms can be viewed as unique complexes of resources and knowledge;
- resources should by used by and for firms to ensure a competitive position (Arnold, 2000).

In addition,Ordoobadi (2009) determined an outsourcing model consisting of three elements: the outsourcing subject (firm that wishes to outsource certain processes), the outsourcing objects (the process that could be outsourced), the outsourcing partners (vendors which are considered for reverse supply chain activities) (Ordoobadi, 2009). In this research The Company is the outsourcing subject, the reconditioning is the outsourcing object and the repair captain is the outsourcing partner. Outsourcing reconditioning activities can have several strategic, operational and financial reasons, such as gaining competitive advantage, avoiding large investments and obtaining more operational flexibility Ordoobadi (2009); Agrawal et al. (2016). These days, The Company is already outsourcing its reconditioning activities to its OEMs for all the product categories. Meanwhile there are thoughts about outsourcing these activities to a Repair Captain. Therefore it is important to determine for which product categories this type of strategy would be interesting.

5.2 Literature review

Over the years, various methods and models are developed to support the outsourcing decision. Ordoobadi (2009) addressed this problem by creating a multi-phased decision-making model. This model takes a strategic and economical point of view. The work of Cheng and Lee (2010) provides a systematic decision-making approach for reverse logistics. They analyze service requirements related to the reverse logistics with the resource-based view (RBV) as theoretical basis, to determine which service requirements should be done in-house and which need to be outsourced. By means of the analytic network process (ANP) method, the relative importance of reverse logistics service requirements is evaluated. Agrawal et al. (2016) proposes a framework for outsourcing decisions in reverse logistics. This framework use graph theory to combine four traditional balance scorecard perspectives. In comparison with the ANP, which is used in the model of Cheng and Lee (2010), graph theory does incorporate hierarchical relationship among attributes. Senthil et al. (2014) made use of AHP and the Fuzzy-TOPSIS method to evaluate parties executing the reverse supply chain activities. Tjader et al. (2014) proposed a decision model based on ANP and balanced scorecard (BSC) to support a firms outsourcing strategy.

5.2.1 MCDM models for the outsourcing decision

The strategic decision problem of outsourcing reconditioning activities or not is modeled by means of a MCDM model. This method is commonly used to evaluate circularity strategies, refering to concepts such as repair, refurbishing and remanufacturing (Alamerew et al., 2020). There are a couple of reasons why this methodology is frequently applied. First, it enables to assess multiple criteria simultaneously. Second, the method does not only require quantitative data input. Qualitative data can be incorporated as well. Third, the method enables to provide structured to complex decision-making problems. Namely, the complexity can by incorporated by determining: (1) the required criteria, (2) information sources that measure the criteria and (3) the criteria weights for a given purpose. In summary, the MCDM considers the importance preference of users or decision-maker during the decision-making activities (Alamerew and Brissaud, 2019; Alamerew et al., 2020). Overall, most research that focuses on outsourcing reverse supply chain activities to another party than the OEM, refers to using 3PLs. The current suppliers are usually not perceived as potential 'repair captains' as well (Shaharudin et al., 2014; Aghazadeh, 2003; Sink and Langley Jr, 1997). This research does consider current suppliers as well. This MCDM model will rank The Company's product categories, where the category highest in rank would have most opportunities for a Repair Captainship. This discrete MCDM decision-making problem could be represented as matrix 5.1:

$$\begin{array}{c} \\ P_1 \\ P_2 \\ \vdots \\ P_n \\ \\ \end{array} \begin{array}{c} \begin{matrix} C_1 & C_2 & \cdots & C_m \end{matrix} \\ \begin{bmatrix} X_{1,1} & X_{1,2} & \cdots & X_{1,m} \\ X_{2,1} & X_{2,2} & \cdots & X_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ X_{m,1} & X_{m,2} & \cdots & X_{n,m} \end{bmatrix} \\ \begin{bmatrix} W_1 & W_2 & \cdots & W_m \end{bmatrix} \end{array} \tag{5.1}$$

In this matrix $P_1, P_2, ..., Pn$ are the product categories in scope. $C^1, C^2, ..., C^m$ refer to the criteria that determine the opportunities to apply a Repair Captainship. The product categories are assessed against each of these criterion. Then X_{ij} refers to the input value per product category P_i for criterion j. Finally, W_j refers to the weight for each criterion j. Thus, this weight determines the contribution of each criterion in determining the opportunities of applying a suppliers repair captainship. Then, $\sum(W_j)$ equals 1. To rank the product categories, for each of them a an overall score should be calculated. This is done via the simple additive weighted (SAW) function, see equation 5.2.

$$S_i = \sum_{i=1}^{m} W_j * X_{ij(norm)} \tag{5.2}$$

In equation 5.2 $X_{ij(norm)}$ is the normalized value of X_{ij}. This $X_{ij(norm)}$ can be calculated via equation 5.3, if the criterion should be maximized:

$$X_{ij(norm)} = \frac{X_{ij}}{max(X_{ij})} \tag{5.3}$$

Subsequently,$X_{ij(norm)}$ can be calculated via equation 5.4, if the criterion should be minimized:

$$X_{ij(norm)} = \frac{min(X_{ij})}{X_{ij}} \tag{5.4}$$

To obtain results from the MCDM model it is crucial to determine the weight W_j for each criterion. There are several methods to calculate the weights. One method that is frequently applied is the AHP (Govindan et al., 2013b). This method is developed by Saaty (1989) and converts a complex problem in smaller less complicated problems, which are easier to understand and to process for decision-makers (Pecchia et al., 2013). After identifying the main criteria, decision makers can compare each of the factors against each other. This comparison enables to calculate a numerical weight for each criterion. This method is chosen, while it is frequently applied in MCDM problems (Govindan et al., 2013b). Besides, the AHP allows to quantify qualitative input, making this method effective when the opinions of experts should be quantified. These opinions could be based on their knowledge and experience (Pecchia et al., 2013). Usage of other methods such as for example the ANP, were considered as well. The ANP enables to incorporate complexity and criteria inter-dependency. This method enables to properly incorporate complex structures and interconnections, but its application in managerial practice is more difficult. That is also an advantage of the AHP, even though inter-dependency between criteria is less incorporated, the application of AHP is easier in managerial practice (Wicher and Lenort, 2014). The exact steps of the AHP and its application will be discussed in further detail in section 5.3.

5.2.2 Crucial criteria in the outsourcing decision

Whether to outsource reconditioning activities or not has been researched by several researchers (Kremic et al., 2006; Hausner, 1998; Ordoobadi, 2009). Furthermore, research has been done on outsourcing reverse supply chain activities (Ordoobadi, 2009; Agrawal et al., 2016; Hassanain et al., 2015). Outsourcing decision factors were summarized by Hassanain et al. (2015). These factors were grouped into the categories 'Strategic', 'Management', 'Technological', 'Economic', 'Quality' and 'Function characteristics'. For example 'cost savings' is mentioned as an economic factor and 'need for specialized management' is mentioned as a technological factor. In contrast to the work of Hassanain et al. (2015), Agrawal et al. (2016) also includes environmental criteria, such as 'life cycle assessment (LCA)' and 'resources'. Their MCDM does not focus on the outsourcing decision, but on the type of reconditioning activity. Here the categories 'Environmental', 'Economic', 'Social', 'Legislative', 'Technical' and 'Business' are used. This research also emphasizes that criteria and sub-criteria depend on the specific context, e.g. depending on the compelxity of the supply chain and data availability (Agrawal et al., 2016). Also, Drtina (1994), mentioned some critical success factors for outsourcing, such as time needed for repairs and cost reduction. Lastly, Garg and Sharma (2020) discusses sustainable outsourcing partner selection. Where, Ordoobadi (2009) lays more focus on the economic aspects in the outsourcing decision, Garg and Sharma (2020) also includes environmental decision factors, such as 'reverse logistics and waste minimization' and 'emission and pollution minimization (EPM)'. All of the above mentioned findings will be kept in mind when deciding to outsource reconditioning activities to the OEMs or to a Repair Captain. The chosen set of criteria, for the outsourcing decision to a Repair Captain, and its sources are discussed in in section 5.4.

5.3 Methodology

The AHP methodology is applied in a couple of steps. These steps are as follows:

- **Step 1: Identification of the decision criteria $C_1, C2, ..., Cm$ and their group categories**

  The performance of each product category is determined for all criteria. These criteria determine how large the opportunity could be to apply a Repair Captainship or not. Possibly these decision criteria could be grouped under similar categories, such as 'Technical' and 'Economic'.

- **Step 2: Determination of the research respondents, or also called individual decision makers $D_1, D_2, ..., D_l$**

  The group of decision makers $D_1, D_2, ..., D_l$ consists of people from several departments and with different experience and backgrounds. In total 10 respondents were used to evaluate the criteria and to determine the corresponding weights. Respondent 1 is working for the environment and health department, respondent 2 is involved in local re-use as global operations manager and respondents 3 to 8 are from the sourcing & procurement department. From these five experts from the sourcing & procurement department, respondent 3 is managing several SPFTs, respondents 4 and 5 are each managing one SPFT, respondent 6 is managing a product category and respondent 7 is focused on supplier quality. Lastly, respondents 8 to 10 are from the Reuse department, where one of them has a financial background, one a sourcing & procurement background and the other one is the head of the re-use department.

  All of these experts are somehow involved with the reuse of products and especially the experts from the reuse department are involved with the strategic decision-making related to reuse at The Company. First 7 respondents were included in the research, as recommended by Saaty and Özdemir (2014), because including more judgments is not always improving the research outcome. However, three more respondents were added to the research, while they were deemed important due to their different knowledge and practical experience. All ten respondents were somehow involved with the research objective, from practical experience and knowledge. This appears to be highly important when selecting the respondents (Saaty and Özdemir, 2014).

- **Step 3: Creation of a questionnaire for the selected pairwise comparison method**

  A questionnaire was created to give insights on the relative importance of each criterion to the objective: 'outsourcing reconditioning activities to a Repair Captain'. The following question was asked to the questionnaire respondents: *"Assuming you'd like to consolidate products to be reconditioned at a Suppliers' Repair Captain, which criterion is more important to consider?"*. These questionnaire questions are provided in Appendix B.
  The respondents could choose an option out of a three-point scale: '1' if equally important, '3' meaning more important and '5' refering to much more important. Reciprocal values were '1/1' if equally important, '1/3' if a criterion is less important and '1/5' if a criterion is much less important. Saaty's natural scale makes use of a nine-point scale with the possibility to give in-between answers Saaty (1989), nonetheless this scale is not applied in this research. According to Pecchia et al. (2013) a three-point scale could be suitable for people with little to no experience in complex mathematics or for people who are unfamiliar with the AHP method. The research of Pecchia et al. (2013) mentions making comparisons between criterion becomes more difficult for some respondents, when faced with a more complex judgmental scale than the three-point scale. During the preparation of the questionnaire also some of the The Company experts mentioned that a nine-point scale would be too large. So a three-point scale is chosen
  There are several ways to make the pairwise comparisons. First of all each criterion could be compared with one-another. This method enables to compare each of the criterion with each other, but also leads to a large number of questionnaire questions (Saaty, 1977). Second,

pivot comparisons could be made. The method divides the criterion in multiple clusters, where two adjacent clusters have a common criterion or also called pivot. This method reduces the number of pairwise comparisons, but there are no strict rules on how to select the pivot. If this pivot is not selected properly this could lead in inaccuracies in the research outcomes. Even though this method reduces the number of questions, the number remains relatively high (Ishizaka et al., 2012). Third, incomplete pairwise comparisons. People would require to answer less answers compared to the other two methods. If people would not or could not answer certain questions, this method could be interesting. However, the method is less accurate compared to the other two and requires higher computational effort (Harker, 1987). Lastly, the applied pairwise comparison method. Namely, pairwise comparisons between criteria, which are grouped in categories. The decision criteria are first grouped in categories. Then, within the categories pairwise comparisons are made. Afterwards also the categories are compared with one-another. This remains an accurate method and makes it easier for decision-makers to compare criteria. It reduces the number of pairwise comparisons, when the criteria are carefully grouped in the right categories (Golden et al., 1989).

- **Step 4: Determination of the judgment matrix to calculate local weights of individual judgments**

  As discussed in step 3, pairwise comparisons are made between criteria per category. Afterwards also pairwise comparisons are made between the criteria categories. Then, out of the questionnaire output, for each category of criteria a judgment matrix is created.

  These matrices are structured as follows (Saaty, 1977):

  - It is assumed that the judgment matrix is transitive.
    This implies that if criterion A is is two times more important compared to criterion B, and criterion B is three times more important than criterion C, then criterion A should be six times more important then criterion C;
  - A_{ij} refers to the ratio between criteria 'i' and 'j';
  - A_{ji} refers to the reciprocal value of A_{ij};
  - A_{ii} is always 1.

  Then, after normalizing the input values in the judgment matrices, local weights are determined. These local weights LW_j refer to the relative importance of a decision criteria within a given category. If the judgment matrices meet the structure, as mentioned by Saaty (1977), then this results in one eigenvector of weights (Golden et al., 1989; Pecchia et al., 2013; Saaty, 1977). If there are multiple eigenvectors, this implies that the judgments are not fully consistent. Thus, before calculating the global weight of each decision criteria, the consistency should be determined and possibly be improved.

- **Step 5: Determination of the consistency index and consistency ratio**

  The individual respondents' consistency can be measured via the consistency index and the consistency ratio. The consistency index formula suggested by Saaty (1977) is given in equation 5.5

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5.5}$$

  In equation 5.5, λ_{max} is equal to the largest eigenvalue and n is equal to the number of criteria that are grouped together. Then, the consistency ratio can be calculated by dividing the consistency index with the random consistency index ($R.I.$). Then the consistency ratio can be calculated via equation 5.6 and the random consistency index for values n=3 to n=9 is shown in Table X. (Aguarón and Moreno-Jiménez, 2003).

$$CR = \frac{CI}{RI} \tag{5.6}$$

Table 5.1: RI(n) values for $n = 3$ to $n = 9$ (Aguarón and Moreno-Jiménez, 2003)

n	3	4	5	6	7	8	9
$RI(n)$	0.525	0.882	1.115	1.252	1.341	1.404	1.452

In general the CR should be below 0.1, but in complex situations a value of 0.2 could also be appropriate (Pecchia et al., 2010). In this research the 0.1 is used as threshold, while this is generally used (Saaty, 1977). In case that the CR is higher than the threshold of 0.1, preferably the questionnaire results would be evaluated with the respondents. However due to limited time and availability of the respondents, the evaluation can not take place. Therefore, if $CR > 0.1$, another inconsistency measure is calculated. The row geometric mean (RGM) is then applied to the judgment matrices and the Geometric Consistency Index (GCI) is then calculated, which is discussed in Crawford (1987). The threshold for the GCI is different than for the CR. Namely, for $n = 3$, $GCI \leq 0.31$, for $n = 4$, $GCI \leq 0.35$ and for $n > 4$, $GCI \leq 0.37$. According to Abel et al. (2018) one of the methods to reduce inconsistency could be to automatically adjust the judgments. This is applied in this research by altering the A_{ij} values having largest impact on the inconsistency after the RGM method is executed. Then, the new input value for this A_{ij} is estimated by calculating $A'_{ij} = \frac{W_i}{Wj}$ and $A'_{ji} = \frac{W_j}{Wi}$. then, the consistency of the model is evaluated again and adjustments are made until the GCI and CR are below the appropriate thresholds (Szybowski, 2018).

- **Step 6: Calculation of global weights for individual judgments**

  Now, the global weight can be calculated. The global weight GW_j refers to the relative importance of a decision criterion j compared to all other decision criteria. So not only the ones that are grouped together in one category of criteria. Multiplying the LWs with the relative importance of each category of criteria (CW_k) gives the GWs (Pecchia et al., 2013). The formula for the GWs is given in equation 5.7.

$$GW_j = LW_j * CW_k \tag{5.7}$$

- **Step 7: Determination of the final rank via group decision making**

  Lastly, the individual priorities of the decision-makers are grouped together. This method is also called the aggregation of individual priorities (AIP) (Forman and Peniwati, 1998). Individual priorities are aggregated (AIP) while the individuals are not assumed to provide input as a unit but as separate individuals. In this case, the AIP is a suitable and useful method (Forman and Peniwati, 1998). Recall that the set of decision makers is $D = (D_1, D_2, ..., D_I)$, where each decision maker is d_r. Let $\alpha = (\alpha_1, \alpha_2, ...\alpha_I)$ be the weight vector per respondent, where $\sum \alpha_l = 1$. Let $W^{(r)} = (W_1^{(r)}, W_2^{(r)}, ..., W_m^{(r)})$, refering to the weight vector (for all criteria) for each of the r respondents 1 to 10. Then, the group weight vector is equal to $W^{(g)} = (W_1^{(g)}, W_2^{(g)}, ..., W_m^{(g)})$ for the group g of respondents. Based on Dong et al. (2010), $W_j^{(g)}$ can by calculated via equation 5.8:

$$W_j^{(g)} = \frac{\prod_{r=1}^{I} (W_j^{(r)})^{\alpha_I}}{\sum_{j=1}^{m} \prod_{r=1}^{I} (W_j^{(r)})^{\alpha_I}} \tag{5.8}$$

Based on these weights W_j and the inputs X_{ij} in each cell. The simple additive weighted function can be applied, see equations 5.2, equation 5.3 and 5.4. This leads to a final score per product category. The higher the score, the higher the category is placed in rank.

5.4 Results

The results are presented in a couple of sub-sections. First, the MCDM model is presented and the criteria descriptions are provided and discussed. Second, the model inputs and the product categories in scope are discussed. The model is build in Microsoft Excel. Third, the obtained local and global weights of the criteria of each respondent are given. Furthermore, the group decision making weights are provided. Fourth, the final rank of product categories are discussed. Afterwards, a scenario analysis and criteria correlation analysis are executed.

5.4.1 The MCDM model formulation

Based on literature and expert opinions, a list of decision criteria is established which gives insights on the opportunities to apply a Repair Captainship. These criteria are grouped into four categories, namely: 'Technical', 'Business', 'Economic' and 'Environmental'. Also, as discussed in Section 5.2.1, per criteria it is determined whether to maximize or minimize it in the SAW function. This results in a list of categories of decision criteria and decision criteria. This is visualized in Figure 5.1. Besides, the decision criteria, related descriptions and consulted scientific sources are provided in Table 5.2 and Table 5.3.

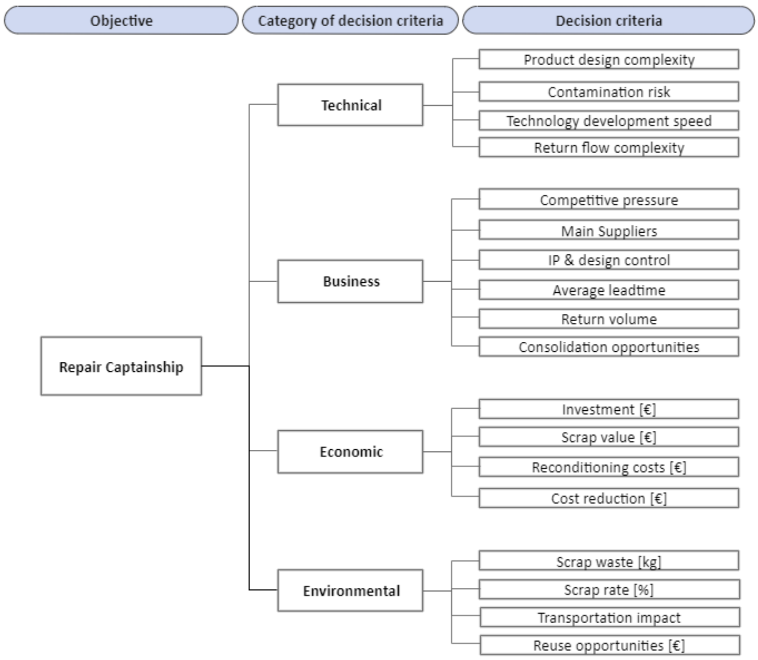


Figure 5.1: The MCDM structure of the product category selection for a Repair Captainship

Table 5.2: Technical & Business decision criteria for a repair captainship

Technical criteria	**Description**	**Sources**
Product design complexity	The impact that product design has on the complexity of reconditioning activities. Perhaps a design could cause that only OEMs have the knowledge to do reconditioning without occasioning collateral risks	Martin et al. (2010); Abbey and Guide (2017)
Contamination risk	The risk products face of getting contaminated during transportation or during reconditioning activities	O'Hanlon and Parks (1992); Tan et al. (2003)
Technology development speed	The speed at which product technology develops (e.g., amount of time in-between "new versions and/or upgrades" of products).	Martin et al. (2010); Balakrishnan and Wernerfelt (1986)
Return flow complexity	The level of The Company's suppliers reconditioning inter dependency that increases the complexity of the return flow (e.g., when they need support from their own n-tier suppliers' network to recondition products)"	Martin et al. (2010)
Business criteria	**Description**	**Sources**
Competitive pressure	Competitive pressure that The Company might experience due to the presence of external third parties reconditioning parts from The Company's customers	Abbey and Guide (2017)
Main suppliers	The number of main suppliers (OEMs) that recondition the products	Lau and Wang (2009)
IP & design control	The level of control that The Company has in terms of IP and design rights on the failed products	Martin et al. (2010)
Average lead time	The average reconditioning lead time (days) of products that failed at the customer site (from product failure until the product is reconditioned succesfully)	Tan et al. (2003)
Return volume	The number of failed products from the customer site, arriving at The Company over a certain time interval	Martin et al. (2010); Guide Jr et al. (2006)
Consolidation opportunities	The possible consolidation opportunities to send failed products from the customer site to a Repair Captain. If most products are already reconditioned at one supplier, then the opportunity to consolidate at a Repair Captain is limited.	Gallo et al. (2012)

Table 5.3: Economic & Environmental criteria for a repair captainship

Economic criteria	Description	Sources
Investment	The average investment [€] in capital & skilled labor to be able to execute reconditioning activities for products failing at the customer site	Agrawal et al. (2016); Fleischmann et al. (2001); Joskow (1988); Martin et al. (2010)
Scrap value	The monetary value [€] of products that failed at the customer site and which were scrapped afterwards	Shaharudin et al. (2017)
Reconditioning costs	Cost [€] related to the actual reconditioning (e.g., price paid to a supplier or an in-house reconditioning facility) of the products that failed at the customer site	Govindan et al. (2013a); Flapper et al. (2005b); Agrawal et al. (2016); Alamerew et al. (2020)
Cost reduction	Cost savings [€] from reconditioning the products that failed at the customer site, instead of buying new products	Shaharudin et al. (2017); Li et al. (2018)
Environmental criteria	**Description**	**Sources**
Scrap waste	The weight [kg] of products that failed at the customer site, and which were then scrapped	Shaharudin et al. (2017); Li et al. (2018); Garg and Sharma (2020)
Scrap rate	The proportion [%] of products that failed at the customer site, and which were scrapped afterwards	Shaharudin et al. (2017); Wadhwa et al. (2009)
Transportation impact	Possible CO_2 emissions impact, related to the transportation recovery of products that failed at the customer site.	Govindan et al. (2019)
Reuse opportunities	The opportunity to recondition products that failed at the customer site, which were seen as economically unrepairable and therefore scrapped (not worth the effort due to financial implications)	Tan et al. (2003)

The reasons for including the decision criteria in the MCDM model are also briefly discussed. First, the technical criteria are discussed. Second, the business criteria. Third, the economic criteria and lastly, the environmental criteria. Besides, together with the two The Company supervisors a decision is made whether to maximize or minimize the criteria for the SAW function (see Section 5.2.1). These two supervisors were involved during the model formulation and got sufficient understanding of the AHP methodology.

Technical decision criteria

1. The first decision criterion that is included in the MCDM is *Product design complexity (C_1)*. According to Martin et al. (2010) remanufacturing steps can be complex. It is important to know several aspects, how to disassemble the product, the sequence of the remanufacturing steps and sometimes the products should be cleaned first. Furthermore, Abbey and Guide (2017) mentioned a relation between product design and whether or not reuse is seen as core competence or not. If product design would complicate the reconditioning process for a repair captain, this could have risks. Therefore this criterion is minimized.
2. The second decision criterion is *Contamination risk (C_2)*. Sometimes due to due to wrong

packaging or issues during transportation the products cannot be reconditioned anymore (Tan et al., 2003). Besides, a clean room could be needed to recondition certain products. Besides O'Hanlon and Parks (1992) discuss the impact that vacuum contamination can have on semiconductor yield. For certain products it is highly important to have a clean room to ensure that any contamination is prevented (O'Hanlon and Parks, 1992). This could require additional effort or investment from a repair captain. This criterion is also minimized.

3. Third, the criterion *Technology development speed(C_3)* is included in the model. For a possible repair captain, assets such as tooling and machinery could be under risk of obsolescence if products experience fast technological evolution (Martin et al., 2010). Therefore this aspect is also considered when evaluating the opportunities to apply a Repair captainship. High rates of technology evolution could lead to shorter product lifecycles and more risk of asset obsolescence (Martin et al., 2010; Balakrishnan and Wernerfelt, 1986). Therefore, also this criterion is minimized.

4. Fourth, *Return flow complexity (C_4)* is included. It is not always clear whether OEMs perform the reconditioning activities themselves or whether they also consult their suppliers to perform the reconditioning activities (Martin et al., 2010). If OEMs would completely rely on other parties than the question remains if a captain would also need the support of other parties. This could potentially complicate the reconditioning process. This criterion is also minimized.

Business decision criteria

5. The fifth criterion is *Competitive pressure (C_5)*. According to Abbey and Guide (2017) third party reconditioning businesses are taking over the reconditioning activities in industries such as the aerospace and the automotive industry. Once the third parties take over the reconditioning market, it is hard to take back the market again. A firm should determine how to arrange its reconditioning activities to minimize competitive pressure. This might play a role in the decision-making to outsource reconditioning activities to a Repair Captain. This criterion is maximized, while The Company would like to prevent or reduce the involvement of external third-parties in the aftermarket support.

6. The sixth criterion is *Main suppliers (C_6)*. This refers to the number of suppliers involved in the category. If there is only one supplier in the category, opportunities to apply a repair captainship is limited. The return volume is then already consolidated at one party. Furthermore, the larger the number of current suppliers in a product category, the more parties that are involved in the management of the reconditioning activities. According to Lau and Wang (2009) reverse supply chain activities are poorly managed in general, while several companies are involved. Therefore this is another criterion that influences the opportunities to apply a Repair Captainship or not. This criterion is maximized, while a repair captainship could help to reduce the number of parties involved.

7. Seventh, *IP & design control (C_7)* is of influence in the outsourcing decision. According to Martin et al. (2010) intellectual property (IP) is hard to transmit across organizational boundaries. Besides, products that contain high levels of IP technology are subject to hazards of exposure during assembly. So if a firm does not posses the IP & design rights this could add complexity when outsourcing reconditioning activities to a repair captain or not. Thus, the criterion is maximized.

8. Then, the *Average leadtime (C_8)*. Research from Tan et al. (2003) uses this factor as a performance indicator for the reverse supply chain. If the current average leadtimes are high when products need to be send to the OEMs for reconditioning, there could be be an opportunity to improve these with a repair captain. Assuming that the possible repair

captain would be close by the customer, whereas the main suppliers are usually further away. Thus, the criterion is maximized.

9. The ninth criterion is the *Return volume (C_9)*. If the volume of defects is very low during certain time intervals this can result in volume uncertainty. Then the Repair Captain could have difficulty to utilize its resources as the volume is limited and the failure types are also uncertain and variable (Martin et al., 2010; Guide Jr et al., 2006). So this criterion is maximized.

10. Tenth, the *Consolidation opportunities (C_{10})*. This is also an important factor to consider for a Repair Captain, while a repair captain could profit from consolidating a large volume of products. This has positive influence on the economies of scale, while this larger return volume enables to spread the fixed costs over a higher volume (Gallo et al., 2012). If all volume is already consolidated at one party, then the repair captainship becomes irrelevant. Also this criterion is maximized.

Economic decision criteria

11. The eleventh decision criterion is *Investment (C_{11})*. Reconditioning often requires specialized physical assets such as machinery and test equipment, or facilities for testing, sorting, and processing of failed products (Fleischmann et al., 2001; Martin et al., 2010) This skilled labor can be created by investing in trainings or gaining more experience in the reconditioning activities (Joskow, 1988). If a Repair Captain would require to make high investments, perhaps the opportunities to apply a Repair Captainship would be less due to the financial implications. Therefore, this criterion is minimized.

12. The twelfth criterion is *Scrap value (C_{12})*. According to Shaharudin et al. (2017) Scrap rate is a good indicator to evaluate the performance of the reverse supply chain. However, this provides just a percentage. The scrap value translates this percentage into an economic value. This criterion is added from practical point of view, whereas The Company experts are also interested in the monetary value of products that are scrapped. This criterion is maximized, while a repair captainship might lower the scrap value.

13. The thirteenth criterion is *Reconditioning costs (C_{13})* This refers to the required costs to recondition a product to recover its value. These costs are important when evaluating different parties to be responsible for the reverse supply chain activities (Govindan et al., 2013a). Reconditioning costs are also used as a performance indicator and way to evaluate the reverse supply chain performance (Flapper et al., 2005b; Agrawal et al., 2016; Alamerew et al., 2020). This criterion is maximized, while the repair captainship would aim to reduce costs. If the reconditioning costs are already low, then the opportunities to lower this amount could be limited.

14. The last economic criterion is *Cost reduction (C_{14})*. This refers to the difference between the total costs for a new product or part and its reconditioning costs. According to Shaharudin et al. (2017) this is a good method to evaluate the reverse supply chain performance. Also, Li et al. (2018) mention cost reduction in their MCDM model for outsourcing decision-making. This criterion is also maximized, while there might be most potential for a repair captainship.

Environmental decision criteria

15. According to Shaharudin et al. (2017) *Scrap waste (C_{15})* is a good way to evaluate the performance of the reverse supply chain. Besides, Li et al. (2018); Garg and Sharma (2020) use waste reduction as a criterion in their MCDM for outsourcing. This criterion is maximized, while the repair captainship aims to reduce the scrap waste. If the scrap waste is already low, then the opportunities to lower this amount could be limited.

16. The decision criterion *Scrap rate (C_{16})* is also a good indicator to evaluate the performance of the reverse supply chain (Shaharudin et al., 2017). Besides, Wadhwa et al. (2009) mention resource conservation as an environmental criteria in outsourcing decision-making. Indirect, scrap rate gives an estimation of the resources that are conserved while this rate shows how much is not conserved. Also this criterion is maximized.

17. Then, *Transportation impact (C_{17})* in terms of related carbon emissions caused by the transportation of defects and recovered products. Among others, Govindan et al. (2019) mentions carbon emissions as an important environmental factor in their MCDM for outsourcing. This criterion is also maximized.

18. The last criterion is *Reuse opportunities (C_{18})*. Tan et al. (2003) mention in their research that a challenge in the return flow can be the volume of low-dollar value returns. The question arises whether certain parts are worth to recondition. However if you would sum up the value of all parts that are perceived not worth to recondition, then these amounts can be relatively high. With a repair captain locally, possibly the reconditioning could be worth the costs and effort. Costs could be reduced due to, for example the reduction of transportation costs (Tan et al., 2003). So this criterion is also maximized.

5.4.2 The MCDM model inputs and product categories in scope

The MCDM model which assesses the opportunities and limitations to outsource reconditioning to Repair Captains has a couple product categories in scope and some product categories that are out of scope. Certain product categories were excluded due to fixed limitations. As discussed in Chapter 3, Abbey and Guide (2017) core competencies could determine whether a firm would outsource or insource certain reconditioning activities. This is taken into consideration when selecting which product categories are in scope for a repair captainship. The following main fixed limitations caused a product category to be out-of-scope for a Repair Captainship:

- *Product uniqueness*
  These product categories include products that are very unique in terms of technology and manufacturing processes. Only the few existing OEMs are capable of reconditioning such products now and in the near future.

- *One supplier only*
  These products in the product categories are manufactured by a single supplier. Products are already consolidated at one party.

- *No IP & design control at all*
  For all products in these product categories The Company has no IP & design control. This makes a Captainship challenging.

Other reasons, could be that any current warranty agreements are too important to even consider a repair captainship, a lack of data, or that the reconditioning type is out of scope (for example recycling). The product categories that are out of scope and the main reasons for this are shown in Appendix B, Table B.1. The product categories that are in scope are provided in Table B.2. For these product categories there might be potential opportunities to outsource reconditioning activities to a Repair Captain. Next, the model inputs are obtained via historical data sources and via interviews with The Company's experts. The category managers of each product category were interviewed. Also for certain categories the inputs were validated by asking similar questions to the group category managers, in charge of a strategic product family. Usually the group category managers and related category managers gave similar answers. When the answers were too different, in collaboration with the company supervisors the most appropriate inputs were chosen. The data sources, interview questions and answer possibilities are shown in Appendix B.

Table 5.4: The Company's product categories P_i in scope for a Repair Captainship

Strategic product family team (SPFT)	**Product categories in scope**
SPFT A	$\{P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, P_9\}$
SPFT B	$\{P_{10}, P_{11}, P_{12}, P_{13}, P_{14}\}$
SPFT C	$\{P_{15}, P_{16}, P_{17}, P_{18}, P_{19}\}$
SPFT D	$\{P_{20}, P_{21}, P_{22}, P_{23}, P_{24}\}$
SPFT E	P_{25}

5.4.3 Weight calculation of the decision criteria

After collecting the MCDM model inputs, the weights of the criteria are determined. Individual judgment matrices were build, based on the questionnaire responses. The questionnaire is shown in Appendix A. Most respondents gave relatively consistent answers, but in a couple of cases new input value for some A_{ij} needed to be estimated. The suggested method of Szybowski (2018) is applied in these cases (see Section 5.3, step 5). The global weights of each of respondent are presented in Appendix C. Those global weights of the respondents have lead to the final group weights. These were calculated via equation 5.8 (see for more details Section 5.3, step 7) and the output is presented in Table 5.5. The weights reflect how dominant each of the criteria are, when considering to outsource reconditioning activities to a repair captain or not. According to the The Company's experts technical criteria are playing a large role in this decision. *Product design complexity* appears to be most important, whereas it has a weight of 0.1218 or 12.18 percent. This seems to be in line with the work of Abbey and Guide (2017) (Chapter 3). Overall, the environmental category of decision criteria has the lowest weight. Thus, according to the The Company's experts the environmental criteria are less influencing the decision to outsource reconditioning activities to a repair captain or not. This does not imply that The Company's experts are less interested in the environmental aspects, but they are convinced that other factors are playing a larger role in the decision-making.

Table 5.5: The final weights of the decision criteria

Category of decision criteria	**Weight category**	**Decision criteria**	**Weight criteria**
Technical	CW_1: 0.3272	C_1: Product design complexity C_2: Contamination risk C_3: Technology development speed C_4: Return flow complexity	W_1: 0.1218 W_2: 0.0444 W_3: 0.1013 W_4: 0.0597
Business	CW_2: 0.2784	C_5: Competitive pressure C_6: Main suppliers C_7: IP & design control C_8: Average leadtime C_9: Return volume C_{10}: Consolidation opportunities	W_5: 0.0430 W_6: 0.0320 W_7: 0.0759 W_8: 0.0472 W_9: 0.0470 W_{10}: 0.0340
Economic	CW_3: 0.2629	C_{11}: Investment C_{12}: Scrap value C_{13}: Reconditioning costs C_{14}: Cost reduction	W_{11}: 0.0580 W_{12}: 0.0522 W_{13}: 0.0824 W_{14}: 0.0703
Environmental	CW_4: 0.1316	C_{15}: Scrap waste C_{16}: Scrap rate C_{17}: Transportation impact C_{18}: Reuse opportunities	W_{15}: 0.0156 W_{16}: 0.0232 W_{17}: 0.0227 W_{18}: 0.0701

5.4.4 Final group score

Then, via the model inputs (see Appendix B) and final weights of the criteria (see Section 5.4.3), the final scores are calculated. The scores are obtained via equations 5.2, 5.4 and 5.3. The product category with the highest score is ranked first, whereas the lowest is 25th in place. The final scores and rank, based on the final group weights, are provided in Table B.2 in Appendix B. After obtaining the results a first evaluation of the rank is done with three to four The Company experts, to validate the rank. Overall, the The Company experts did recognize the results. However, there were doubts about the category which is first in rank, P_2. The experts were not sure what kind of reconditioning activities are done in this category. There were some doubts whether the opportunities to apply a repair captainship would be the highest for this product category. The rest of the rank meets all expectations. The top ten of product categories are coming from three strategic product families. The top ten is also colored in blue in Table B.2 (see Appendix B).

5.4.5 Scenario analysis

This section provides a scenario analysis to observe how the final rank of the model can change per respondent. Each respondent gives different weights to the criteria and these might result in diverse ranks. The global weights per respondent, provided in Appendix C are used to compare different final scores. According to Stewart (1997) scenarios are commonly used to represent possible future states. The different rankings per respondent are shown in Table C.2 in Appendix C. In general, product category P_2 is placed first in the final rank of most respondents. Only for two respondents this category was not ranked first, but still positioned in the top three. Then, the remaining top three. Product category P_{10} and P_{14} are in the top three in the final rank and these are usually in the top five among the respondents. Only for one respondent product category P_{10} is placed outside the top five, on place 6. It can be concluded that the top three product categories in the final rank are relatively robust, whereas the remaining top ten in the final rank can differ per respondent. Overall the categories P_4 and P_{21} until P_{24} are never in the top ten. Therefore these categories are also ranked low in the final rank.

5.4.6 Criteria correlations

This section provides insights in the association between criteria. Namely, Spearman's rank correlation is used to calculate the correlation between criteria. This method is commonly used to evaluate MCDM approaches and the strength of the association between criteria. The statistical hypothesis test for the Spearman's rank assumes that criteria are uncorrelated. When the P-value is below 0.05, then there is a significant correlation (Pecchia et al., 2013; Yurdakul and Ic, 2009). Spearmans' rank correlation coefficient and the corresponding p-value are provided for the technical, business, economic and environmental criteria. The results are shown in Tables 5.6, 5.7, 5.8 and 5.9. The output is shown in bold for the criteria that positively or negatively correlate with each other.

Table 5.6: Spearmans' rank correlation for the technical criteria

	C_1	C_2	C_3	C_4
C_1		**SC: 0.548** **P: 0.005**	SC: 0.090 P: 0.668	SC: 0.112 P:0.594:
C_2			SC: 0.062 P:0.767	SC: -0.147 P:0.484
C_3				**SC: 0.561** **P:0.004**
C_4				

Table 5.7: Spearmans' rank correlation for the business criteria

	C_5	C_6	C_7	C_8	C_9	C_{10}
C_5		SC: 0.142 P:0.498	**SC:-0.577** **P: 0.003**	SC:0.152 P: 0.469	SC: 0.390 P: 0.054	SC: -0.048 P: 0.819
C_6			SC: -0.009 P:0.964	SC: 0.042 P:0.842	**SC: 0.409** **P: 0.043**	**SC: 0.467** **P: 0.019**
C_7				SC:-0.154 P: 0.463	SC: -0.285 P:0.168	SC: 0.005 P: 0.980
C_8					SC: -0.100 P: 0.634	SC: 0.094 P:0.655
C_9						**SC: 0.457** **P: 0.022**
C_{10}						

Table 5.8: Spearmans' rank correlation for the economic criteria

	C_{11}	C_{12}	C_{13}	C_{14}
C_{11}		SC: -0.007 P: 0.975	SC: 0.040 P: 0.848	SC: 0.091 P: 0.665
C_{12}			**SC: 0.905** **P: 0.000**	**SC: 0.919** **P:0.000**
C_{13}				**SC:0989** **P:0.000**
C_{14}				

Table 5.9: Spearmans' rank correlation for the environmental criteria

	C_{15}	C_{16}	C_{17}	C_{18}
C_{15}		**SC: 0.438** **P: 0.029**	**SC: 0.771** **P: 0.000**	**SC: 0.479** **P: 0.015**
C_{16}			SC: 0.364 P: 0.074	SC: 0.236 P: 0.256
C_{17}				**SC: 0.429** **P: 0.032**
C_{18}				

Tables 5.6, 5.7, 5.8 and 5.9 show that there is some association between the criteria per category. Especially, for certain economic and environmental criteria the correlation is high. Though, this is not a surprise. For example *Scrap rate* (C_{16}) is calculated by taking the portion of products that are scrapped from the entire return volume. Then, *Scrap waste* (C_{15}) is calculated by multiplying the number of products that are scrapped with their average weight. Thus, already from the calculation the association could be observed. Besides, there are also some 'less-obvious' correlations between other criteria. For example, the level of competitive pressure in the aftermarket appears to be correlated with the level of IP & design control and technology development speed is correlated with return flow complexity.

5.5 Discussion product category selection

The goal of this chapter is to answer sub-research question 3: *How to determine the opportunities and limitations of applying a Repair Captainship?* Several criteria are selected which play a significant role in the strategic decision-making whether to outsource reconditioning to a Repair Captain or not. Overall, the technical criteria such as *Product design complexity* (C_1) and *Technology development speed (C_3)* are perceived to have strong influence or importance on the opportunity to recondition products at a repair captain. This can be concluded from practical point of view (from The Company's experts) and from scientific point of view (in line with the research of Abbey and Guide (2017)). The MCDM model is created via the AHP methodology and this appeared to be a good method, when comparing the MCDM outcomes with the expectations of the The Company's experts. Though it should be noted that according to Wicher and Lenort (2014), the AHP ignores criteria inter-dependency, whereas some criteria are correlated. According to the results from the following Spearmans' rank correlation test (See Section 5.4.6) there is certain association between criteria. This chapter helps to answer the main research question, while it discussed the criteria that influence the opportunity to outsource the reconditioning activities, of a product category, to a Repair Captain. It is not beneficial for every product category to apply a Repair Captainship. Furthermore, if the opportunities are relatively high, still a firm should assess if a Repair Captain would meet expectations, considering any related risks. These will be discussed in Chapter 6.

6 Application of a Repair Captainship

This chapter provides some additional insights on the topic of a Repair Captainship. After analyzing the opportunities and limitations of a Repair Captainship, it is also important to consider the selection criteria. Several criteria could be important to a firm when selecting a Repair Captain. Based on scientific insights and input from The Company, a couple of criteria are presented. These were obtained via open-ended interviews with The Company experts and through a short literature search. Due to time constraints the selection criteria are not investigated in to depth. Future research should investigate this in further detail. Furthermore, potential risks are not ignored. These main risks are also discussed in this chapter. Overall, this chapter aims to provide some support for firms, in case that a Repair Captainship would be applied in the future. First the Repair Captain selection criteria are discussed. Second the advantages and disadvantages of selecting a current supplier as Repair Captain are discussed. Firms could select a current supplier as repair Captain or select another third-party (repair shop). Third, the advantages and disadvantages of selecting an external third-party are discussed. Lastly, potential risks are discussed that play a role in the selection and of a Repair Captain.
The chapter answers sub-research question 4:

What are criteria, considering related risks, to decide on a suitable Repair Captain?

6.1 Selection criteria to decide on a suitable Repair Captain

Over the last decades, supplier selection has been researched extensively, where the main focus usually lays on choosing the most suitable suppliers. Less attention is given on the criteria formulation (Rezaei et al., 2016). Though, according to Rezaei et al. (2016) criteria formulation should receive more attention. In the past, supplier selection focused on quantitative performance measures such as price and quality. Weber et al. (1991) presented a list of 23 supplier selection criteria, established by Dickson (1966). These 23 supplier criteria are used as base criteria in this research and are summarized in Table E.1 in Appendix E. Besides, Gupta (2013) mentions the following selection criteria: Quality of the delivered products (e.g. could be expressed in terms of the defective rate), Service rate or On-time delivery, Proximity to the customer and Cultural & strategic issues (e.g., flexibility, level of cooperation, information exchange, supplier's green image, supplier's financial stability/ economic performance).

During this research several The Company experts involved with the product category P_{10} were interviewed. The interviews were semi-structured interviews, thus this enabled to ask follow-up questions. The interviewees were always asked the following two main questions:

1. *What are important decision criteria when selecting a Repair Captain and could you elaborate on them?*
2. *Are there any other relevant criteria that are not mentioned in the base supplier selection criteria provided by Weber et al. (1991)?*

In total ten The Company experts answered the interview questions. These ten The Company experts were the group category manager of the electronics; the previous and current category manager of the product category; the senior supply chain manager involved with the logistics concerning the electronic products. Also two experts involved with quality management, namely a supply chain architect and quality supplier manager for one of the main suppliers. Lastly, two current sourcing leads and one previous sourcing lead were a respondent in this research. These sourcing leads are or were each in direct contact with one of the main suppliers. The interviews resulted in a list of selection criteria. These are provided in Figure 6.1.

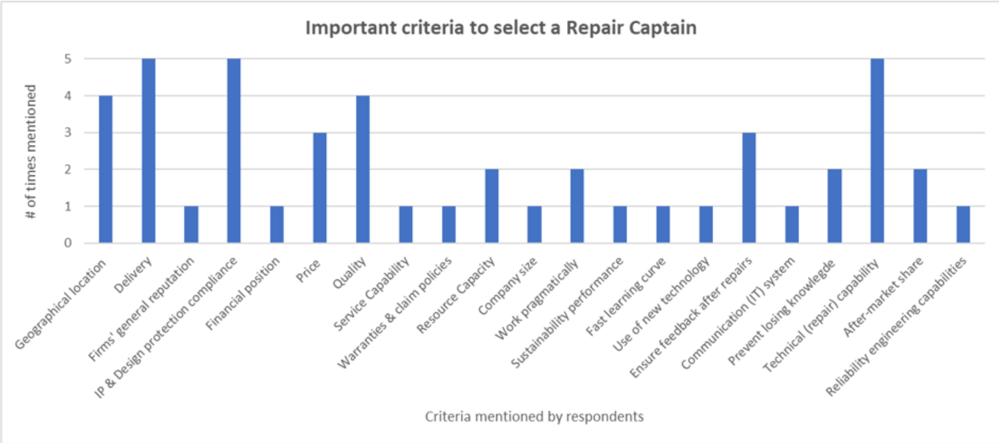


Figure 6.1: Important criteria to select a suitable Repair Captain

According to the respondents, *Delivery*, *IP & design protection compliance* and *Technical (repair) capability* are the most important factors. Respondents emphasize that it is important to make strict agreements with the Repair Captain on the IP & design restrictions. The IP & design are under control of OEMs and The Company and in some cases just the OEMs. During product disassembly a Captain might learn of it, so there is the risk of exposure. The Company and the Captain should ensure that there is a protocol in place according to the respondents. The technical (repair) capability is also important according to the respondents. Due to the high downtime costs of the electronic machines, The Company wants to ensure the products last for a long time period. So the technical (repair) capability of a Captain is essential. The respondents mention that the Captain should not only repair products, but also ensure that the products are repaired against the same quality standards as the OEMs. Though, two respondents mention that they would choose a Captain that *works pragmatically*. According to them, the Captain should ensure good quality of the reconditioned products, but not in the current context. According to them The Company sets relatively high standards to the reconditioned products. They wonder if a Captain should also focus on the physical appearance of the product. The most important aspect is that the product is reconditioned at good quality, according to them. Then, the *Delivery* of a possible Repair Captain. Delivery refers to the delivery leadtimes and the ability of a firm to meet predefined delivery agreements (Weber et al., 1991). They would prefer to choose a Captain close by the customer to keep fast response-times and to reduce the carbon emissions caused by transportation. When respondents mentioned *Geographical location*, they referred to firms close by the customer, but also to the geographical footprint of the firm. A respondent mentioned that the global footprint of a firm could give flexibility (in case of unforeseen circumstances). There seems to be a difference in importance of criteria, when selecting a Repair Raptain in comparison to the regular supplier selection in the forward supply chain. Namely in the forward supply chain, price, quality and delivery are the most important factors (Weber et al., 1991). This criteria are also mentioned by the respondents, but criteria like *geographical location*, *technical (repair) capability* and *IP & design protection compliance* are also frequently mentioned for a Repair Captain.

To identify the most important criteria or the weights of these criteria an AHP method could be applied to obtain criteria weights, see Chapter 5 for this methodology. An MCDM approach with usage of AHP could enable to rank possible Repair Captains (see Chapter 5). There is also the MCDM method that uses the Best-Worst methodology (BWM). This methodology is less time consuming, in comparison with the AHP. This could save a firm some time and would still be a reliable and an accurate method. The BWM method is a relatively new method and, according to Rezaei et al. (2016), it consists of the following five steps: Step 1) Determine a set of decision criteria; Step 2) Determine the best and worst criteria to be used for the decision environment;

Step 3) Determine the preference of the best criterion or best criteria over the other criteria; Step 4) Determine the preference of the other criteria over the worst criterion or worst criteria; Step 5) Find the optimal weights via linear programming.
More details about this method can be found in Rezaei et al. (2016). If a firm would apply a Repair Captainship, more attention should be given to the determine and define the most important selection criteria. Rezaei et al. (2016) mentions that it is important to give attention to the formulation of the selection criteria. The availability of the information and the required time and effort to obtain the data should be considered as well (Govindan et al., 2019).

6.2 Selection of a current supplier as Repair Captain

This section discusses the advantage and disadvantage of selecting a current supplier as Repair Captain. The advantage of selecting a current supplier lays in the trusted relationship between a firm and its current suppliers. If a current supplier would be the Repair Captain, it is not likely that they would abuse a firms' trust. Let's take The Company as an example and suppose that it selects a Repair Captain for a product category. If this Repair Captain would offer its reconditioning activities to The Company's customers directly, this could harm their current business with The Company. Namely, they have business with The Company by providing new-buys to The Company as well. The research of Mokhtar et al. (2019) mentions the importance of trust between firms. According to Mokhtar et al. (2019) firms are more likely to trust eachother when there is mutual interdependence. Nonetheless, selecting a current supplier as Repair Captain has also disadvantages. Certain The Company experts are worried that selecting a current supplier as Captain could lead to conflicts of interest. The Repair Captain is in competition with other suppliers and these may feel threatened by the fact that the Repair Captain would also recondition their products. This could be similar for any other firms than the company. In this case it would be crucial for The Company to work collaboratively with their current suppliers. To involve them in the selection process and to communicate about possible implications of a Repair Captainship. According to Mokhtar et al. (2019) communication gives suppliers the feeling that a firm is concerned about their successes. Note that the reasons provided by Govindan et al. (2019) in Chapter 2 could also influence the advantages or disadvantages to select a current supplier as a Repair Captain.

6.3 Selection of an external third-party as Repair Captain

This section discusses the advantage and disadvantage of selecting an external third-party as a Repair Captain. This third-party could for example be a dedicated repair shop. This third-party could be focused on reconditioning activities only. An advantage of selecting an external third-party as Repair Captain could be that the third-party is not in competition with the current suppliers. Suppliers might be less afraid of IP & design exposure during disassembly, while the third-party is not involved in the forward supply chain. After all, moving products under IP & design control between companies could be complex (Martin et al., 2010). Selecting a third-party has also disadvantages. There is not yet a trusted relationship between The Company and the third-party. Furthermore, the mutual independence as mentioned by Mokhtar et al. (2019) is lower than with the current suppliers. The third-party would only have the reconditioning business with The Company. So, how to prevent that the third-party offers their services directly to the customers (excluding The Company in the process)? Delbufalo (2012) mentions that actively involving a firm in discussions and by providing rewards, the relationship between two firms could be optimised. Lu et al. (2014) also mentions that outsourcing of reconditioning activities depends on the technical capability of third-parties and their brand reputation with regards to ensuring quality. The decision to outsource reconditioning activities to a third-party is also often related to the required investments (Lu et al., 2014). Note that, similar to the current suppliers, the reasons provided by Govindan et al. (2019) in Chapter 2 could also influence the advantages or disadvantages of selecting an external third-party as a Repair Captain.

6.4 Incorporating risks in Repair Captain selection

This section discusses some risks that play a significant role in the selection of a Repair Captain. The first risk is operational risk. This risk is mentioned by some of the research respondents in the interviews. Three respondents mention the challenge to ensure that information systems are able to track the performance history of products, when the defect products are transferred from one supplier to another. This is also related to the challenge of transparency in the reverse supply chain (Thierry et al., 1995; Rogers and Tibben-Lembke, 1998) (see Chapter 3). Furthermore, ideally the Repair Captain would provide feedback about the failure types and design flaws. This requires good technical capabilities, but the Repair Captain is not necessarily the OEM. There could be the risk of loosing knowledge if the Captain does not provide feedback to the firm its reconditioning for. Then, firms should also communicate with the OEMs about the feedback. This could cause operational challenges. One way of dealing with the operational risk is to brainstorm with several people across your firm, the Repair Captain and, possibly, with related OEMs. This gathering should focus on identifying potential operational challenges related to for example, inventory implications of spare parts at the OEMs and the Repair Captain, the capabilities of IT systems, changes to the consolidation of defects and more. This would create awareness for the potential challenges and possibly mitigate the operational risks.

Second, regulations are an important factor, when selecting the Repair Captain and its location. According to Lu et al. (2014) reconditioning has taken place historically in the United States and in Europe, whereas the opportunities to recondition in Asia are growing now. Though, in countries such as China and India reconditioned products are not allowed to be imported. Government support from regulatory perspective and from financial perspective play a role in selecting the location of a Repair Captain. Other reasons are the logistic capabilities and the quality of skilled engineers in a country (Lu et al., 2014). Especially the legislation and regulations in a country can limit the possibilities of a Repair Captainship and should be one of the key drivers in the decision-making. A firm cannot select a Repair Captain without considering the location of a Captain and related regulations and legislation. Thus, a Captain should not be located in a country where important and export of defect products is restricted.

Lastly, political risks should be kept in mind. Govindan et al. (2015) mentions that political risks are uncertain factors as well. Political risk or uncertainty refers to unexpected threats or opportunities caused by political systems or regimes (Miller, 1992). Political uncertainty can be caused by for example war or democratic changes in governments. Political risks should be kept in mind when selecting a Repair Captain. Firms should keep an eye on the political situation in countries. Moreover, when selecting a Repair Captain, a Captain could be chosen that has a global footprint. If for example the political situation changes in a country, the Captain might move the reconditioning activities to one of its facilities in a different country.

6.5 Discussion application of a Repair Captainship

This chapter started with sub-research question *What are criteria, considering related risks, to decide on a suitable Repair Captain?* This is question is answered by discussing several important decision criteria and risks. The criteria and risks are discussed from scientific and practical point of view. The geographical location of a firm, compliance to protect IP & design, meeting delivery agreements and technical (repair) capabilities appear to play a large role. Besides, risks play a role in the selection. There are risks related to selecting a current supplier or an external third-party. Creating a trusted-relationship with the Repair Captain is crucial. Overall, this chapter helps to answer the main research question, while Repair Captain selection criteria and risks are very important in the outsourcing decision-making. A potential captain could have the best economic and environmental performance, but some operational, regulatory or political risks could reduce or even limit the benefits of a captainship. Therefore, these are highly important and crucial to consider.

7 Modeling the implications of a Repair Captainship

This chapter discusses possible economic and environmental implications related to the outsourcing of reconditioning activities to a Repair Captain. Suppose that a firm would have a product category where the opportunities to apply a Repair Captainship are large. Moreover, after establishing selection criteria and considering related risks, a potential Repair Captain is found. Then, a firm would still wonder how to model and compare the performance of a Repair Captain. This chapter aims to support a firm in this situation. Again, results are obtained by applying scientific research methods at The Company. After evaluating the ten product categories with most opportunities to apply a Repair Captainship (see Chapter 5), product category P_{10} is selected for further research. This product category is ranked second and the experts involved in this category are already in ongoing discussions about a possible Repair Captainship. They are also in discussions about this topic with current suppliers as well. Therefore, this product category is selected. This category involves electronic service parts which are placed in electronic racks & cabinets at The Company's customers. The economic and environmental implications of applying a Repair Captainship for this category will be modeled by means of an MCDM model (see Chapter 5). Preferably, other factors such as the risks would be incorporated in the model as well. Though, due to the difficulty to quantify these risks, these are left out of the model. Next, the MCDM model requires to incorporate uncertainty. This is done via the Monte Carlo simulation technique, where several scenarios are analysed. The chapter is structured as follows. First an introduction is given on the selected product category and its characteristics in the reverse supply chain. Second, a short literature review is provided on Monte Carlo simulations and performance indicators for the reverse supply chain. Then, the methodology is discussed and afterwards the results are shown. Next, special attention is given to the scenario analysis of the MCDM model output. In summary, this chapter provides the answer on sub-research question 5:

How to model the economic and environmental implications of a Repair Captainship strategy?

7.1 Introduction product category

This product category represents about 1136 different products and due to upgrades or version changes the product category can even represent thousand different products. The category represents electronic racks & cabinets, but in less than 0.01 % of the cases a defect is an entire cabinet. The electronic cabinets are build in such a modular manner that not the entire cabinet is taken out of the machines of the customers. Therefore most defects are service parts or smaller assemblies. From 2018 until 2020 this product category experienced about 2170 defects. These defects are worth €77,746,680.30 when bought new. These defects are mainly coming from Asia and the United States. The total return volume coming from Asia is 74.39 % of the 2170 defects, 17.2 % is coming from the United States and the remaining 8.41 % is coming from Europe. The new-buy value of these products is also in similar order of magnitude. The defects that are reconditioned successfully are in general repaired and requalified. This holds for about 67.2 % of the defects. Next to this, about 30.7 % of the defects is repaired and requalified with an additional upgrade as well. The remaining 2.1 % of the defects is for part cleaning or an analysis or upgrade only. The focus in this research lays on the repairs (including requalification) and the repairs with upgrades (including requalification), while these represent most of the reconditioning costs and volume. Together with The Company experts, the assumption is made that a Repair Captain could also clean parts if they are also capable of repairing it. There are four main OEMs responsible for manufacturing and reconditioning the products in this category. They have a global footprint with electronics facilities in the United States and Asia, but the reconditioning takes place in their locations in the Netherlands and in Germany. The main reason for this is because their expensive equipment is in the Netherlands and Germany. They cannot just move this equipment to another location for reconditioning, while they usually need this equipment to build new products as well. The investment costs for The Company's specific tooling can vary a lot, but they are usually expensive. A tool can easily cost €147,439.50 for a single product.

7.2 Literature review

This section provides a brief literature review on the evaluation of the reverse supply chain from economical and environmental perspective and on Monte Carlo simulations. MCDM models are already discussed in Chapter 5, Section 5.2. First the performance measurement in the reverse supply chain is discussed and second relevant research about Monte Carlo simulations is provided.

7.2.1 Performance indicators for reverse supply chains

First, the work from Flapper et al. (2005b) suggests to use performance measures that are similar for the forward and reverse supply chain, such as the percentage of returned products, average product quality, average collection costs of returned products and processing costs of returned products. Though, others such as Shaharudin et al. (2017) suggest to use different performance measures for the reverse supply chain. Recently, Shaharudin et al. (2017) mentioned that little has been written about measuring the overall performance or effectiveness of reverse supply chains. Though, their research also addresses this issue. According to Shaharudin et al. (2017), effectiveness of the reverse supply chain can be expressed among others in terms of: Operational cost savings, cost reduction for purchasing raw materials, components or sub-assemblies, minimization of waste for disposal, reduced scrap rates, increased revenue from services after products are sold and increased commitment to invest in environmental management practices. Tan et al. (2003) discusses that other performance metrics (not the traditional metrics) are required and mentions the following metrics: number of returned spare parts having a lower product cost than transportation cost, number of returned spare parts, which had no demand in the past six months or longer ago, number of part that should be scrapped due to authorisation issues, number of returned parts that lack something such as incomplete shipment data and throughput time for the reverse supply chain activities. The performance metrics in the work of Tan et al. (2003) focus more on the financial aspects of the reverse supply chain than the environmental aspects. The work of Kongar (2004) does address the environmental aspects. Sangwan (2017) mentions that there is a need for improved performance measures for both the forward and reverse supply chain, due to recent legislation and environmental issues. Therefore the new performance measures should consider environmental implications in addition to the financial implications. Kongar (2004) discusses five categories of performance indicators, namely:

- From the customer perspective (e.g. on-time delivery ratio and fill rate)
- From process perspective (e.g. demand forecasting, inventory forecasting and resource utilization)
- From financial perspective (e.g. cost-benefit ratio and return on investment)
- From learning and growth perspective (e.g. R&D ratio and Number of employees under training)
- From environmental perspective (the amount of waste, the usage of hazardous material and expenditures for health and safety and for environmental activities)

The research from Ordoobadi (2009) presents formulas to quantify the costs per remanufactured products for an in-house or outsourced remanufacturing strategy. Lastly, the Greenhouse Gas protocol (GHG) enables to calculate carbon emissions caused by transportation. This GHG has world-wide focus and is discussed by Bhatia et al. (2011). There are several other carbon measurement methods such as the network for transport and environment (NTM) method which is applied in Hoen et al. (2014a). Hoen et al. (2014a) select this method because it provides a higher level of detail, but the methodology has a focus on Europe. Other methods such as Artemis and EcoTransIT method are providing more details than the GHG protocol, but these methods are also less known then the GHG methodology and they also have a focus on Europe (Greene and Lewis, 2016). In addition, the more detailed methods also require more detailed information or assumptions to calculate the carbon emissions.

7.2.2 Monte Carlo simulation and scenario analysis

Scenario analyses in combination with Monte Carlo simulations is applied in the context of strategic decision-making for the reverse supply chain by Diaz and Marsillac (2017). Their research focuses on strategic remanufacturing supply chain decisions. According to Diaz and Marsillac (2017), simulations are powerful tools while they can capture complex information. The research of Raychaudhuri (2008) mentions that Monte Carlo simulation is based on repeated random sampling and statistical analysis. The method can be seen as a so-called what-if analysis, while results are not known in advance. Several experiments are done to obtain results. A decision-maker decides on input parameters depending on several factors. These factors are usually subject to risk and evaluated with the Monte Carlo simulation. Often a base case scenario is established that could be a best possible scenario. This scenario is then compared with other scenarios to evaluate possible implications of risk (Raychaudhuri, 2008). According to Stewart (1997), scenarios represent ranges of uncertainties in the real-world that may have consequences. Scenarios are built in such a manner that they represent a possible future state or trend. They should be chosen in such a manner that they reflect possible future uncertainties (Stewart, 1997). Researchers have used a wide range of replications for Monte Carlo simulations, from 50 to 21 000. 5000 replication may be enough, but this is not always the case. However, not much is written on the required number of replications. 7500 to 8000 replications gives stable results according to the research of (Mundform et al., 2011). This research started with 1000 replications and increased this number with 1000 each time to obtain stable results. After around 5000 replications the results became more stable.

7.3 Methodology

This section discusses the steps to model the economic and environmental implications of a Repair Captainship. These steps are modeled by means of an MCDM model including Monte Carlo simulations. The steps are as follows:

- **Step 1: Identification of the model parameters and the economic and environmental decision criteria** $C_1, C2, ..., Cm$

  Several parameters are playing a role in the selection of the most suitable parties to execute the reconditioning activities. These parameters are depicted with The Company's experts. For example, whether a Repair Captain could recondition the entire return volume or whether the Repair Captain is only capable to recondition products under The Company's IP & design control. These parameters will impact the economic and environmental implications of a Repair Captainship. Those implications are represented via certain performance indicators as discussed in Section 7.2. The most important performance indicators are chosen together with the The Company's experts involved in the product category of Racks & Cabinets. More about the selected criteria and the calculation of the economic and environmental implications will be discussed in step 4 and step 5.

- **Step 2: Creation of base assumptions of alternative Repair Captain scenarios**

  The goal of this step is to make an estimation of where a Repair Captain could be located and how a Repair Captain could perform in real-life. In comparison to the current situation (reconditioning at the OEMs), assumptions are made on the performance of the Repair Captain, for example on the reconditioning costs. Certain parameters, such as the reconditioning costs, are assumed to be uncertain over a certain range compared to the OEMs. The statistical distribution of these parameters is unknown and therefore assumed to follow a uniform distribution. According to Barmish and Lagoa (1997) a uniform distribution can be assumed for parameters with limited statistical information.

- **Step 3: Creation of a decision-making tool**

  After step 1 and 2, a decision-making tool is created. This decision-making tool is based on historical data of the defects in the racks & cabinets category P_{10} coming from the field from the year 2018 until 2020. This tool is created in Microsoft Excel, while the The Company's experts are most familiar with Excel. This makes it possible for them to use or adjust the model also after the duration of the research. The historical data does only represent the return volume from 2018 until 2020, whereas strategic planning decisions are usually based on a five year planning horizon (Manzini and Bindi, 2009). Therefore, return volume forecasts should be made for 2021 until 2026.

After analysing the historical data (see Appendix D), there seems to be an upward trend, where the number of returns is increasing over time, with some fluctuations. In addition The Company's experts are expecting the return volume to grow in the upcoming years. Therefore the double exponential smoothing (DES) method is applied to forecast the return volume. This method takes a trend in to account (Nahmias and Olsen, 2015). Besides, additive triple exponential smoothing, also known as additive Holt-Winters (HW), is applied as well. This methodology considers a trend and seasonality. The additive type of the HW method is used for time series where the the amplitude of the seasonal pattern is independent of the level of the series (Chatfield, 1978). If there is any seasonality in the return volume, then this seasonality seems to be additive. More about the forecasting methods could be found in Nahmias and Olsen (2015); Nazim and Afthanorhan (2014); Gardner Jr (2006); Taylor (2003).These forecasts are evaluated using the Mean Square Error (MSE), Mean Absolute Percentage Error (MAPE) and the Root Mean Square Error (RMSE) (Nahmias and Olsen, 2015; Chang et al., 2007; Sidqi and Sumitra, 2019). According to Chang et al. (2007), a MAPE between 10 percent and 20 percent has a good forecasting accuracy. Double exponential smoothing (DES) gave the best forecasting results after evaluating the MAPE, MSE and RMSE. The MAPE was also within the range of 10 to 20 percent. This is a widely used method that considers any trends and seasonality (Taylor, 2003). It should be taken into account that building these forecasts is not the main focus of the research. Thus, the forecasts are not perfect, but accurate enough according to the MAPE (see Appendix D).

Next to the return volume, the model will include variables such as the total return volume per year per country, the total reconditioning costs for all defects per year per country, the new-buy value of the defect products, the total transportation costs per year from The Company's local warehouses to its central warehouses and back for the specific defects in this product category, the percentage of successful reconditioning activities, percentage of scrapped products and products waiting to be processed per year and defects their lead times from defect until action (scrap or reconditioning). The calculations for required parameters are discussed in Section 7.4.1.

- **Step 4: Calculation of an economic score**

  The economic score is determined by the total average reconditioning costs per reconditioned product per year for each alternative strategy (e.g. OEMs and Repair Captains) in the MCDM. This reconditioning cost includes transportation costs, duty costs, the NOK analysis costs, hidden costs and investment costs in The Company's specific tooling. These parameters are discussed in more detail in Section 7.4.1. The average total costs per reconditioned unit per year is expressed in equation 7.1.

  After calculating UC for each alternative strategy, an economic factor is calculated via the SAW function, see equation 5.2 in Chapter 5. The lowest value of UC is preferred, implying that equation 5.4 is used in the SAW function. A single criterion is used for the economic score output and therefore the weight of this criterion is 1. When only focusing on the economics, the alternative with the highest economic score is the optimal reconditioning strategy.

$$UC = \frac{\frac{1}{5} * C_a^I + \sum_{n=0}^{N}(C_{ap,n}^R + C_n^H) + SS * C^{NOK} + \sum_{x=0}^{N+O+SS}(2 * C_{w^t odm,x}^T + C_x^D)}{N} \quad (7.1)$$

Parameter	Description
N	Amount of products that are successfully reconditioned
SS	Amount of products that are scrapped after analysis done by the supplier
O	Amount of products 'open', not yet scrapped or reconditioned successfully
C_a^I	Investment costs for The Company's specific tooling depending on the reconditioning activity a. The assumption is made that these investments would last five years and that they are depreciated in five years.
$C_{ap,n}^R$	Reconditioning costs for a product n under reconditioning activity a and of type p
$C_{w^t odm,x}^T$	Costs for transporting a product x of average transportation weight w^t between origin o and destination d by transportation mode m. The transportation from local warehouse to central warehouse or from central warehouse to Repair Captain is considered and the other way around. Namely, after reconditioning the parts are send back to the local warehouse again. Therefore this parameter is multiplied by two in equation 7.1
C_x^D	Duty costs for importing and exporting a product. These are assumed to be between 2 % to 8 % of $C_{ap,n}^R$
C_n^H	Hidden costs for knowledge transfer, when reconditioning at a Repair Captain. These are assumed to be between 5 % to 7 % of $C_{ap,n}^R$
C^{NOK}	Costs for a product that is scrapped after analysis by the supplier

- **Step 5: Calculations of an environmental score**

  The environmental score is determined by the scrap rate SR, CO_2 emissions caused by transportation CO_2^T and the scrap waste SW for each alternative strategy. The used calculation for the scrap rate is as follows:

$$SR = \frac{SS + SL}{N + SS + SL} \quad (7.2)$$

$$SR = 1 - RY \quad (7.3)$$

In equation 7.10 and 7.11, RY is the repair yield and the formula for RY is shown in Section 7.4.1, equation 7.10 or 7.11. SL is the amount of products that are scrapped at the local warehouse without undergoing any analysis at the supplier. The assumption is made that the ratio between scrap after analysis at the supplier and scrap at the local warehouse remains similar to the ratio in the current situation for a Repair Captain.

The scrap waste is expressed in equation 7.4:

$$SW = \sum_{x=0}^{SS+SL}(w_x) \quad (7.4)$$

In equation 7.4, w_x refers to the average weight of product x, excluding packaging. Then the carbon emissions caused by transportation are expressed with equation 7.5. This equation is based on the distance-based method to calculate scope 3 emissions caused by transportation, according to the GHG protocol (Bhatia et al., 2011).

$$CO_2^T = 2 * \sum_{x=0}^{N+SS+O} (w_x^t * Y_{od,x} * f_{m,x}^{co_2}) \tag{7.5}$$

Parameter	Description
w_x^t	Average transportation weight of product x (including packaging)
$Y_{od,x}$	The average distance between the origin o and destination d for product x
$f_{m,x}^{co_2}$	Transportation emission factor for transportation mode m in kilogram CO_2 emissions per ton*kilometer. The transportation mode $m = \{1$: Air, 2: Sea, 3: Rail, 4: Road$\}$. According to The Company's experts and their third-party logistics service providers, $f_{m,x}^{co_2}$ can be expressed as follows in kilogram CO_2 emissions per ton$*$kilometer: $f_{1,x}^{co_2} = 0.742$, $f_{2,x}^{co_2} = 0.010$, $f_{3,x}^{co_2} = 0.016$ and $f_{4,x}^{co_2} = 0.140$.

After calculating SR, SW and CO_2^T for each alternative strategy, an environmental factor is calculated via the SAW function, see equation 5.2 in Chapter 5. Again, lower values are preferred per criterion. So equation 5.4 is used in the SAW function. The weights for the three environmental criteria are based on the weights obtained in Chapter 5. This results in the following weights for respectively SR, SW and CO_2^T:

$$W_{SR} = \frac{0.0232}{0.0615} = 0.3772 \tag{7.6}$$

$$W_{SW} = \frac{0.0156}{0.0615} = 0.2537 \tag{7.7}$$

$$W_{CO_2^T} = \frac{0.0227}{0.0615} = 0.3691 \tag{7.8}$$

When only focusing on the environmental implications, the alternative with the highest environmental score is the optimal reconditioning strategy.

- **Step 6: Calculation of one final score**
This model enables to play with economic and environmental weights. These are not calculated via for example an AHP method like in Chapter 5. Instead, these weights are flexible in the decision-making tool. The weight W_i for the economic score is always between 0 and 1 and this holds for the environmental score as well. Thus equation 7.9 holds:

$$\sum W_i = 1 \tag{7.9}$$

In equation 7.9 i refers to either economic or environmental. These weights are runned over the entire scale from 0 to 1 to investigate when the decision for OEMs or Repair Captainship might change. The weights are changed in steps of 0.1. These weights should still meet equation 7.9, where $0 \geq W_{Economic} \leq 1$ and $0 \geq W_{Environmental} \leq 1$. Running the results over the entire scale from 0 to 1 enables to analyse the extremes (e.g. $W_{Economic} = 1$ & $W_{Environmental} = 0$) and all other weight combinations.

These weights are then used in the SAW function, see equation 5.2 in Chapter 5. The MCDM consists then of two criteria, namely the economic factor and the environmental factor. Depending on the chosen weights for the economic score and for the environmental score a final score is obtained.

7.4 Results

This section provides insights on the MCDM model that is build. First the model, the parameters and additional mathematical equations are discussed. Second, the base assumptions for the performance of a Repair Captain are provided. Third, a couple of scenarios are analyzed.

7.4.1 Multi-criteria decision-making model

The goal of the MCDM is to select the optimal reconditioning strategy. Three reconditioning strategies are compared:

- Reconditioning at the OEMs, mainly located in the Netherlands and Germany. This is the current strategy at The Company
- Reconditioning of products at a possible Repair Captain in Korea
- Reconditioning of products at a possible Repair Captain located in both Korea and Taiwan

The comparison is done by creating a model with flexible input parameters, for example by determining the type of reconditioning activities that are executed. These parameters influence the strategic decision when comparing possible Repair Captains with the current reconditioning at the OEMs. At the moment, The Company is using a couple of criteria when evaluating suppliers performance. Namely Quality, Logistics, Technology, Costs and Sustainability. Therefore, these criteria are also considered when comparing the different reconditioning alternatives (e.g. Repair Captainship versus OEMs). Per criteria there are several parameters to consider when evaluating the performance per reconditioning alternative. These parameters enable to calculate an economic score and an environmental score. Depending on the given input weight for the economic implications and the weight for the environmental implications a final score is calculated. Then, the strategy with the highest score is the preferred reconditioning outsourcing strategy. The goal, relevant criteria, parameters and process of selecting a reconditioning strategy are visualized in Figure 7.1. The parameters, shown in Figure 7.1 are shortly described per criteria.

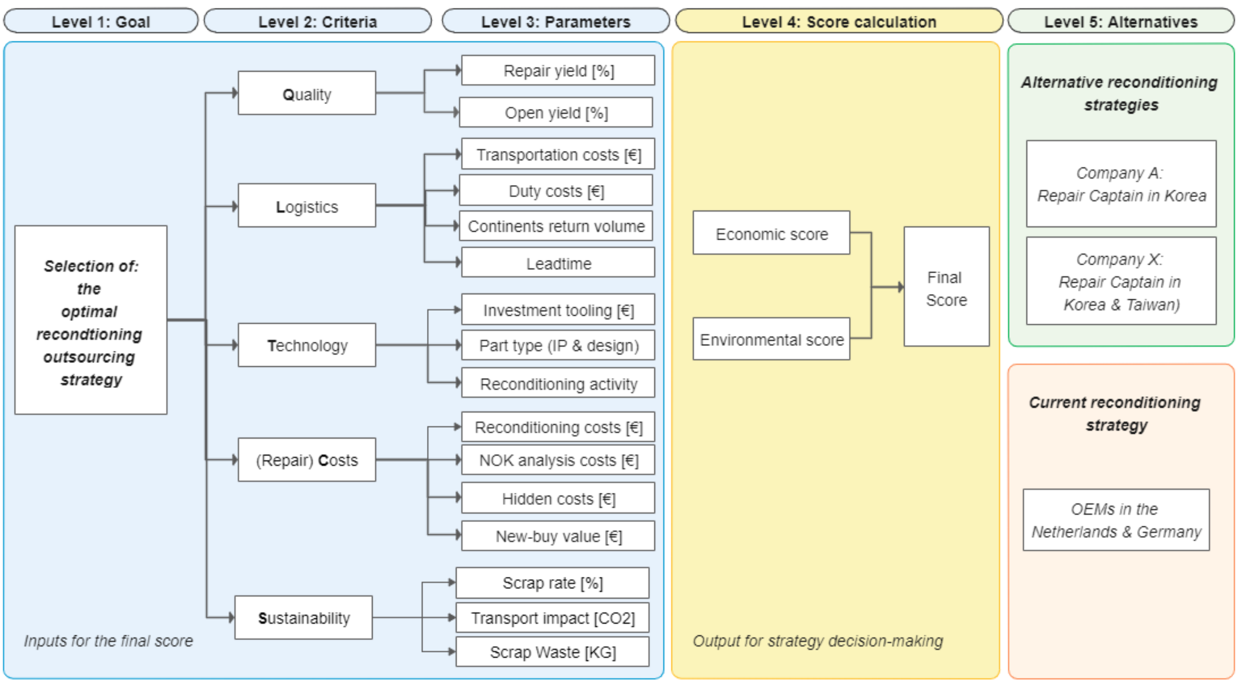


Figure 7.1: The decision-making model parameters

Quality parameters

- *Repair yield* (RY) is the fraction of defect products that are successfully reconditioned out of the products that were either reconditioned successfully or scrapped. The repair yield is calculated via equation 7.10 or 7.11:

$$RY = \frac{N}{N + SS + SL} \tag{7.10}$$

$$RY = 1 - SR \tag{7.11}$$

- *Open yield* (OY) refers to the fraction of defect products that are not yet scrapped or reconditioned successfully of all returned defects. This is calculated via equation 7.12

$$OY = \frac{O}{N + SS + SL + O} \tag{7.12}$$

Logistics parameters

- *Transportation cost* ($C^T_{w^t odm,x}$) refers to the average cost to transport a product of average transportation weight w^t between origin o and destination d by transportation mode m. The transportation mode $m = \{1\text{:Air, 2:Sea, 3:Rail, 4:Road}\}$. The origin and destination are either the local warehouse, central warehouse or the possible location of the Repair Captain.
- *Duty cost* (C^D_x) refers to the cost to import or export a product x. This cost is somewhere between 2 % to 8 % of the reconditioning cost per defect $C^R_{ap,n}$.
- *Continents return volume* refers to the returns per continent. The model enables to decide which defects to recondition at a Repair Captain based on the location of the defects. A user can decide to include or exclude the defect products from Europe, Asia and the United States.
- *Leadtime* ($L^R_{a,n}$) refers to the average reconditioning lead time in days depending on the reconditioning activity a for a product n. From the moment that products fail at the customer site until the products are reconditioned successfully.

Technology parameters

- *Investment tooling* (C^I_a) refers to the costs for The Company's specific tooling. A firm that would execute the reconditioning would require to make additional investments to be able to execute reconditioning activity a for a large variety of defects.
- *Part type (IP & design) (p)* refers to whether or not the defect products are under The Company's IP & Design control or not. $p = \{1\text{: IP \& Design control, 2: No IP \& Design control}\}$
- *Reconditioning activity (a)* refers to the type of reconditioning activities that a Repair Captain could do, where $a = \{1\text{: Repair (including requalification) and repair \& upgrades (including requalification), 2: Repair (including requalification) only}\}$

(Repair) Costs parameters

- *Reconditioning costs* ($C^R_{ap,n}$) for a reconditioned product n depend on reconditioning activity a and of type p.

- *NOK analysis costs (C^{NOK})* are the costs for a defect product that is analysed by the supplier, but scrapped in the end. A fixed value of €786 is assumed, but any decision-maker can change this input in the model.
- *Hidden costs (C_n^H)* are the costs per defect n for knowledge transfer, when reconditioning at a Repair Captain. These are between 5 % to 7 % of $C_{ap,n}^R$, assuming a uniform distribution.
- *New-buy costs (V_n^B)* refers to the costs for buying a new product n, e.g. price paid to the supplier to obtain this product (excluding transportation and duty costs). Thus this reflects the value of a new product instead of a reconditioned product.

Sustainability parameters

- *Scrap rate (SR)* is the fraction of defect products that are scrapped out of the products that were either reconditioned successfully or scrapped. Equations 7.2 and 7.3 show how the scrap rate is calculated.
- *Transportation impact (CO_2^T)* refers to the total CO_2 emissions caused by transportation of the defect products between local warehouses and central warehouses or between local warehouses and a Repair Captain. The GHG protocol is used to calculate this impact in kilogram of CO_2 emissions per ton per kilometer. Equation 7.5 shows the required computation.
- *Scrap waste (SW)* refers to the total weight in kilograms of the defect products that are scrapped. This is calculated via equation 7.4.

The parameters included in the model enable to calculate the economic score and environmental score mentioned in section 7.3. Four forecasts have been made to determine the demand for combinations of reconditioning activity a with the type of products P. These forecast are provided in Appendix D. Based on the historical data of the defects from 2018 until 2020, the portion of the volume, costs and values of the defects are determined per origin o. This origin refers to the country where the defects occur. While the model enables to select the return volume from Asia, United States and Europe, also weighted-average calculations are done. This enables to obtain the data for these locations. Furthermore, some additional economic insights can be determined in terms of the cost reduction for reconditioning products instead of buying a new product. This is shown in equation 7.13.

$$CR = \frac{\sum_{n=0}^{N}(V_n^B + C_{w^t odm,n}^T)}{N} - UC \tag{7.13}$$

Also, the total reconditioning costs excluding transportation and duty costs can be calculated to determine the impact that transportation has on the total reconditioning costs. This leads to equation 7.14.

$$UC_{excl.transport\&duties} = \frac{\frac{1}{5} * C_a^I + \sum_{n=0}^{N}(C_{ap,n}^R + C_n^H) + SS * C^{NOK}}{N} \tag{7.14}$$

Next, the return-on-investment (ROI) can be calculated. This is a parameter that some of The Company's experts would like to see. Besides, Brealey et al. (2012) mention that managers are sometimes using the ROI to assess the performance of certain divisions or production facilities. To calculate this first the total reconditioning costs per reconditioned product excluding the investments should be calculated and the cost reduction or savings excluding the investments. These are respectively equation 7.15 and 7.16 and the ROI is given in equation 7.17.

$$UC_{excl.investment} = \frac{\sum_{n=0}^{N}(C_{ap,n}^R + C_n^H) + SS * C^{NOK} + \sum_{x=0}^{N+O+SS}(2 * C_{w^t odm,x}^T + C_x^D)}{N} \tag{7.15}$$

$$CR_{excl.investment} = \frac{\sum_{n=0}^{N}(V_n^B + C_{w^t odm,n}^T)}{N} - UC_{excl.investment} \quad (7.16)$$

$$ROI = \frac{C_a^I}{(CR_{excl.investment,captain})(N_{captain}) - (CR_{excl.investment,oem})(N_{oem})} \quad (7.17)$$

In equation 7.17, $N_{captain}$ and N_{oem} are respectively the number of succesfully reconditioned products by the Captain and the OEMs. Similarly, the cost reduction is included for the repair Captain and the OEMs.

Certain economic and environmental implications are not included in the model. The first implications that are not included are warranty costs. The Company would potentially absorb these costs, if products under warranty are reconditioned at a Repair Captain instead of the OEM. However the number of successful warranty claims at the OEMs represent less then 0.1 % of the return volume. Besides, perhaps The Company could make new warranty agreements with the OEMs to include Repair Captainship. Second, the lead time reductions are not expressed in cost reductions due to a lack of detailed information. Certain approximations could be made in terms of calculating the impact that lead time reduction has on the change of the inventory of service parts, for example by 'the average value of the reconditioned products per year' ∗ 'lead time reduction' ∗ 'weighted average cost of capital (WACC)'. This calculation is determined with two The Company experts. Note that this would remain an estimation only.

7.4.2 Assumptions per alternative Repair Captain scenarios

There is much uncertainty in the performance of a possible Repair Captain. Therefore assumptions are made on the location and performance of a possible Repair Captain, compared to the OEMs. Two alternatives are determined. The first one is a Repair Captain located in Korea. As the largest fraction of the return volume is coming from Korean customers, namely 29.76 %. At first for certain parameters the assumption is made that these are similar to the performance of the OEMs. Additionally, The Company's experts have made an assumption on the required investment costs for The Company's specific tooling for the Repair Captain. These parameters are shown in Table 7.1.

Table 7.1: Base assumption on selection parameters for a Repair Captain

Input	Assumption
Reconditioning activity	Captain does all reconditioning activities. Namely, repair (incl. requalification) and repair & upgrades (incl. requalification). The average number of remanufactured products per year will impact the costs per remanufactured unit. The costs decrease for larger succesfully reconditioned volumes (Ordoobadi, 2009).
Type of products (IP & design)	Captain reconditions all defect products, with or without The Company's IP & design control. Also here the volume can determine the costs per remanufactured unit and the benefit of the investments (Ordoobadi, 2009).
Continents return volume	Captain reconditions all defect products, from each continent in the world. Also here the volume can determine the costs per remanufactured unit and the benefit of the investments (Ordoobadi, 2009). Besides, carbon emissions can change depending on the origin and reconditioning location of the defects.
Investment tooling	Investments in The Company's specific tooling are € 3 million for repair (incl. requalification) and repair & upgrades (incl. requalification). For repair (incl. requalification) only the investments are € 1 million
NOK analysis costs	The costs for analyzing defects that will be scrapped are € 524 per defect that is sent to the supplier and is scrapped afterwards. This assumption is based on available data estimations, but the number can always be changed.
Transportation mode	Defect products are transported from local warehouse to the Repair Captain and back via airplane (like in the current situation). Only defects in the country of the Repair Captain are sent via road to the Captain.

Also other base assumptions are made. Certain parameters, such as repair yield and reconditioning costs, are assumed to be uncertain over a certain range compared to the OEMs. The distribution of these parameters is unknown and therefore assumed to follow a uniform distribution According to Barmish and Lagoa (1997) a uniform distribution can be assumed for parameters with limited statistical information. These range assumptions, on lower and upper bounds for the uniform distribution, with the related reasoning are provided in Table 7.2. The second Repair Captain would be a company with a repair facilities in both Korea and Taiwan. According to the The Company's experts it could be interesting to compare a Repair Captain in one country with a Captain that would be located in two countries. The second largest fraction of the return volume is coming from Taiwan (23.56 %) making this an interesting location next to Korea. The base assumptions are assumed to remain the same as for the Repair Captain in Korea, only the location would be different. Thus, the assumptions in Table 7.1 and 7.2 are assumed to be similar for a Repair Captain in Korea and Taiwan. The parameters in Table 7.1 and 7.2 enable to build Monte Carlo simulations for the Repair Captain alternative in Korea and the alternative in Korea & Taiwan. The following variables are simulated: 'Reconditioning costs $C^R_{ap,n}$', 'Reconditioned volume N', 'Open volume O', 'Scrap volume' $SS+SL$, 'Leadtime L^R_a, 'Duty costs C^D_x' and 'Hidden costs C^H_n'.

Table 7.2: Base assumptions on (uniform) parameter ranges for a Repair Captain

Input	Lower bound compared to OEMs	Upper bound compared to OEMs	Practical & scientific explanation
Repair yield	-5 %	+10 %	The Company's experts mention that for example their current suppliers have the capabilities to recondition products produced by other manufacturers. They expect the repair yield to slightly increase, but the repair yield could also be slightly lower.
Open yield	0%	0%	There is not enough information to assume that the volume of products awaiting to be scrapped or reconditioned would be higher or lower than the OEMs
Reconditioning costs	-15 %	+0 %	Maximum cost saving due to the economies of scale, when consolidating the return value, could be around 9 % to 15 % according to Ketler and Willems (1999). Besides a current supplier estimated a possible reduction of 6%. There are also differences in labor rates per country and these are assumed to be considered in this cost reduction.
Lead time	-50 %	-30 %	The lead time would already decrease due to reduced transportation times and reduced time spent on cost alignment. Next, The Company's experts expect that consolidation of the returns and the collection of the reconditioned parts would be improved. While the reconditioning takes about 35 out of 119 days and the Repair Captains could initially require more time to recondition the products, no more than a 50 % reduction is assumed.
Hidden costs	+5 %	+7 %	Egorova and Sorokina (2018) mentions that there could be hidden costs related to outsourcing. Besides, The Company's experts would also expect the Repair Captain to provide feedback on design flaws or other issues related to the defects products. According to Egorova and Sorokina (2018) the additional hidden costs for knowledge transfer could be between 5% and 7% of the total costs payed to the third party. Senthil et al. (2018) mentions that unknown hidden costs could be a potential risk in reverse supply chains.

The Repair Captainship will be compared in six different scenarios. These will be discussed in Section 7.4.3 to 7.4.8. A short description of the scenarios and the main reason for modeling these are provided in Table 7.3.

Table 7.3: Short scenario motivation

Scenario	Description	Reasoning
1: Base scenario	This scenario follows the assumptions made in Table 7.1 and Table 7.2	To evaluate the performance of a potential Repair Captain based on scientific and practical performance expectations.
2: Base scenario, equal repair yield	This scenario follows the same assumptions as the base scenario, only the repair yield of the Repair Captain is assumed to be equal to the repair yield of the OEMs.	To eliminate the impact of repair yield in the performance comparison.
3: Base scenario, excluding locations	This follows the same assumptions made as in the Base scenario, only certain locations of defects are excluded for the Repair Captain.	To evaluate whether a Repair Captainship would still make sense, when less volume is consolidated and to evaluate the environmental implications of excluding locations.
4: Base scenario, including different intercontinental transportation mode	This follows the same assumptions made as in the Base scenario, only the intercontinental transportation is shipped via ocean instead of by plane.	To evaluate the environmental implications of this decision.
5: Worst case scenario	This scenario incorporates the risk that a Captain could not meet all base assumptions. This would decrease the volume for a Repair Captain	To evaluate whether a Repair Captainship would still make sense, when less volume is consolidated. Moreover, this also incorporates the uncertainty whether or not a Repair Captain could meet the technical repair specifications.
6: Different Repair Captains in one country	This scenario compares potential Repair Captain candidates, where the selection of a current supplier and an external third party is compared.	To show how the model can be used to compare potential candidate Captains. Besides, different type of Captains are evaluated. These have been discussed in Chapter 6.

7.4.3 Scenario analysis 1: Base scenario

This section compares the current reconditioning strategy (at the OEMs) with two possible alternatives. One alternative is a Repair Captain located in Korea, whereas the other Repair Captain is a company that would be located in both Korea & Taiwan. The base assumptions determined in Section 7.4.2 hold initially for the Repair Captain(s). So the OEMs, Repair Captain in Korea and the Repair Captain in Korea & Taiwan are compared assuming that they would recondition all product types (with and without IP & design control) and do all reconditioning activities (both repair and upgrades). There are no investments for the OEMs while they are already in possession of the required equipment in the current situation. For the Repair Captain in Korea € 3 million euros investment are assumed and these are doubled for the Repair Captain in Korea & Taiwan. The assumption is made that having a Captain in two locations would double the investment costs. This assumption could always be adjusted if The Company or the Repair Captain would decide to distribute the defects in a more optimal way between the two locations. For now it is assumed that the defects are sent to the closest location. When comparing the three alternatives in this scenario, the corresponding costs can be analyzed. These are presented in Figure 7.2.

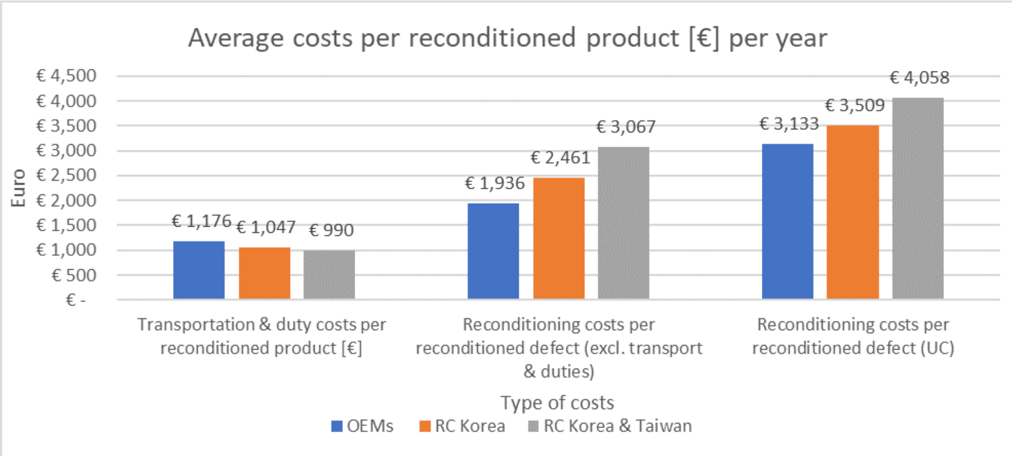


Figure 7.2: Comparison of the three base alternatives on costs

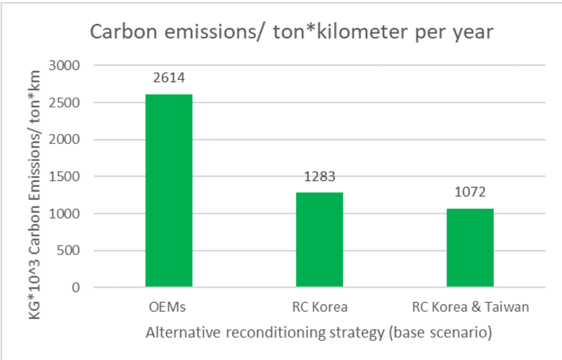
Overall, the OEMs are cheaper while their reconditioning costs (excluding transportation and duties, but including investments) per reconditioned product are lower. The repair yield (RY) of the Repair Captains is just slightly higher than the repair yield of the OEMs. RY of both the Repair Captains is 40 %, whereas the RY of the OEMs is 37 % . So this has not sufficient impact on the reconditioning costs (excluding transportation and duties). Moreover, both the Repair Captains have to make investments in specific tooling. This explains why the Repair Captain in Korea & Taiwan would be more expensive than the Repair Captain in Korea. However, the transportation costs per reconditioned product (including duties) are more expensive in the current situation (OEMs): these are about € 1047 for the captain in Korea and € 990 for the captain in Korea & Taiwan. If the Repair Captain in Korea & Taiwan is chosen, then the products coming from Taiwan, China, Singapore and Hongkong would be reconditioned in Taiwan. This accounts for 44 % of the defects in the product category. The remaining 56 % is sent to Korea. This explains why the transportation & duty costs are lower for the Repair Captain in Korea & Taiwan. In the end, the cost reduction (CR) or savings are positive for all three scenarios. The new-buy value of the products is on average € 5735 and the related transportation costs are € 572, so even reconditioning at a Repair Captain is always cheaper than buying a new product. Besides, the ROI is equal to 5.7 years for the Repair Captain in Korea. According to a The Company expert usually a threshold of 1.5 years is used to evaluate such decisions. The Repair Captain in Korea would not meet this requirement. The Repair Captain in Korea & Taiwan has an ROI of 9.6 years, so this alternative would also not meet the treshold. The ROI is calculated via equation 7.17 and the numbers to calculate this ROI are presented in Table 7.4.

Table 7.4: ROI input parameters

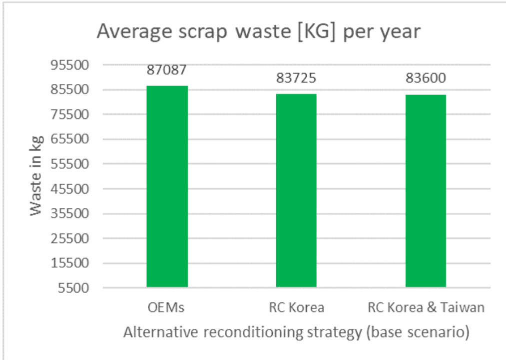
	OEMs	**RC Korea**	**RC Korea & Taiwan**
Reconditioning costs per reconditioned defect/year, excluding investment ($UC_{excl.investment}$)	€ 3113	€ 2897	€ 2835
Cost reduction per reconditioned defect/year, excluding investment ($CR_{excl.investment}$)	€ 2316	€ 2532	€ 2594
Investment cost C_a^I		€ 4.5 million	€ 9 million
Number of reconditioned defects/year, (N)	2070	2204	2210
ROI in years	0.0	5.7	9.6

Next, the environmental implications are investigated. On the one hand, the two alternative

Repair Captain strategies would both lead to a scrap rate of about 60 %, whereas currently the scrap rate is 63 %. The Scrap rate of the Repair Captains is obtained via equation 7.2 and 7.3, with the assumptions provided in Table 7.2. Thus, this decrease is relatively small. Therefore the average scrap waste per year is similar. This is also visualized in Figure 7.3b. On the other hand, there are also carbon emissions caused by transportation. Changing the reconditioning strategy to the Repair Captain in Korea leads to a 50 % reduction of the CO_2 emissions. The Repair Captain in Korea & Taiwan would even reduce the CO_2 emissions by 58 %. Those carbon emissions caused by transportation are calculated via equation 7.5 and are visualized in Figure 7.3a.



(a) Comparison of the three base alternatives on carbon emissions



(b) Comparison of the three base alternatives on scrap waste

Figure 7.3: Environmental implications base scenario

To decide on the most optimal reconditioning strategy, an MCDM is created and solved as discussed in Section 7.3. The criteria to solve this MCDM and the performance values are provided in Table 7.5. The resulting final scores, depending on the weight of the economic and environmental criteria, are shown in Figure 7.4. The alternative with the highest score is the most optimal reconditioning strategy, depending on the weight of the economic and environmental implications.

Table 7.5: MCDM performance values for the base scenario comparison

Alternative	**Reconditioning costs per reconditioned defect** (UC)	**Scrap rate** (SR)	**Scrap waste** (SW) [KG]	**Transportation impact** (CO_2^T) [KG]
OEMs	€ 3113	63 %	87087	2614004
RC Korea	€ 3509	60 %	83725	1283052
RC Korea & Taiwan	€ 4058	60 %	83600	1072453

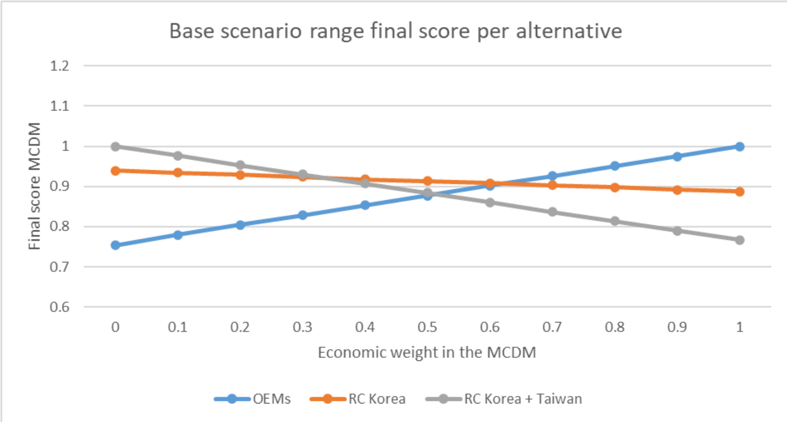


Figure 7.4: Final score comparison of the three strategies in the base scenario

Figure 7.4 shows that the Repair Captain in Korea & Taiwan is preferred for $W_{Economic} \leq 0.3$. The Repair Captain in Korea is preferred for $0.4 \geq W_{Economic} \leq 0.6$ and the OEMs are preferred when the economic weight exceeds 0.6. When the focus lays on the economic implications only, reconditioning at the OEMs is the optimal reconditioning strategy. If the focus lays on the environmental implications only, then the Repair Captain in Korea & Taiwan would be the best alternative. This final score depends on several parameters and the assumptions made. Therefore it is also important to understand how the score could change in a different setting. Therefore, a sensitivity analysis is conducted.

A couple of parameters are changed in isolation now. Thus, all other assumptions remain the same and only a selected parameter is changed. First the assumptions on the repair yield, investment costs and reconditioning costs for the Repair Captain in Korea are changed separately. It is done for the Repair Captain in Korea only, but any decision-maker could use the model to check this for the Repair Captain in Korea & Taiwan as well. The ranges for these parameters, as mentioned in Table 7.2, are reduced by 10 % for the first comparison, and increased by 10 % for the second comparison, to observe the impact on the reconditioning costs (UC) per reconditioned defect. The results are shown in Figure 7.5.

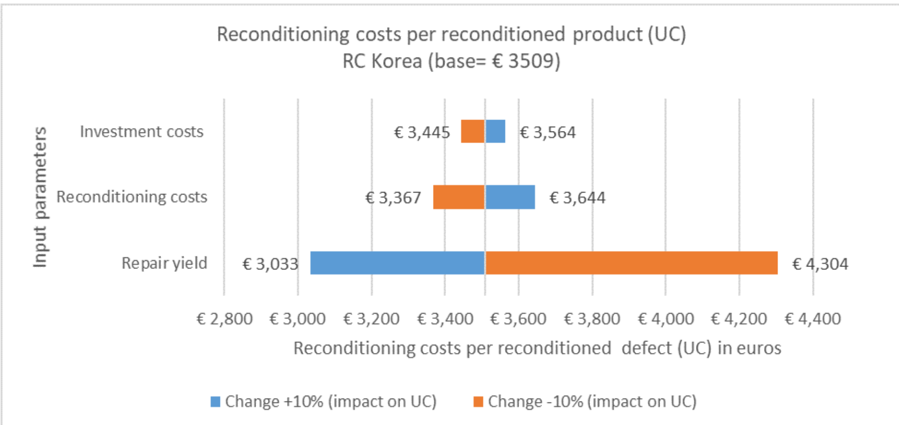


Figure 7.5: Impact of input parameter changes on the reconditioning costs per defect (UC) for RC Korea

Figure 7.5 shows that, assuming all other assumptions hold, a small increase (+10%) of the repair yield will lead to a significant lower UC. Increasing the assumed repair yield with 10% leads even to a lower cost than the OEMs: UC will be € 3033 for the Repair Captain, while UC of the OEMs currently is € 3113. This would imply that the Repair Captainship is preferred over reconditioning at the OEMs, when the repair yield is increased by 10% compared to the base assumptions. For a Repair Captain located in Korea & Taiwan, the repair yield should increase by 20 % to become cheaper than the OEMs. Changing the parameter ranges for the investment costs and reconditioning costs appear to have less influence on the UC of the Repair Captain in Korea. After running multiple simulations to test this, it appears that the investments should decrease by 70 % to obtain a UC lower than the OEMs. Some investments are unavoidable, making this not a plausible option in real-life.

Similarly, the impact of a 10 % increase or decrease in repair yield range is also evaluated for the emissions caused by transportation for the Repair Captain in Korea. The impact of a different repair yield is also investigated for the carbon emissions caused by transportation for the Repair Captain in Korea. Though, this increases or decreases the kilograms of carbon emissions by about 5 %. These emissions are far below the emmissions in the current situation (OEMs). The impact of repair yield on the carbon emissions is shown in Figure 7.6 and is calculated via equation 7.5.

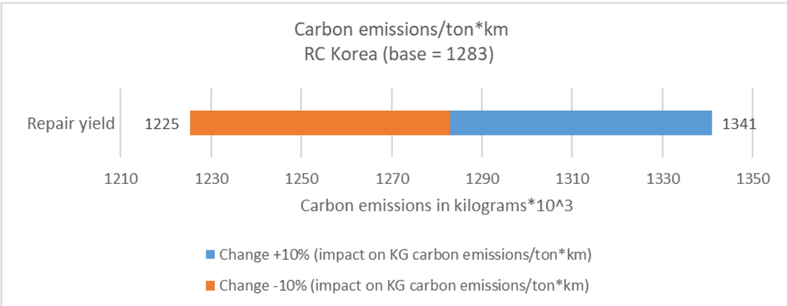


Figure 7.6: Impact of repair yield range change on the carbon emissions for RC Korea

7.4.4 Scenario analysis 2: Base scenario, equal repair yield

This section shows the comparison between OEMs, the Repair Captain in Korea and the Repair Captain in Korea & Taiwan. Again the base scenario is modeled, but the repair yield is assumed to be equal among all alternatives. Except the repair yield, all other assumptions provided in Table 7.1 and 7.2 hold. This scenario is analysed to eliminate the impact that repair yield has on the results. The main costs of the three alternative strategies are provided in Figure 7.7.

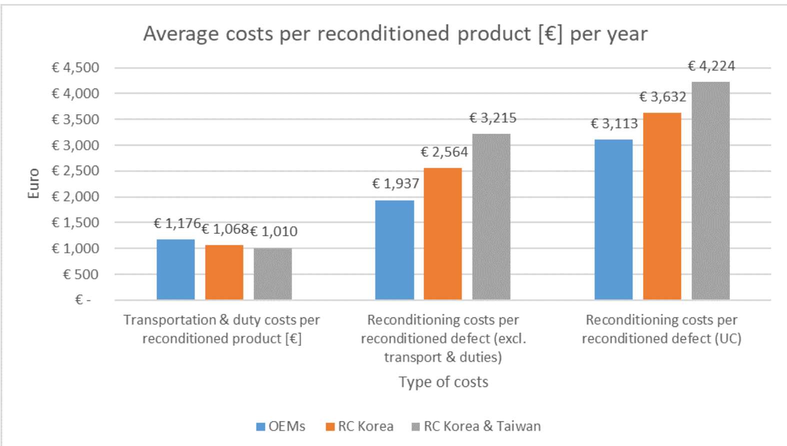
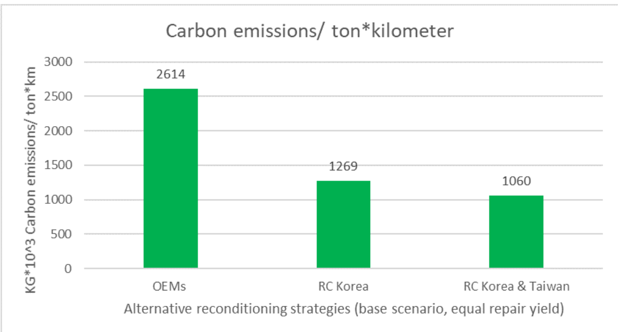


Figure 7.7: Cost comparison of the three base alternatives with equal repair yields

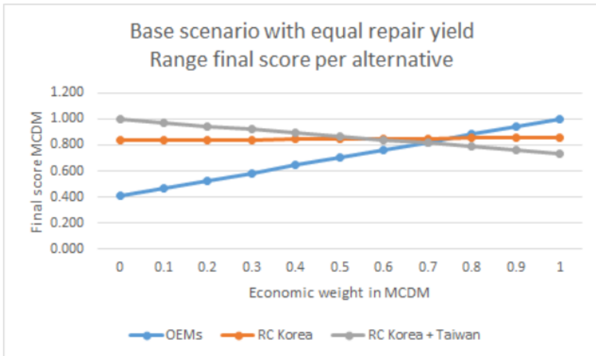
As shown in Figure 7.8a, the transportation & duty costs per reconditioned product are slightly higher for the Repair Captain in Korea and the Captain in Korea & Taiwan. This is caused by the lower repair yield, since the repair yield of both captain alternatives is assumed to be 37 %. This also leads to the slightly higher reconditioning costs per defect (excluding transportation & duties) for the Repair Captain alternatives. Overall, the difference in reconditioning costs per reconditioned defect (UC) between the OEMs and the Repair Captains is larger than in the first base scenario analysis. The ROI of the Repair Captain in Korea equals 16.2 years and the ROI of the Repair Captain in Korea & Taiwan equals 22.4 years. The ROI input parameters are provided in Table 7.6. The scrap waste is equal to 87087 kilograms per year in all scenario's since an average product weight of 25 kilograms is assumed. The reduction of CO_2 emissions is about 51 % for the Repair Captain in Korea and 59 % for the Captain in Korea & Taiwan, in comparison to the OEMs. The CO_2 emissions caused by transportation are shown in Figure 7.8a.

Table 7.6: ROI input parameters

	OEMs	**RC Korea**	**RC Korea & Taiwan**
Reconditioning costs per reconditioned defect/year, excluding investment ($UC_{excl.investment}$)	€ 3113	€ 2979	€ 2919
Cost reduction per reconditioned defect/year, excluding investment ($CR_{excl.investment}$)	€ 2316	€ 2450	€ 2510
Investment cost C_a^I		€ 4.5 million	€ 9 million
Number of reconditioned defects/year, (N)	2070	2070	2070
ROI in years	0.0	16.2	22.4



(a) Carbon emission comparison of the base alternatives with equal repair yields



(b) Final score of the three strategies in the base scenario with equal repair yield

Figure 7.8: Emissions and financial score in the base scenario with equal repair yield

In this scenario, only the carbon emissions and the reconditioning costs per reconditioned product (UC) are relevant. Based on these final scores are obtained for the three alternatives. This score is shown in Figure 7.8b.

7.4.5 Scenario analysis 3: Base scenario, excluding locations

Now, assuming that all other assumptions hold (see Table 7.1 and 7.2), the return volume from certain locations is excluded to compare the alternative reconditioning strategies. Namely, if the OEMs are located in Europe, why would they not remain reconditioning the defects coming from Europe. Furthermore the question arises what would happen if the return volume from Europe and the US would be excluded. A Repair Captain would then just be responsible for the defects coming from Asia. Lastly, excluding the return volume from the United States might be an option as well. Perhaps it could be interesting to recondition these products in the United States.

First the return volume excluding Europe is investigated. So, also for the reconditioning at the OEMs the return volume from Europe is excluded. In real-life the volume from Europe would still be reconditioned at the OEMs, even if a Repair Captainship is applied. However, the volume from Europe is excluded on purpose to make similar comparisons between the alternatives. When the return volume from Europe is excluded, the average transportation costs per reconditioned defect are significantly lower for the Repair Captains. The costs are shown in Figure 7.9. This can be explained by the fact that, according to the data input, the weighted-average transportation costs from Europe to Korea or Taiwan are significantly higher than the weighted-average transportation costs from countries in Asia to Korea or Taiwan. The carbon emissions are also significantly reduced when the volume of Europe is excluded for the Repair Captains. The carbon emissions caused by transportation would be reduced by 60 % for the return volume (excluding Europe), if sent to the Repair Captain in Korea. The Repair Captain in Korea & Taiwan would even reduce the emissions by 70 % compared to the current situation. This is shown in Figure 7.10.

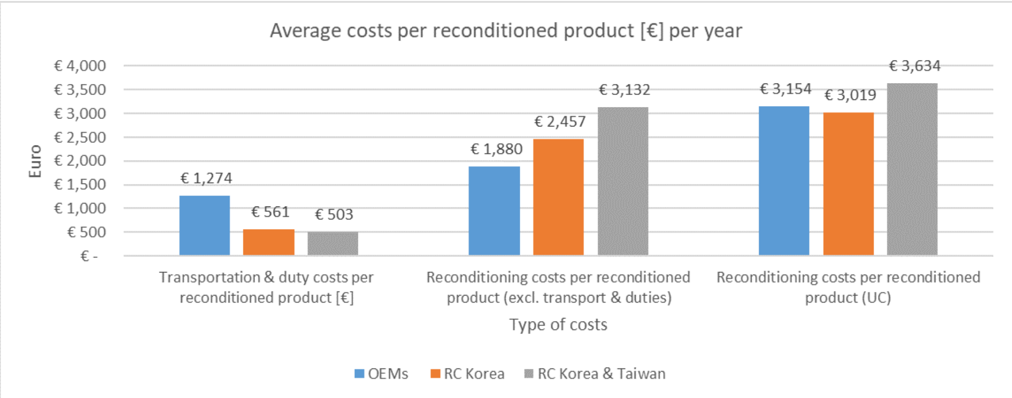


Figure 7.9: Base scenario costs comparison excluding the defects from Europe

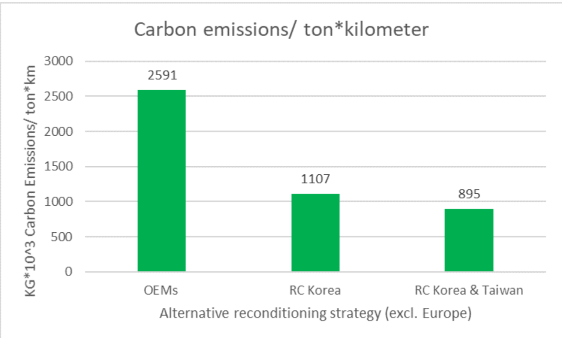


Figure 7.10: Base scenario emissions comparison excluding the defects from Europe

Similarly the return volume excluding the United States is investigated. The transportation costs for the return volume excluding the United States are lower for the Repair Captains than the OEMs, but the differences are small. Average transportation and duty costs account for about € 1112 for the OEMs, € 855 for the Repair Captain in Korea and € 791 for the Repair Captain in Korea & Taiwan. The differences are not as large as when only the return volume from Europe is excluded (see Figure 7.9). According to the data input the weighted-average transportation costs from Europe to Korea or to Korea and Taiwan are about three times higher than the transportation costs from the United States to Korea or Taiwan.

Then, excluding both Europe and the United States. In that scenario, the Repair Captain is always preferred from environmental point of view, since the transportation cots are minimized and sending the volume from Asia to Europe and from the United States to Asia have a negative impact on the carbon emissions caused by transportation. The transportation and duty costs per reconditioned defect are than on average € 1202 for the OEMs Captains, € 242 for the Captain in Korea and € 168 for the Captain in Korea & Taiwan. The influence of excluding certain locations from the return volume is shown in Figures 7.11, 7.12 and 7.13.

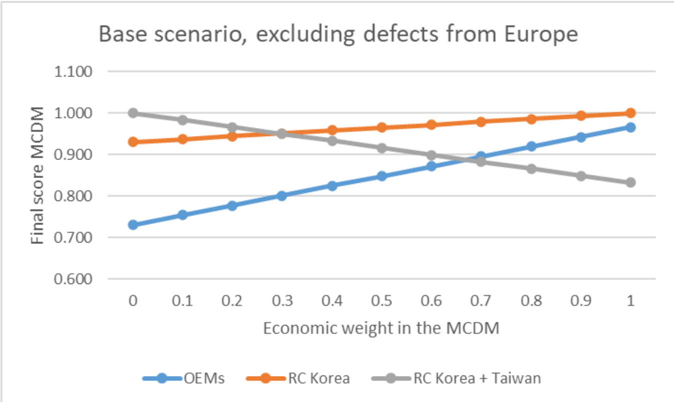


Figure 7.11: Final rank of base alternatives (excluding volume Europe)

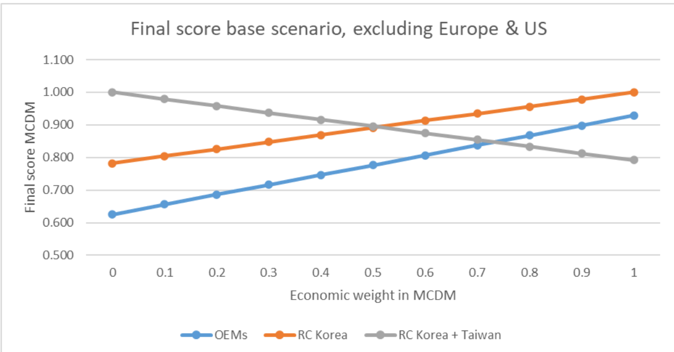


Figure 7.12: Final rank of base alternatives (excluding volume Europe & US)

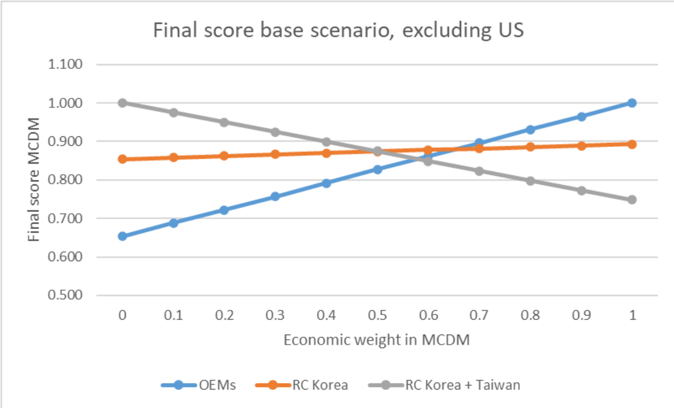


Figure 7.13: Final rank of base alternatives (excluding volume US)

In conclusion, excluding the return volume from Europe only is beneficial for a Repair Captain in Korea, regardless of the economic and environmental weight. This saves a lot of transportation costs, even though the return volume is low (about 9 %). Excluding both the return volume from Europe and from the United States seems to be beneficial for the Repair Captain in Korea as well. Excluding the United States only is not always beneficial, since this would reduce the volume for the Repair Captains by a significant portion (about 17 %). At the same time, the relatively high transportation costs from Europe to Asia remain present.

7.4.6 Scenario analysis 4: Base scenario with a different intercontinental transportation mode

Now, assuming that all other assumptions hold, the transportation mode is changed in the base scenario. After all, transportation causes carbon emissions and it is seen as one of the largest sources of pollution in the logistics supply chain (Wu and Dunn, 1995). In the current base scenario intercontinental transportation is done via air, whereas shipment via sea could be an option as well. The impact of intercontinental transportation via ocean on the carbon emissions is shown in Figure 7.14.

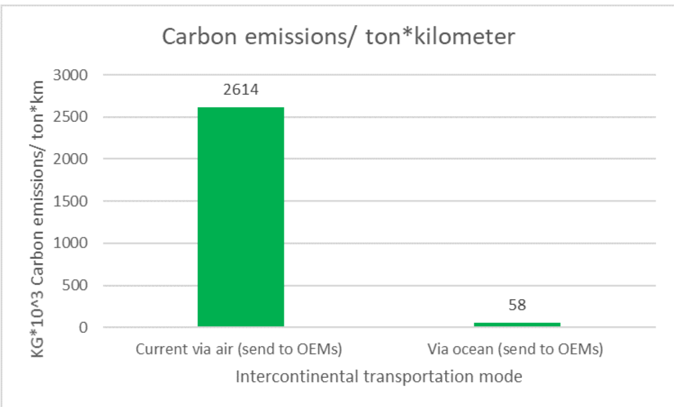


Figure 7.14: Comparison of intercontinental transportation mode selection for the current reconditioning strategy at the OEMs

Ocean freight would increase the transportation lead time, but significantly reduce the carbon emissions (Hoen et al., 2014b). Besides, ocean freight is not always less costly than air freight due to the pipeline inventory costs for expensive items (in transit). Certain other variables are also important when deciding to change the transportation mode. Namely, the transportation costs, the transportation lead time, the variance in transportation time and the carrying costs per products (Baumol and Vinod, 1970). If The Company would consider changing transportation mode, it would require to investigate the implications on the other parameters as well. Ocean freight would increase the transportation time, but reconditioning at a Repair Captain is estimated to lower the overall lead time by 30 to 50 percent. On an average current lead time of 119 days this implies a reduction of 35 to 60 days. Transportation via air is now assumed to be within a week according to The Company experts. So if ocean freight would increase the transportation lead time 7 times, then this would still not cause a higher total reconditioning lead time (from defect to successful recovery) than in the current setting.

7.4.7 Scenario analysis 5: Worst case scenario analysis

This subsection evaluates a possible 'worst case-scenario', assuming the same range parameters as in Table 7.2, but any alternative Repair Captain could only recondition products under IP & design control. Furthermore, the Repair Captain would only be capable of doing repairs (including requalification). This scenario incorporates the risk that a Repair Captain would not have the technical capabilities to perform the reconditioning activities for all returned products. So the OEMs would remain doing the reconditioning for the products that are not under IP & design control and for all repair and upgrade activities. This comparison is modeled by comparing the OEMS, Repair Captain in Korea and the Repair Captain in Korea & Taiwan again, but now only for the repair (including requalification) only and only for the products under IP & design control. In real-life the excluded return volume would still be reconditioned at the OEMs, even if a Repair Captainship is applied. However, this volume is excluded on purpose to make equal comparisons between the alternatives. In this scenario the investment costs are only € 1.5 million for the Repair Captain in Korea and € 3 million for the Repair Captain in Korea & Taiwan. The related costs in this scenario are presented in Figure 7.15.

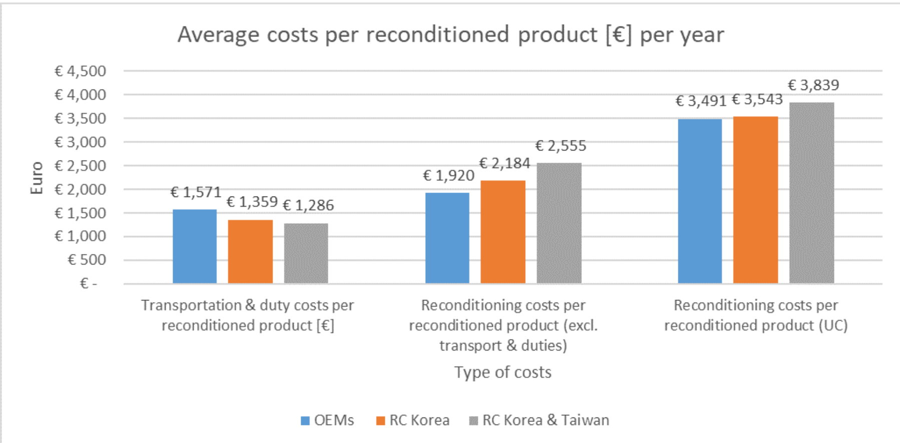


Figure 7.15: Worst case cost comparison of the three alternatives

Figure 7.15 shows how the transportation costs are impacting the total reconditioning costs per reconditioned product. The total volume of successfully reconditioned products lays around 1200 products per year for the OEMs and the Repair Captains. This is much lower than in the base case scenario, where between 2000 to 2300 products are reconditioned. The new-buy value of the products is on average € 4115 and the related transportation costs are €768, so again even reconditioning at a Repair Captain is always cheaper than buying a new product. The *ROI* of the Repair Captain in Korea is equal to 2.5 years and for the Repair Captain in Korea & Taiwan it is 5.1. The *ROI* is calculated via equation 7.17 and the numbers to calculate this ROI are presented in Table 7.7.

Table 7.7: ROI input parameters

	OEMs	**RC Korea**	**RC Korea & Taiwan**
Reconditioning costs per reconditioned defect/year, excluding investment ($UC_{excl.investment}$)	€3490	€3176	€ 3104
Cost reduction per reconditioned defect/year, excluding investment ($CR_{excl.investment}$)	€ 1392	€ 1707	€ 1779
Investment cost C_a^I		€ 1.5 million	€ 3 million
Number of reconditioned defects/year, (N)	1139	1227	1224
ROI in years	0.00	2.5	5.1

The cost reduction is positive for every alternative. From environmental point of view the scrap rates are close to eachother. The OEMs have a scrap rate of 67 %, the Repair Captain in Korea has a scrap rate of 64 % and the Repair Captain in Korea & Taiwan has a scrap rate of 65%. The MCDM related to this worst case scenario is presented in Table 7.8 and the resulting output is provided in Figure 7.16.

Table 7.8: MCDM performance values for the worst case scenario comparison

Alternative	**Reconditioning costs per reconditioned defect** (UC)	**Scrap rate** (SR)	**Scrap waste** (SW) [KG]	**Transportation impact** (CO_2^T) [KG]
OEMs	€ 3491	67 %	57813	1062691
RC Korea	€ 3543	64 %	55602	946658
RC Korea & Taiwan	€ 3839	65 %	55655	790725

The final scores in Figure 7.16 show similar ranks as in the base scenario. From economic point of view, the OEMs are preferred. From environmental point of view the Repair Captain in Korea & Taiwan would be the optimal choice. When considering both the economics and the environmental implications, the Repair Captain in Korea is preferred. This implies that even with a reduced scope of product types and reconditioning activities, a Repair Captainship could still make sense.

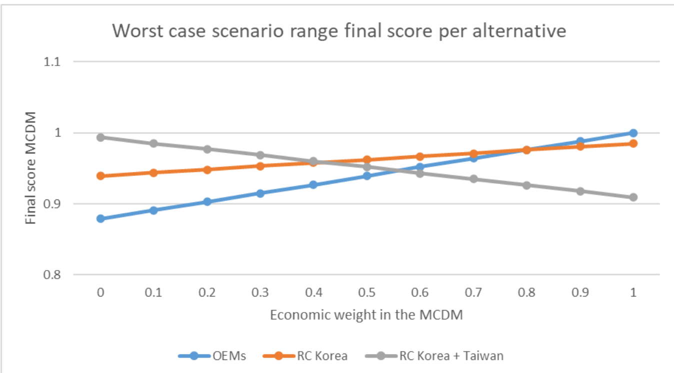


Figure 7.16: Final score comparison of the three strategies in scenario analysis 4

7.4.8 Scenario analysis 6: Potential Repair Captains in one country

This subsection shows how the model can be used to compare potential Repair Captains with different characteristics, considering possible advantages and disadvantages of the chosen type of firm (e.g. a supplier opening a new repair shop versus an existing third party repair shop).

These type of firms were also compared in Chapter 6. Assume assumptions from 7.1 hold for each potential Repair Captain. However, certain ranges for the parameters mentioned in 7.2 are different for Company B and Company C.
The first candidate is Company A in Korea who meets the base captain assumptions. The second candidate is Company B. Company B in an existing supplier, who offers to open a new repair shop in Korea against lower reconditioning costs than Company A (base captain). However, the repair yield of Company B is lower and more uncertain than the repair yield of company A. Other parameters remain the same as the base captain assumptions. The third candidate is Company C. Company C is an existing repair shop in Korea who offers a higher reconditioning yield. It is assumed that company C has a variety of flexible tools that reduces the investment costs compared to company A and B. However, reconditioning costs are higher at company C in comparison with Company A and B. Company C would even be more expensive then the OEMs in the current situation. The three candidates and the parameter range changes are shown in Figure 7.17.

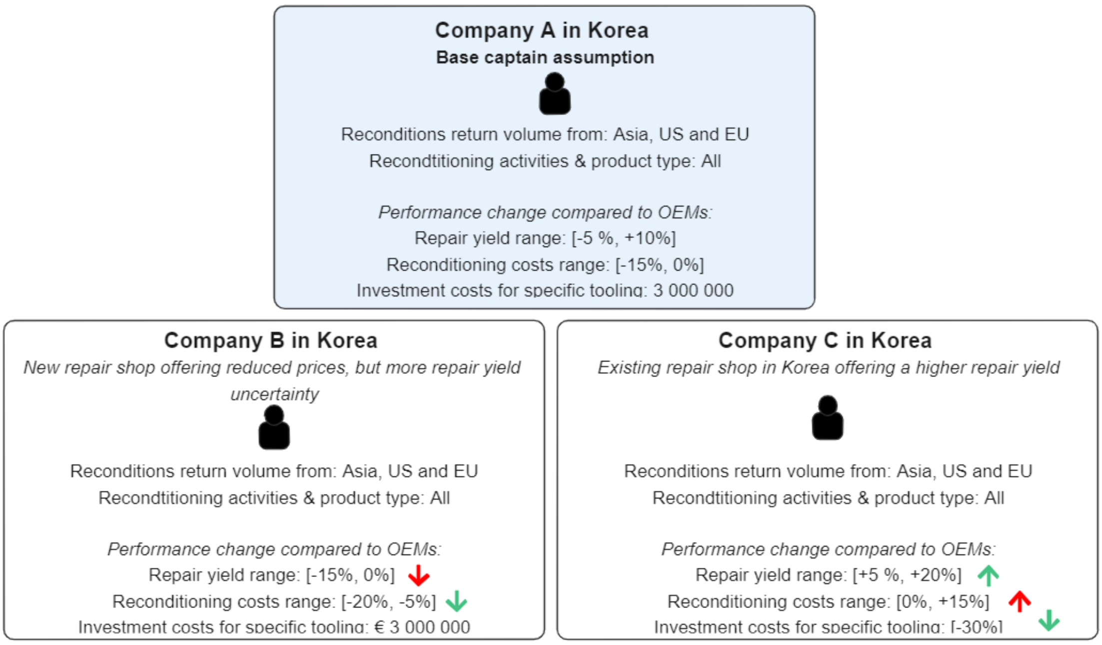


Figure 7.17: Comparison of three candidate Repair Captains in the same country

The performance comparison of the different companies is shown in Table 7.9. Also, here repair yield is thriving the reconditioning costs per reconditioned product (UC). The existing repair shop company C is more costly than Company B, but overall UC is lower for company C. The scrap rate and scrap waste are much lower than for company A and B. Only the carbon emissions are higher. In this context, a lower scrap rate leads to higher carbon emissions caused by transportation. When the repair yield increases, more products are sent for reconditioning to the Repair Captain. This is because the assumption is made that the open yield remains constant (see Table 7.2). Thus, when the repair yield increases, the scrap rate will decrease and more products are sent to the reconditioning facility.

Table 7.9: MCDM performance values for the candidate captains

Alternative	**Reconditioning costs per reconditioned defect** (UC)	**Scrap rate** (SR)	**Scrap waste** (SW) [KG]	**Transportation impact** (CO_T^2) [KG]
Company A	€ 3509	60 %	83725	1283052
Company B	€ 4233	70 %	97554	1225503
Company C	€ 3087	50 %	69696	1341434

Finally, the companies are ranked as shown in Figure 7.18. Company C is almost always the preferred Repair Captain. This is not surprising, since company C would even have a slightly lower reconditioning cost per reconditioned product UC than the OEMs (UC OEMs base scenario equals € 3113), due to a high yield, low transportation costs and low investment costs.

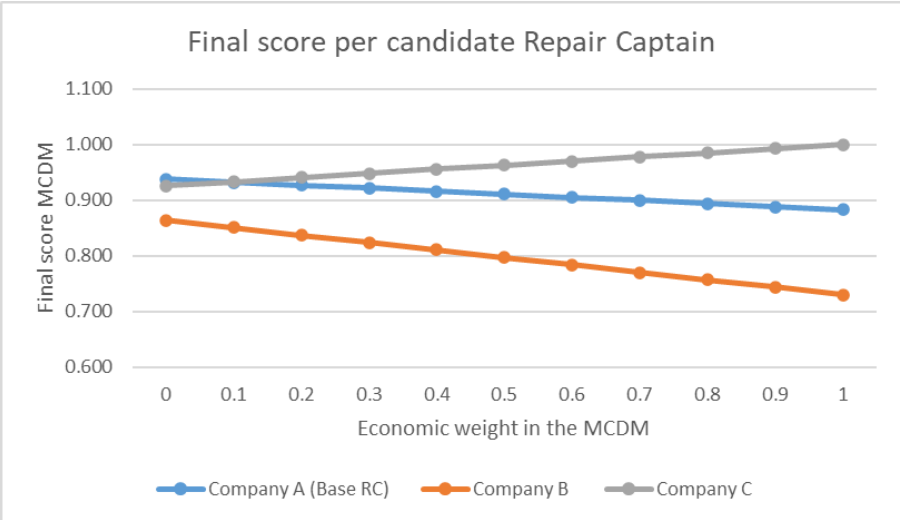


Figure 7.18: Final rank of different potential Repair Captains

7.5 Discussion implications of a Repair Captainship

This chapter started with sub-research question 4: *How to model the economic and environmental implications of a Repair Captainship strategy?* To answer this question performance indicators for the reverse supply chain are depicted. Moreover, a decision-making tool is created that allows to simulate the economic and environmental implications of a Repair Captainship. The uncertainty is incorporated by use of Monte Carlo simulations. The model allows to create several scenario's and gives insight in the parameters that have a strong influence on the performance of a Repair Captain. Certain parameters that play a role in the decision-making, are the investment costs in specific equipment, the number of products that a Repair Captain can recondition successfully (repair yield), transportation costs and also the carbon emissions caused by transportation. Overall, outsourcing reconditioning activities to a Repair Captain is a plausible solution. Especially from environmental perspective. However, if the Repair Captain could increase the repair yield compared to the OEMs, then the Captain is also interesting from economic perspective. If The Company could choose between a Captain at one location or a Captain in two locations, then a Captain at one location is preferred from economic and environmental perspective. This is caused by the large investments that would be required at two locations. If The Company or the Repair Captain would be capable of optimizing the allocation of the defects, then investments might be reduced. This would improve the economic implications for the Repair Captain at two locations and would result in the lowest environmental impact. Changing the transportation mode for intercontinental transport from air to sea freight would even improve the environmental impact. This would increase the transportation time. However, reconditioning at a Repair Captain is estimated to lower the lead time by 30 to 50 percent, so this increase in transportation time should not prevent The Company to consider ocean freight for intercontinental transportation. Overall, this chapter compared the current reconditioning strategy with potential Repair Captainship scenario's. Depending on the assumptions and main goal of a firm, a firm can determine whether a captainship has the desired business outcomes.

8 Conclusion

This thesis included extensive research on the strategic outsourcing decision-making in reverse supply chain management. A new concept is introduced, namely a Repair Captainship. The Repair Captain would be a firms' current supplier or another external third-party specialized in reconditioning defect products. This concept, of managing the reverse supply chain via a Repair Captain, is analyzed by asking the following research question:

How could a firm determine whether it is beneficial to manage the reverse supply chain with a Repair Captainship strategy?

To provide firms support in this decision-making, several sub-research questions are answered. This chapter discusses the main conclusions per sub-research question, provides recommendations and provides the limitations and future research opportunities.

8.1 Revision of the research questions

This section provides the main conclusions per research question.

1. *How are reverse supply chains managed, in terms of challenges and applied reconditioning strategies in the capital goods industry, according to literature?*

   A literature study is done to define the reverse supply chain, investigate the challenges in reverse supply chains and to understand how other firms in the capital goods industry are managing the reverse supply chain. This search resulted in six main challenges: variability (in demand, quantity, timing and volume of returned products), legislation, disposition decisions, transparency, coordination and awareness in the reverse supply chain (Gupta, 2013; Guide Jr et al., 2003; Abbey and Guide Jr, 2018; Fleischmann et al., 1997; Thierry et al., 1995; Rogers and Tibben-Lembke, 1998; Souza, 2013). Next to this, several industries are investigated. Reverse supply chain practices in the aerospace, healthcare and automotive industry were discussed. It appears to be difficult to compete against third-parties, if OEMs chose not to be involved in the reconditioning activities in the past (Abbey and Guide, 2017). Next, a strategic framework is presented. This framework shows that product design and whether or not reconditioning is seen as core competency, have a large impact on the decision-making in the reverse supply chain. Abbey and Guide (2017) discussed three concepts: vertically integrated, hybrid and outsourced closed-loop supply chains. The hybrid CLSC appears to be applied most often, where certain activities are outsourced and others executed inhouse (Abbey and Guide, 2017).

2. *How does The Company's reverse supply chain look like in terms of the product return flow and challenges?*

   Interviews took place and field notes were created to understand and visualize The Company's reverse supply chain and to depict the current challenges. The reconditioning is outsourced to the OEMs in general. Some reconditioning activities are also taking place at in-house facilities closed by the customers. The reverse supply chain is shown in detail in Figure 4.1 and a summarized representation is shown in Figure 4.2. There are five main challenges in the current reverse supply chain. The first challenge is that there is no first physical analysis of the products before sending them to the OEMs for potential reconditioning. The second challenge is the risk of contamination or damage of returned products due to wrong packaging and issues during transportation. Third, there are no standardized reconditioning agreements or contracts with the OEMs. The fourth challenge is that the overall lead time for reconditioning is long. The last challenge is the gap and difference in data definitions among employees and information systems. Lastly, the possible implication of a Repair Captain on the return flow is visualized in Figure 4.3.

3. *How to determine the opportunities and limitations of applying a Repair Captainship?*

By conducting interviews and creating questionnaires, the opportunities and limitations of a Repair Captainship were determined. This led to the creation of a MCDM model including important criteria that reflect the opportunities and limitations of a Repair Captainship for several product categories. The model is visualized in Figure 5.1 and the criteria are summarized in Table 5.2 and 5.3. The frequently used AHP method was applied to determine weights for the decision criteria. The company implementation showed the ranking of product categories based on the decision criteria and their weights. The higher in rank, the more opportunities to apply a Repair Captainship. According to experts, product design complexity should influence the opportunity the most and the uniqueness of a product was perceived as a limitation. This is also in line with the scientific framework by Abbey and Guide (2017). Following Spearmans' rank correlation test, there was some correlation between the decision criteria. This holds for criteria such as 'reconditioning costs' and 'cost reduction'. The method was easy to use in practice, even when people were not familiar with the AHP methodology.

4. *What are criteria, considering related risks, to decide on a suitable Repair Captain?*

   Based on supplier selection criteria found in scientific sources, The Company's experts mentioned important Repair Captain selection criteria. These selection criteria were determined via interviews with the experts. The criteria are shown in Figure 6.1. The geographical location of a firm, compliance to protect IP & design, meeting delivery agreements and technical (repair) capabilities appear to play a large role in the decision-making. The advantages and disadvantages of selecting a current supplier or an external third-party as Repair Captain were discussed. A trusted-relationship, possible conflict of interest and investment implications appear to influence the decision between either a current supplier and an external third-party (Mokhtar et al., 2019; Lu et al., 2014). Besides three main risks were discussed, operational risk, regulatory risk and political risk.

5. *How to model the economic and environmental implications of a Repair Captainship strategy?*

   Implications of a Repair Captainship were modeled in an MCDM model for a specific product category. The model allows decision-makers to change the location of the Repair Captain, change the base assumptions, the type of products to recondition, costs and transportation mode. It also includes flexible economic and environmental weight inputs. A Monte Carlo simulation, a so-called what-if analysis, is used to represent the possible performance of a Repair Captain. This type of simulation is seen as a powerfull tool in strategic decision-making (Diaz and Marsillac, 2017). Second, several scenarios were created to investigate the implications of a Repair Captainship. From economic perspective, total reconditioning costs per reconditioned product were investigated. Besides, the ROI, cost reduction and transportation costs were investigated as well. From environmental perspective, scrap rate, scrap waste and carbon emissions caused by transportation were investigated. Several scenario's are analysed: a base scenario that compares the performance of OEMs with two different Repair Captains; the base scenario with modifications in the repair yield, return volume & transportation mode; a worst-case scenario and a comparison of potential candidate Captains. The analysis shows that a Captain's repair yield has a strong influence on the economic performance. Besides, it is more beneficial to exclude the return volume from Europe for the Repair Captain. This volume could be reconditioned by the OEMs, resulting in an economic and environmental benefit.

In conclusion, this thesis provides steps that are needed to answer the main research question. The first MCDM model enables to compare several products or product categories and to determine the opportunities of a Repair Captainship. Next to this, the second MCDM model enables to compare a Repair Captain with OEMs, from economic and environmental perspective. The model also allows to compare different (candidate) Repair Captains. In addition, any firm or organisation could use this model to compare the reconditioning performance of others. The assumptions can be changed to a firms' specific context. The model can support firms' in their decision-making regarding the outsourcing of reconditioning activities to a Repair Captain.

8.2 Recommendations

This section provides three main recommendations for firms considering to apply a Repair Captainship. Two generic recommendations are provided that are relevant to any firm interested to apply a Repair Captainship and one recommendation is provided that is The Company specific.

8.2.1 General recommendations

First of all, it is crucial for a firm to determine the long-term reuse strategy. From there, a firm determines where the reconditioning should take place. This research supports a firm in this decision. A flowchart is provided that shows the steps that support a firm to outsource reconditioning activities to a Repair Captain or not. This flowchart is shown in Figure 8.1.

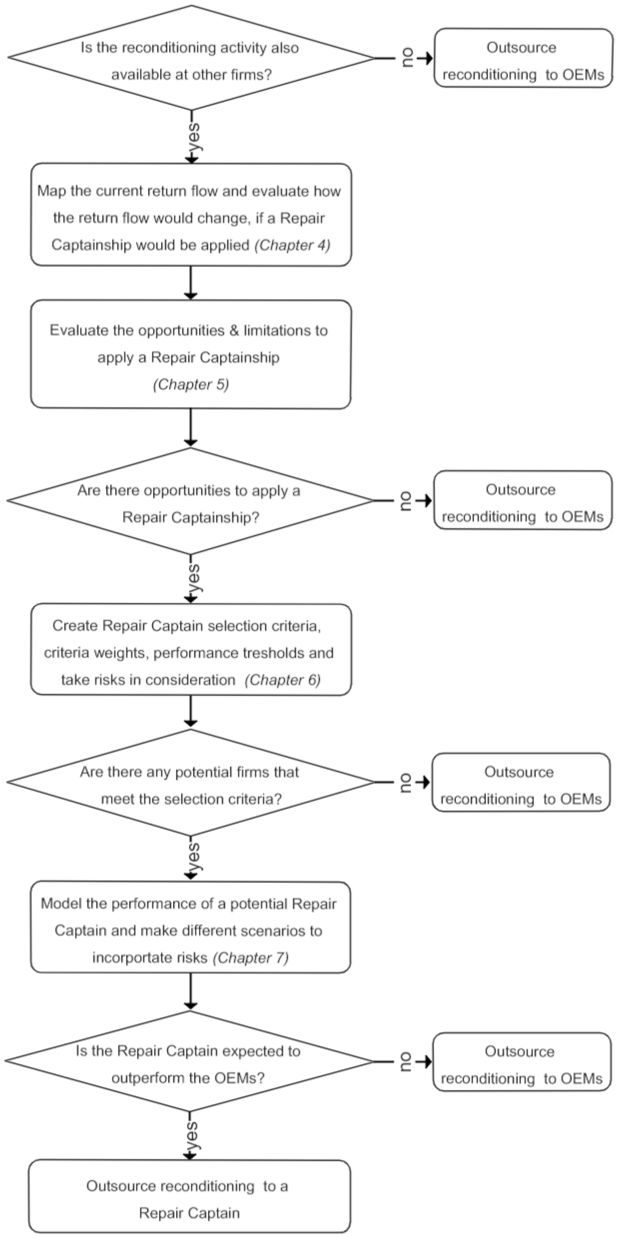


Figure 8.1: Repair Captainship decision-making flowchart

It is important to keep in mind that a firm should also (continuously) evaluate the reconditioning performance in the selected strategy. This is also the reason why it is crucial that The Company should think of its reconditioning goals. This allows a firm to remain in control of the reconditioning, even when outsourced. This control is already partially established after creating selection criteria for a potential Repair Captain. However, decisions may change over time and therefore it is also important to evaluate OEMs and Repair Captains on their reconditioning performance. If a firm is not involved in the reconditioning strategy and evaluation, then parties responsible for the reconditioning would not be incentivized to improve the performance. Thus, a firm should feel responsible for the reverse supply chain performance, even if it is outsourced (to OEMs or a Repair Captain). This implies that certain steps in the flowchart (Figure 8.1) should be repeated, whenever necessary.

Second, an additional environmental indicator is recommended to include in the last MCDM. Namely, the energy consumption that a firm saves when a product is reconditioned instead of buying a new product. This is another indicator that reflects the environmental performance of OEMs or potential Repair Captains. Energy consumption is also frequently used as an environmental performance indicator for reconditioning activities (Graham et al., 2015; Gutowski et al., 2011). Energy consumption during manufacturing appears to be a small part from the total lifecycle energy consumption for many products. Therefore, this is often overlooked. Nonetheless, energy consumption comes with a cost (Sutherland et al., 2008). Sutherland et al. (2008) also mention that the difference between manufacturing and remanufacturing energy consumption (energy savings), are about 85 %. To include this performance indicator, a firm should know the CO_2 emission intensity of the energy consumption in kilowatt-hours, both for manufacturing and for reconditioning activities. Thus, it is also important to know how much time is spent on product manufacturing and on reconditioning. These energy consumption savings are interresting for any firm, since it will have a positive influence on a firms environmental footprint. Other factors such as water usage and material usage might be interresting to investigate as well.

8.2.2 The Company specific

These recommendation are specifically addressed to The Company. It is important that The Company sets reconditioning goals. The Company should think about what it would like to achieve with regards to the reconditioning performance in the upcoming years. This would also enable to determine the economic and environmental importance in the outsourcing decision-making. Considering the ambitious sustainability targets set by The Company, it is recommended to consider a Repair Captainship strategy. At the same time, The Company should also focus on increasing the Repair Captain's repair yield.

As mentioned in Chapter 1, The Company wishes to cut the amount of waste per revenue by 50 % and working towards zero carbon emissions across all operations. After the company implementation, it can be concluded that a Repair Captainship in one country significantly improves the environmental impact of The Company. A Repair Captain in Korea would decrease the CO_2 emissions caused by transportation by 50 %. It is also recommended for The Company to outsource the reconditioning activities for the return volume from Asia and the United States only to a Repair Captain. The volume from Europe would still be reconditioned at the OEMs. This reduces the CO_2 emissions caused by transportation by 57 % and is also preferred from a cost perspective. Then the reconditioning costs per reconditioned defect are slightly lower than in the current situation. The Repair Captainship would even be an interresting choice if, for some reason (such as an existing repair facility in the United States), the volume from the United States would be excluded as well. However, The Company should mainly focus on increasing the repair yield. Especially if the Repair Captain would not be capable of reconditioning all types of products and reconditioning activities. In that scenario, the Repair Captain would have slightly higher economic costs than the OEMs. Thus, in that scenario it would be crucial to slightly increase (+10%) the repair yield. Besides, to reduce the waste per revenue, it is important for The Company to increase the repair yield.

It is recommended that The Company collaborates with the Repair Captain to improve the repair yield. The Company could offer incentives to the Captain for repair yield improvements. According to Terpend and Krause (2015) competitive incentives reward suppliers on their performance compared to the competition. This type of incentive is among others effective for delivery and quality improvements. Rewards are given to the supplier only. The Company could reward the Captain if their repair yield is increased by a certain percentage. Terpend and Krause (2015) also mention cooperative incentives that focus on the benefits coming from joint efforts. These are useful if there is high mutual interdependence between two parties (Terpend and Krause, 2015). Here incentives coming from mutual efforts would be shared between The Company and the Captain. For example, reducing the energy consumption could reduce the costs for a Repair Captain and the environmental footprint of both firms. The Company should investigate which type of incentive would be preferred.

8.3 Limitations and future research

The main limitations of this research and future research opportunities are presented in this section. First of all, the reliability of the assumptions made to model the economic and environmental implications of a Repair Captainship is a limitation. The assumptions are mainly based on estimates of the The Company's experts and scientific insights. The research did not include the expectations and estimations of OEMs or third-party reconditioning firms. The OEMs or third parties could make better estimates about the performance of a possible Repair Captain. Furthermore, estimates are made for a large set of failure types, products and several reconditioning activities. To obtain accurate estimations, every product and failure type should be analyzed individually.

Second, the environmental implications of a Repair Captainship are mainly based on the CO_2 emissions caused by transportation, but there are many other indicators that could influence the environmental performance of a Repair Captain. One of them could be the energy savings obtained by reconditioning instead of manufacturing a new product. Other indicators could be material and water usage (Neri et al., 2021). Besides, the applied GHG protocol to measure the CO_2 emissions caused by transportation provides less details than other methods such as the NTM (Hoen et al., 2014a). Future research could incorporate a method that provides more detail. This would improve the accuracy of the calculated CO_2 emissions caused by transportation. In return, a more detailed method, requires more detailed information as well. One could think of the type of airplanes, fuel usage of the transportation modes, trucks or vans that are used and about short- and long-haul transportation. In addition, the first and last leg of transportation could be incorporated in the cost and CO_2 emissions as well. Now, the second MCDM model does only include the transportation between local warehouses and central warehouses or from local warehouse to the repair captain location. The first and last leg of transportation are not included, the transportation from customer to the local warehouse and from central warehouse to the OEMs are not included. These costs and emissions are expected to be relatively low, but this information would improve the model.

Third, the accuracy of the data input for the first and second MCDM models could be improved. Certain inputs for variables, such as the investment needs, product design complexity and weights of products, are based on the estimation of one or two experts. Preferably, the inputs could be based on reliable data. Next, the economic and environmental implications are based on three years of historical data, where more years of historical data would improve the research. Also, some attention is given to forecasting the return volume for the upcoming years, but this is not completely accurate. Also the decision-makers are assumed to have similar importance in the first MCDM model. This MCDM model showed the opportunities and limitations of applying a Repair

Captainship per product category. To obtain weights for the criteria, the priorities of multiple decision-makers were aggregated. These decision-makers are assumed to be equally important in the decision-making, but in reality this is probably not the case. The methodology allows to give different weights per decision-maker, so a firm could always improve the model.

Future research could incorporate the influence of legislation and regulations on the preferred reconditioning strategy. Legislation appears to be one of the main challenges in the reverse supply chain (as shown in Chapter 3). Besides, the risks mentioned in Chapter 6 could possibly be incorporated in a MCDM model. This model would not only focus on economic and environmental implications, but also include risks. Besides, additional focus could be given on modeling the selection of a Repair Captain. An MCDM model could be build via the BWM briefly discussed in Chapter 6, but other methodologies could be interresting as well. In Chapter 2 reasons were provided for outsourcing reconditioning activities, such as the geographical location and opportunity to consolidate the return volume Govindan et al. (2019). However, firms' their potential service capabilities and outstanding reconditioning capabilities are not investigated in this research. Thus future research could focus more on these two aspects. Lastly, future research could focus on operational aspects of the Repair Captainship. The consolidation of products could change if products are reconditioned at a Repair Captain. Decisions should be made on how to consolidate the products and on the frequency of sending defects to the Repair Captain. In Chapter 4 possible implications to the return flow are presented, if a Repair Captainship would be applied. There, the assumption is made that instead of sending defects to a global warehouse first, defects could directly be sent from nearby the customers (local warehouses) to the Repair Captain. From operational point of view, the question would arise whether the Repair Captain would have enough storage space or if there is enough storage space at the local warehouses. Besides, the Captain is expected to reduce the overall throughput time in the reverse supply chain. Future research could investigate this leadtime reduction, also for the possible situation where transportation modes are changed. The Repair Captain would also require materials or spare parts for the reconditioning of several products. This would require to investigate optimal inventory policies.

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Appendix A Pairwise comparisons questionnaire

This appendix provides the pairwise comparison questionnaire is provided. The purpose of this questionnaire is discussed in Chapter 5.

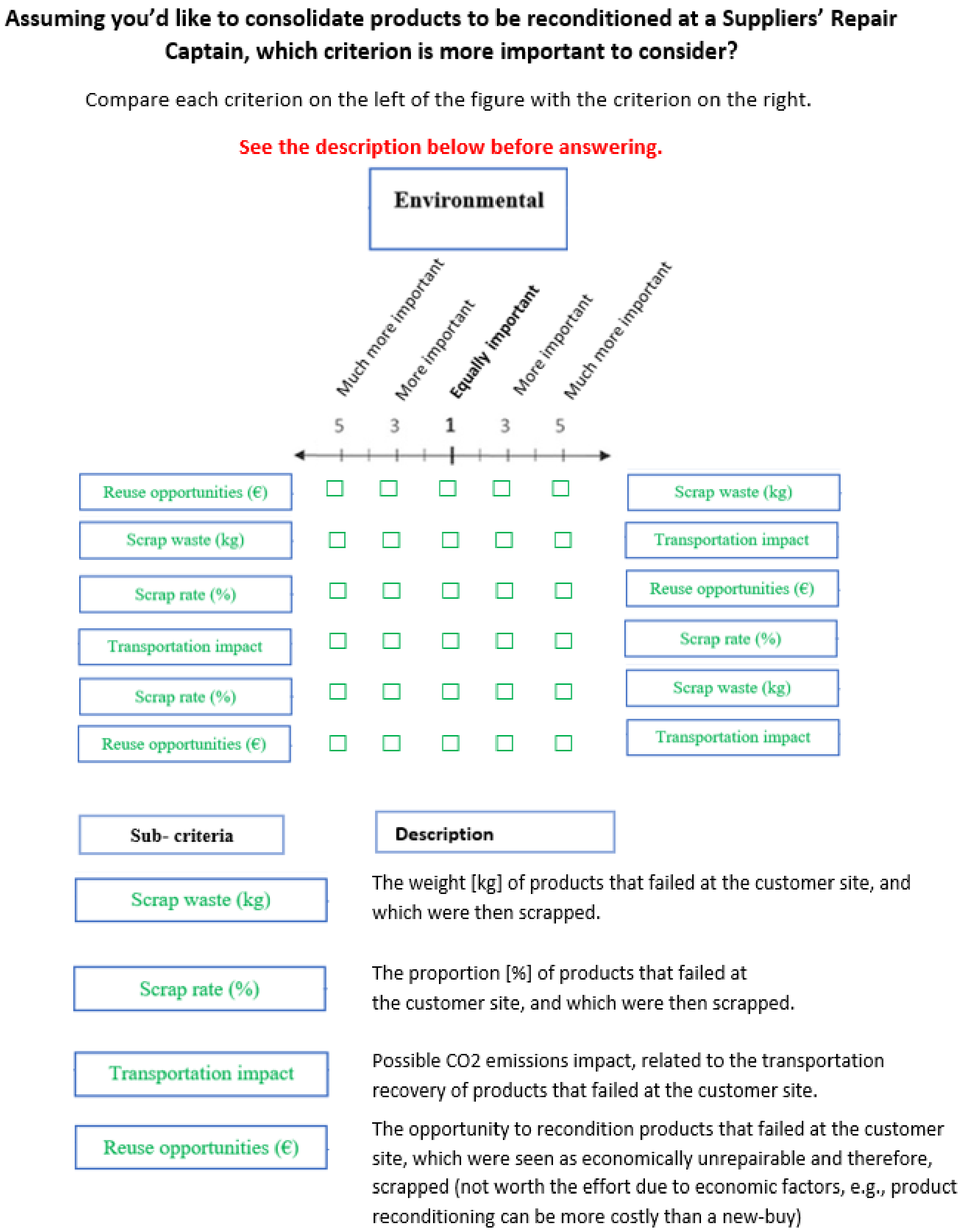


Figure A.1: The environmental pairwise comparison questions

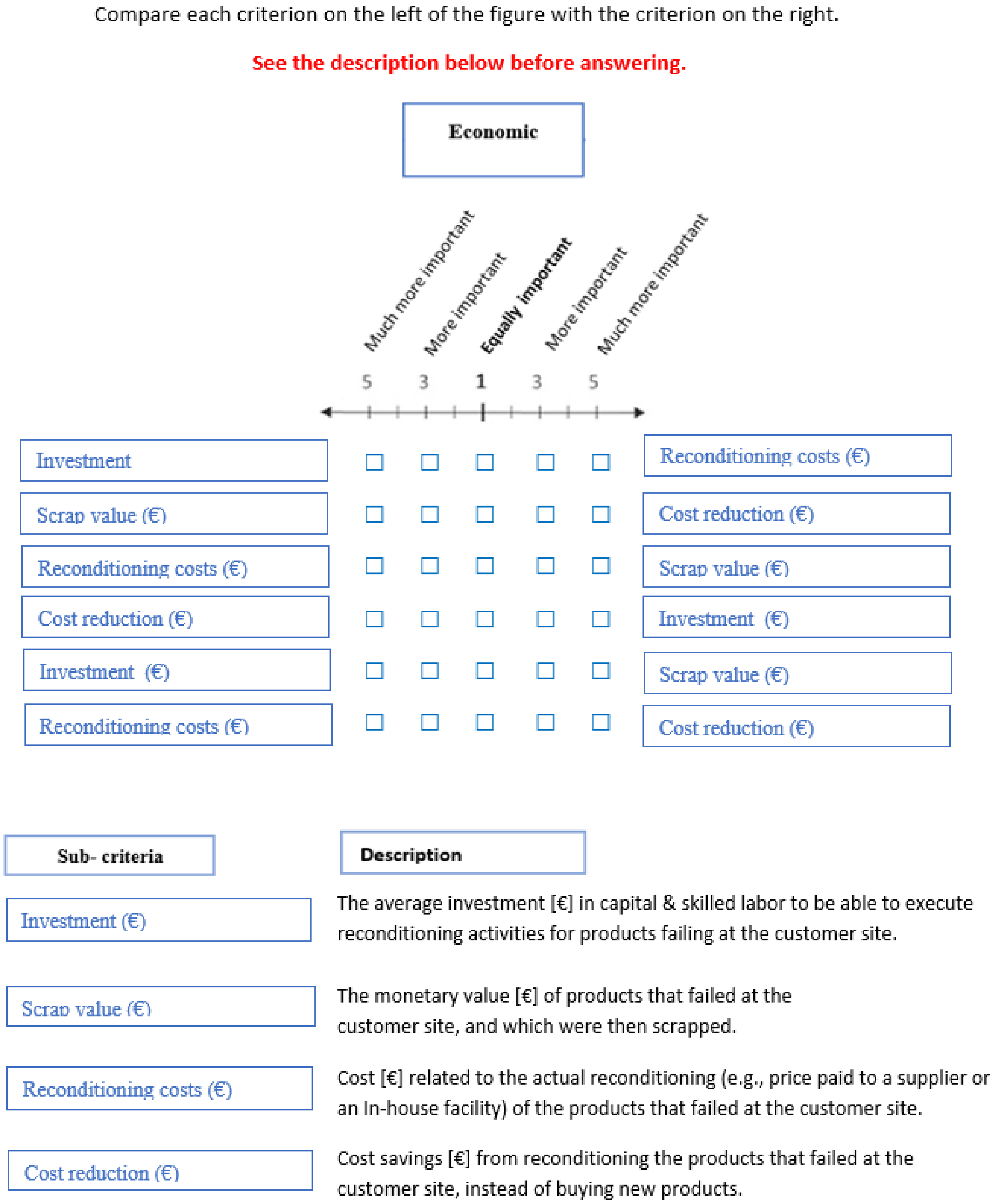


Figure A.2: The environmental pairwise comparison questions

The business criteria comparisons are divided in two parts. This is part 1

Compare each criterion on the left of the figure with the criterion on the right.
See the description below before answering.

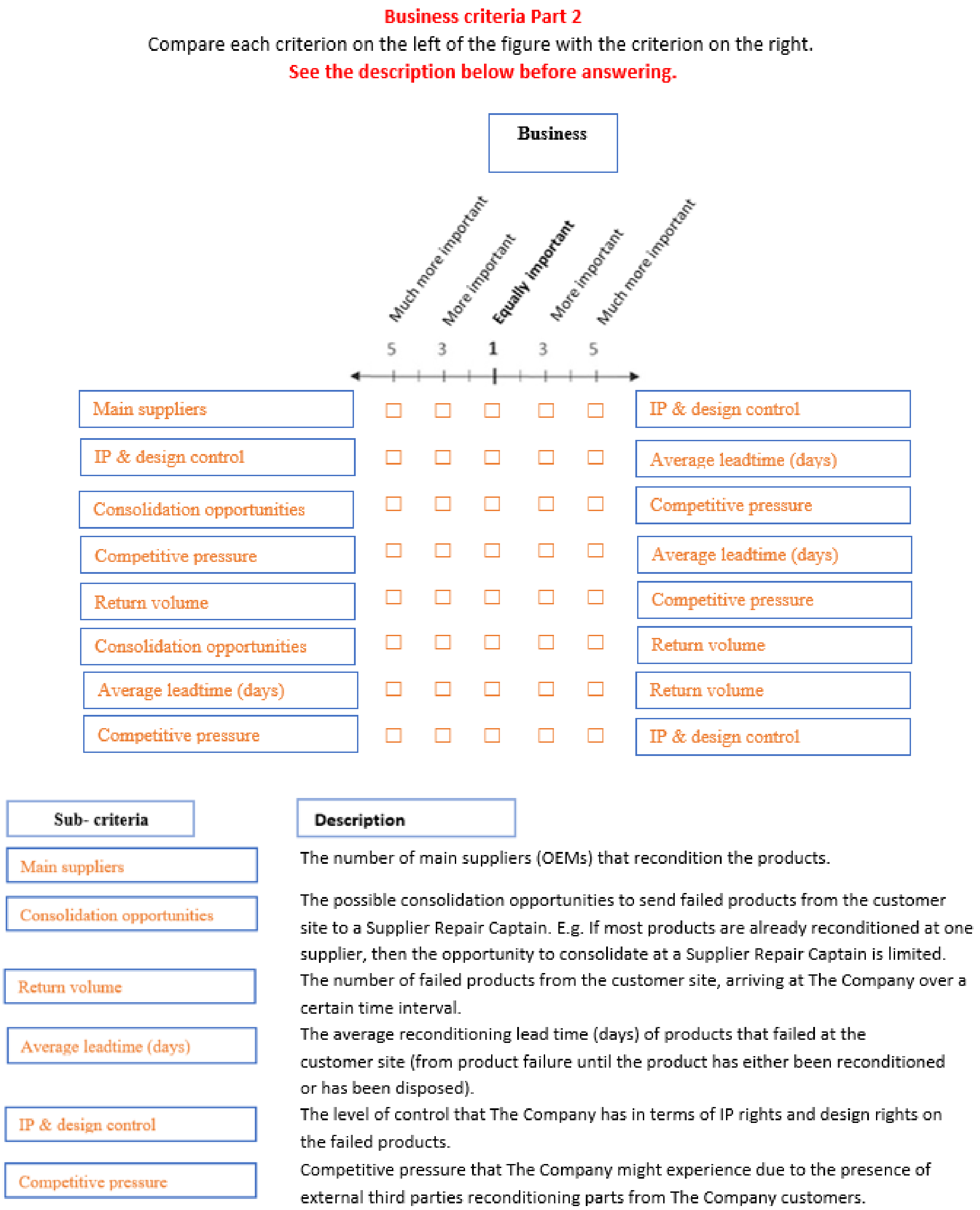
Business

	Much more important (5)	More important (3)	**Equally important (1)**	More important (3)	Much more important (5)	
Main suppliers	☐	☐	☐	☐	☐	Competitive pressure
Consolidation opportunities	☐	☐	☐	☐	☐	Average leadtime (days)
IP & design control	☐	☐	☐	☐	☐	Return volume
Main suppliers	☐	☐	☐	☐	☐	Consolidation opportunities
Average leadtime (days)	☐	☐	☐	☐	☐	Main suppliers
IP & design control	☐	☐	☐	☐	☐	Consolidation opportunities
Main suppliers	☐	☐	☐	☐	☐	Return volume

Continue on the next page for part 2 of the business criteria

Sub- criteria	Description
Main suppliers	The number of main suppliers (OEMs) that recondition the products.
Consolidation opportunities	The possible consolidation opportunities to send failed products from the customer site to a Supplier Repair Captain. E.g. If most products are already reconditioned at one supplier, then the opportunity to consolidate at a Supplier Repair Captain is limited.
Return volume	The number of failed products from the customer site, arriving at The Company over a certain time interval.
Average leadtime (days)	The average reconditioning lead time (days) of products that failed at the customer site (from product failure until the product has either been reconditioned or has been disposed).
IP & design control	The level of control that The Company has in terms of IP rights and design rights on the failed products.
Competitive pressure	Competitive pressure that The Company might experience due to the presence of external third parties reconditioning parts from The Company customers.

Figure A.3: The business pairwise comparison questions, part 1



Business criteria Part 2

Compare each criterion on the left of the figure with the criterion on the right.

See the description below before answering.

Business

	Much more important (5)	More important (3)	Equally important (1)	More important (3)	Much more important (5)	
Main suppliers	☐	☐	☐	☐	☐	IP & design control
IP & design control	☐	☐	☐	☐	☐	Average leadtime (days)
Consolidation opportunities	☐	☐	☐	☐	☐	Competitive pressure
Competitive pressure	☐	☐	☐	☐	☐	Average leadtime (days)
Return volume	☐	☐	☐	☐	☐	Competitive pressure
Consolidation opportunities	☐	☐	☐	☐	☐	Return volume
Average leadtime (days)	☐	☐	☐	☐	☐	Return volume
Competitive pressure	☐	☐	☐	☐	☐	IP & design control

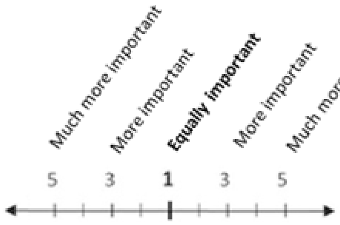
Sub- criteria	Description
Main suppliers	The number of main suppliers (OEMs) that recondition the products.
Consolidation opportunities	The possible consolidation opportunities to send failed products from the customer site to a Supplier Repair Captain. E.g. If most products are already reconditioned at one supplier, then the opportunity to consolidate at a Supplier Repair Captain is limited.
Return volume	The number of failed products from the customer site, arriving at The Company over a certain time interval.
Average leadtime (days)	The average reconditioning lead time (days) of products that failed at the customer site (from product failure until the product has either been reconditioned or has been disposed).
IP & design control	The level of control that The Company has in terms of IP rights and design rights on the failed products.
Competitive pressure	Competitive pressure that The Company might experience due to the presence of external third parties reconditioning parts from The Company customers.

Figure A.4: The business pairwise comparison questions, part 2

Compare each criterion on the left of the figure with the criterion on the right.

See the description below before answering.

Technical



Product design complexity	□	□	□	□	□	Technology development speed
Return flow complexity	□	□	□	□	□	Contamination risk
Contamination risk	□	□	□	□	□	Product design complexity
Technology development speed	□	□	□	□	□	Return flow complexity
Return flow complexity	□	□	□	□	□	Product design complexity
Contamination risk	□	□	□	□	□	Technology development speed

Sub- criteria	Description
Product design complexity	The impact that product design has on the complexity of reconditioning activities (others could easily do reconditioning, only after learning others could do reconditioning, or only OEM have the knowledge to do reconditioning without occasioning collateral risks such as safety or quality)
Contamination risk	The risk products face of getting contaminated during transportation or reconditioning activities.
Technology development speed	The speed at which product technology develops (e.g., amount of time in-between "new versions and/or upgrades" of products).
Return flow complexity	The level of The Company's suppliers reconditioning interdependency that increases the complexity of the return flow (e.g., when they need support from their own suppliers' network to recondition products)"

Figure A.5: The technical pairwise comparison questions

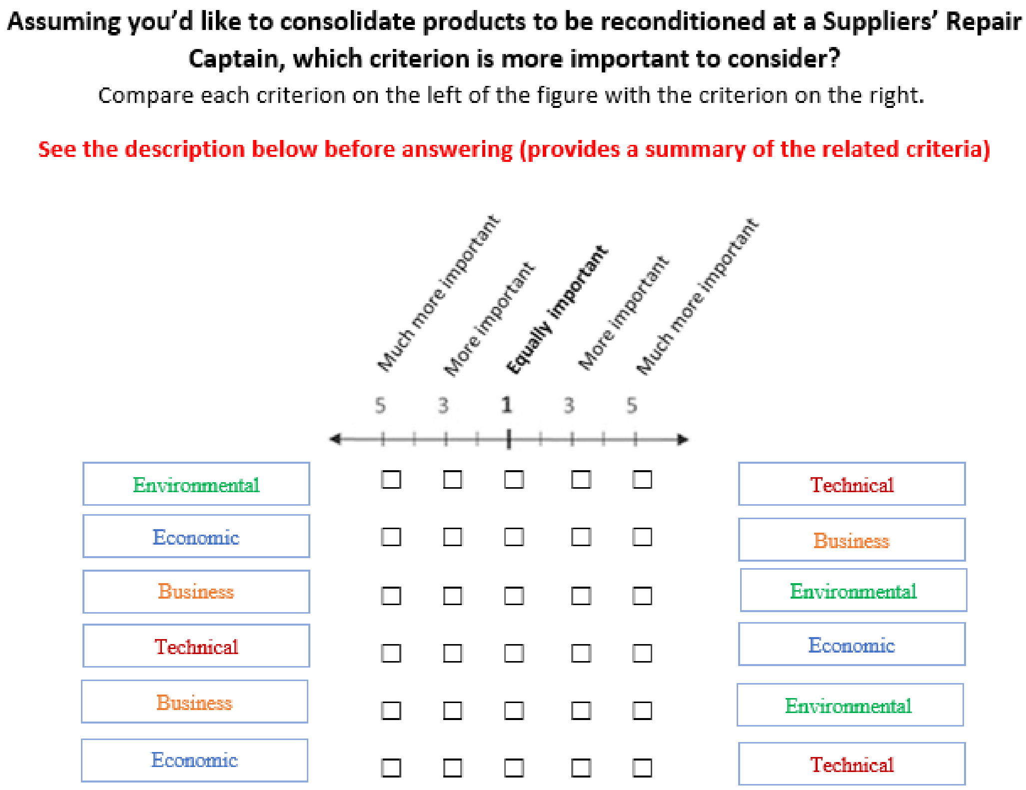


Figure A.6: The criteria category pairwise comparison questions

Appendix B MCDM input sources and questions

This appendix provides the interview questions that were required to determine the MCDM model inputs. This model ranks product categories based on opportunities and limitations to apply a repair captainship. More about this is discussed in chapter 5. First the product categories that are excluded from the model are shown in Table B.1. Second, the data sources, interview questions and answer possibilities of the questionnaires are provided in this appendix. Third, the final rank of product categories in scope is shown in Table B.2.

SPFT	**Product category out of scope**	**Short reasoning**
SPFT A	P_{26}	Only 1 main supplier
	P_{27}	Experiences design issues
	P_{28}	Lack of data
	P_{29}	Reconditioning type out of scope (recycling)
SPFT C	P_{30}	Reconditioning type out of scope (recycling)
	P_{31}	Reconditioning type out of scope
	P_{32}	Reconditioning type out of scope
	P_{33}	Only 1 main supplier and no IP & design control at all
SPFT D	P_{34}	Reconditioning type out of scope (recycling)
	P_{35}	Reconditioning type out of scope
	P_{36}	Product too unique and current warranty too important
SPFT F	P_{37}	Product too unique and regular maintenance due to product wear
	P_{38}	Product too unique and no IP & design control at all
SPFT G	P_{39}	No IP & design control at all
	P_{39}	No IP & design control at all
SPFT H	P_{40}	Product too unique and 1 main supplier only
SPFT I	P_{41}	Product too unique, no IP & design control and 1 main supplier

Table B.1: The categories excluded from the MCDM model for outsourcing to a Repair Captain

Assessment question Product design complexity:
What is the degree of design complexity for reconditioning for this product category?
Possible assessment answers:
1 = Low: Easy to follow procedures of how to reconditioning products and less complicated or not many steps involved. Others can easily take over the reconditioning steps **2 = Medium**: Important to understand the procedures and protocols, when learning others can take over the reconditioning steps **3 = High**: Complicated producers are required to execute the reconditioning, even experts can experience difficulty while executing the reconditioning. Only OEMs can deliver the expected quality.

Assessment question Contamination risk:
What is the level of contamination risk for reconditioning for the product category?
Possible assessment answers:
1 = Low: The contamination risk is low. No to limited special packaging or clean room are required **2 = Medium**: It might require special packaging and/or a cleanroom **3 = High**: High contamination risk, implying that there is always special packaging and/or cleanroom required

Assessment question Technology development speed:
What is the level of technology development speed for the product category?
Possible assessment answers:
1 = Low The product experiences a slow technology evolution. The product doesn't experience many version upgrades or competition of other products that might replace the product. **2 = Medium**: The product has some upgrades over time. There are also other products that might replace the product in the future. **3 = High**: The product experiences a high technology evolution. The product experiences many version upgrades and competition of other products

Assessment question Return flow complexity:
What is the degree of interdependency between the category and other categories and/or other parties?
Possible assessment answers:
1 = Low: Low interdependency, when OEMs can recondition all the parts of the products themselves **2 = Medium**: Medium interdependency when the OEM sometimes needs support from other suppliers for certain reconditioning activities **3 = High**: There is much interdependency, while the OEMs will always need reconditioning support from other suppliers.

Figure B.1: Technical MCDM resources and interview questions

Assessment question Competitive pressure:
What is the presence degree of third party (reconditioning) firms in this category?
Possible assessment answers:
1=Low: The customers are rarely using reconditioning services of third party (reconditioning) firms **2=Medium**, The customers are occasionally using the reconditioning services of third party (reconditioning) firms **3= High:** The customers are frequently using third party (reconditioning) firms. The Company is losing possible profit in this area.

Assessment question main suppliers:
What is the number of main suppliers in this category?
Data collected from historical data and verified with The Company experts (check if numbers are correct):
Number of main suppliers in the category

Assessment question IP & design control:
What is the most common type of supplier in the category?
Possible assessment answers:
1= if OEM A suppliers, implying that The Company has no IP & design control over the products **2= if OEM B suppliers**, implying that The Company has some level of IP & design control over the products **3= if OEM C suppliers**, implying that The Company has full IP & design control over the products

Data source Return volume
The Company reuse dashboard
Data collected from historical data and verified with The Company experts (failure mode products):
Number of material notifications (MNs) coming from the field (FSDs) between 2018-2020 per category

Data source Consolidation opportunities
The Company reuse dashboard
Data collected from historical data
Largest fraction (%) of material notifications (MNs) coming from the field (FDs) between 2018-2020 that went for reconditioning to one supplier per category

Data source Average leadtime
The Company reuse dashboard
Data collected from historical data
Average leadtime or throughput time in days of MNs coming from the field (FSDs) between 2018-2020 per category

Figure B.2: Business MCDM resources and interview questions

Data source Reconditioning costs
The Company reuse dashboard
Data collected from historical data
Sum of total reconditioning costs in euros for material notifications (MNs) coming from the field (FSDs) between 2018-2020 per category

Data source Cost reduction
The Company reuse dashboard
Data collected from historical data
Sum of standard price clean – sum reconditioning costs of material notifications (MNs) coming from the field between 2018-2020 per category

Assessment question Investment
What is the required level of investment in capital & knowledge to be able to recondition product category the products in this category ?
Possible assessment answers:
1 = Low: This category requires a minimum investment of 0 to 500 000 euros to recondition **2 = Medium**: This category requires investments of 500 000 to 1 million euros to recondition **3 = High**: This category requires more than 1 million euros to recondition

Data source Scrap value
The Company reuse dashboard
Data collected from historical data
Sum of the standard price clean of products closed 'Scrap'

Figure B.3: Economic MCDM resources and interview questions

Data source Scrap waste
The Company reuse dashboard
Data collected from historical data and average weight estimations in kg provided by The Company experts
Number of 'Closed scrap' material notifications (MNs) coming from the field (FSDs) between 2018 – 2020 per The Company category * (average weight of a product in kilograms)

Data source Scrap rate
The Company reuse dashboard
Data collected from historical data
Fraction (%) of 'closed scrap' MNs (i.e. fraction of MNs that are NOT 'closed ok' or 'open') of the total sum of the material notifications (MNs) coming from the field (FSDs) between 2018-2020 per category

Data source Transportation impact
The Company reuse dashboard
Data collected from historical data and average size estimations in cubic metre provided by The Company experts
Possible CO2 emission impact in terms of the average size (height*width*length) of a product multiplied by the return volume (i.e., number of failed products in the field) per category, while making the assumptions that all products are transported via the same transportation mode and same distance (due to lack of transportation data at this stage of the research)

Data source Resource opportunities
The Company reuse dashboard
Data collected from historical data
Sum of standard price clean per category of 'closed scrap' and 'economically not repairable' MNs coming from the field (FSDs) between 2018-2020

Figure B.4: Environmental MCDM resources and interview questions

Table B.2: The Company's product categories in scope

SPTs	**Product categories P_i**	**Final score**	**Rank**
SPFT A	P_1	0.442	**10**
	P_2	0.745	**1**
	P_3	0.497	**7**
	P_4	0.231	24
	P_5	0.451	**9**
	P_6	0.546	**5**
	P_7	0.332	19
	P_8	0.411	13
	P_9	0.322	20
SPFT B	P_{10}	0.598	**2**
	P_{11}	0.373	17
	P_{12}	0.381	16
	P_{13}	0.476	**8**
	P_{14}	0.589	**3**
SPFT C	P_{15}	0.390	14
	P_{16}	0.381	15
	P_{17}	0.556	**4**
	P_{18}	0.416	12
	P_{19}	0.506	**6**
SPFT D	P_{20}	0.352	18
	P_{21}	0.208	25
	P_{22}	0.263	23
	P_{23}	0.293	21
	P_{24}	0.264	22
SPFT E	P_{25}	0.430	11

Appendix C Global weights MCDM and rank comparison

Criteria **Sub-criteria**	**Weight** D_1	**Weight** D_2	**Weight** D_3	**Weight** D_4	**Weight** D_5	**Weight** D_6	**Weight** D_7	**Weight** D_8	**Weight** D_9	**Weight** D_{10}
Environmental	*0.1342*	*0.0999*	*0.1792*	*0.0844*	*0.0384*	*0.0984*	*0.0979*	*0.0979*	*0.0934*	*0.2827*
Scrap waste	0.0130	0.0100	0.0299	0.0033	0.0048	0.0123	0.0168	0.0104	0.0226	0.0190
Scrap rate	0.0338	0.0067	0.0299	0.0133	0.0048	0.0369	0.0097	0.0136	0.0172	0.0824
Transportation impact	0.0130	0.0334	0.0299	0.0133	0.0048	0.0080	0.0357	0.0271	0.0087	0.0426
Reuse opportunit-ies	0.0745	0.0499	0.0896	0.0545	0.0240	0.0410	0.0357	0.0469	0.0450	0.1388
Economic	*0.4948*	*0.0668*	*0.3042*	*0.2614*	*0.1918*	*0.2749*	*0.2104*	*0.2104*	*0.4232*	*0.1220*
Investment	0.1237	0.0067	0.0474	0.435	0.0480	0.0291	0.1013	0.0423	0.0756	0.0366
Scrap value	0.1237	0.0045	0.1081	0.0237	0.0480	0.1316	0.0443	0.0166	0.0995	0.0122
Reconditioning cost	0.1237	0.0334	0.0942	0.0435	0.0480	0.0382	0.0443	0.1093	0.1724	0.0366
Cost reduction	0.1237	0.0223	0.0544	0.1454	0.0480	0.0760	0.0206	0.0423	0.0756	0.0366
Technical	*0.1540*	*0.4994*	*0.1292*	*0.3854*	*0.6415*	*0.2396*	*0.4813*	*0.2104*	*0.1618*	*0.4732*
Product design complexity	0.0769	0.2494	0.0180	0.1934	0.3203	0.0874	0.0699	0.0510	0.0396	0.1790
Contamination risk	0.0154	0.0499	0.0618	0.0316	0.0428	0.0411	0.0319	0.0387	0.0124	0.0486
Technology development speed	0.0514	0.1668	0.0137	0.1291	0.2142	0.0237	0.1389	0.1013	0.0879	0.0785
Return flow complexity	0.0103	0.0334	0.0357	0.0316	0.0641	0.0874	0.2406	0.0195	0.0220	0.1671
Business	*0.2170*	*0.3340*	*0.3875*	*0.2688*	*0.1283*	*0.3874*	*0.2104*	*0.4813*	*0.3216*	*0.1220*
Main suppliers	0.0220	0.0489	0.0295	0.0128	0.0214	0.0357	0.0102	0.0821	0.0164	0.0172
Consolidation opportunities	0.0154	0.0219	0.0672	0.0126	0.0214	0.0206	0.0552	0.1080	0.0284	0.0053
Return volume	0.0338	0.0146	0.0672	0.0218	0.0214	0.0619	0.0671	0.0474	0.0491	0.0228
Average leadtime (days)	0.0096	0.0732	0.0510	0.0641	0.0214	0.1072	0.0110	0.0360	0.0851	0.0202
IP & design control	0.0988	0.1636	0.1531	0.0487	0.0214	0.0470	0.0233	0.1870	0.0153	0.0512
Competitive pressure	0.0374	0.0117	0.0195	0.1089	0.0214	0.1149	0.0437	0.0208	0.1273	0.0053

Table C.1: Global weights individual decision-makers

Table C.2: Decision makers' rank comparison

Product categories P_i	**Final rank**	**Rank** D_1	**Rank** D_2	**Rank** D_3	**Rank** D_4	**Rank** D_5	**Rank** D_6	**Rank** D_7	**Rank** D_8	**Rank** D_9	**Rank** D_{10}
P_1	**10**	14	**6**	12	11	11	**7**	11	**7**	15	11
P_2	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	**1**	**2**	**1**
P_3	**7**	**4**	**9**	**4**	**7**	12	**3**	12	**4**	**3**	15
P_4	24	24	24	22	24	24	23	20	22	24	22
P_5	**9**	13	**5**	14	**10**	**5**	18	**10**	**8**	18	**8**
P_6	**5**	**2**	12	**2**	**5**	11	**4**	**9**	**6**	**1**	**9**
P_7	19	22	18	24	14	17	15	18	25	14	17
P_8	13	11	11	**10**	12	18	**9**	16	**9**	11	13
P_9	20	20	**10**	25	18	**10**	24	17	21	21	19
P_{10}	**2**	**3**	**3**	**3**	**4**	**3**	**6**	**4**	**2**	**4**	**4**
P_{11}	17	12	22	17	17	19	14	13	19	**10**	18
P_{12}	16	17	19	16	15	16	**10**	15	16	13	14
P_{13}	**8**	**8**	**7**	**8**	**9**	**6**	13	**7**	**5**	**9**	**10**
P_{14}	**3**	**5**	**4**	**5**	**3**	**4**	**2**	**1**	**3**	**5**	**3**
P_{15}	14	16	14	13	16	15	16	14	12	16	12
P_{16}	15	18	15	19	20	13	19	**6**	14	20	**7**
P_{17}	**4**	**10**	**2**	11	**2**	**2**	**7**	**2**	11	**8**	**2**
P_{18}	12	15	13	18	13	**8**	12	**5**	13	17	**6**
P_{19}	**6**	**6**	**8**	**6**	**6**	**9**	**5**	**8**	**10**	**6**	**5**
P_{20}	18	**9**	21	**7**	19	20	11	21	15	12	21
P_{21}	25	25	25	23	25	25	25	25	24	25	25
P_{22}	23	21	20	21	23	21	22	24	23	23	20
P_{23}	21	19	23	15	21	23	20	22	17	19	23
P_{24}	22	23	17	20	22	22	21	23	20	22	24
P_{25}	11	**7**	16	**9**	**8**	14	**8**	19	18	**7**	16

Appendix D Return volume product category P_{10}

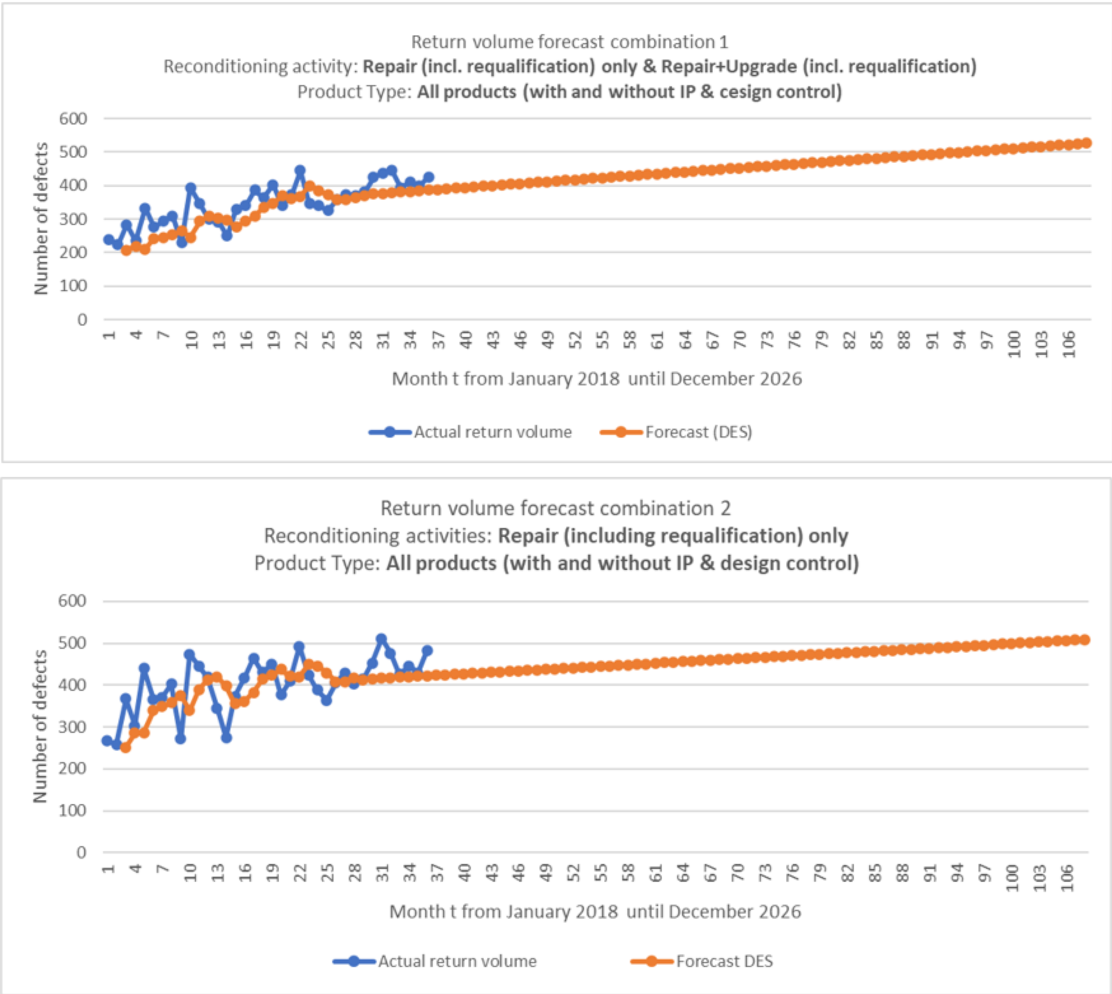
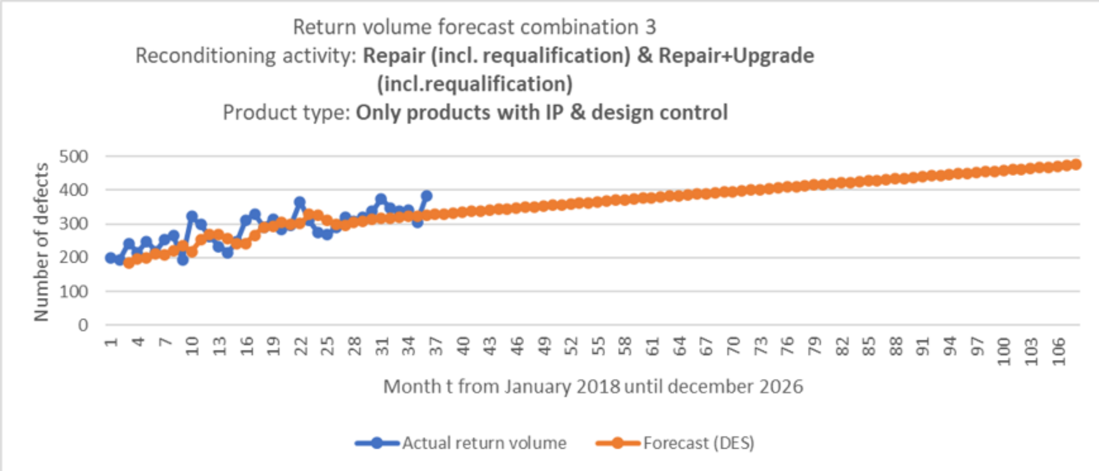


Figure D.1: Return volume forecast combination 1 and 2



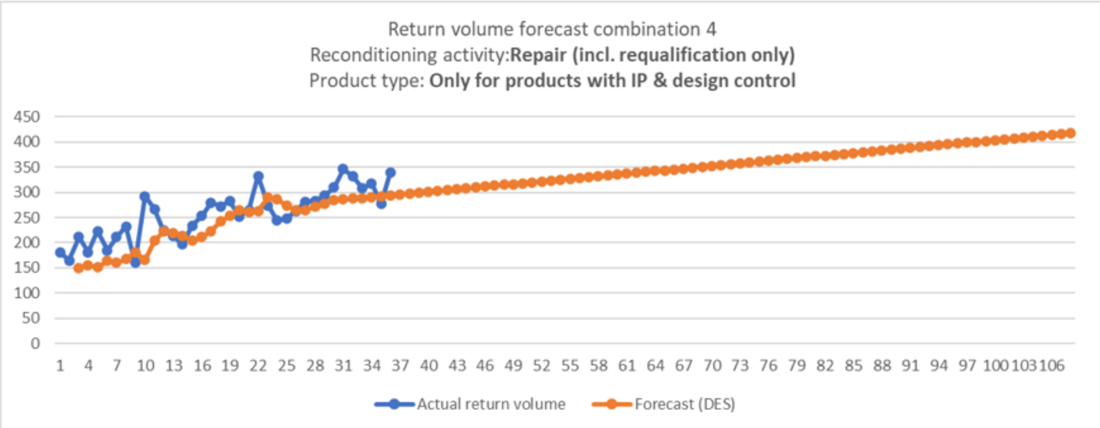


Figure D.2: Return volume forecast combination 3 and 4

Appendix E Scientific supplier selection criteria

This appendix shows supplier selection criteria provided in Weber et al. (1991). These served as a basis for the selection criteria for a repair captain. This is discussed in 7.

Table E.1: Base supplier selection criteria according to Weber et al. (1991)

Criteria	Description
Quality	The ability of each vendor to meet quality specifications consistently
Delivery	The ability of each vendor to meet specified delivery schedules
Performance history	The performance history of each vendor
Warranties and claim policies	The warranty and claim policies of each vendor
Production facilities and capacity	The production facilities and capacity of each vendor
Price	The net price (including discounts and freight charges) offered by each vendor
Technical capability	The technical capability (including research and development facilities) of each vendor
Financial position	The financial position and credit rating of each vendor
Procedural compliance	Compliance or likelihood or compliance with your procedures (both bidding and operating) by each vendor
Communication system	The communication system (with information on progress data of orders) of each vendor
Reputation and position in industry	The position in the industry (including product leadership and reputation) of each vendor consistently
Desire for business	The desire for your business shown by each vendor
Management and organization	The management and organization of each vendor
Operating controls	The operational controls (including reporting, quality control and inventory control systems) of each vendor
Repair service	The repair service likely to be given by each vendor
Attitude	The attitude of each vendor toward your organization
Impression	The impression made by each vendor in personal contacts with you
Packaging ability	The ability of each vendor to meet your packaging requirements for his product
Labor relations record	The labor relations record of each vendor
Geographical location	The geographical location of each vendor
Amount of past business	The amount of past business that has been done with each vendor
Training aids	The availability of training aids and educational courses in the use of the product of each vendor
Reciprocal arrangements	The future purchases each vendor will make from your firm