Eindhoven University of Technology

MASTER

A life cycle cost model for used systems of Vanderlande

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A life cycle cost model for used systems of Vanderlande

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In partial fulfilment of the requirements for the degree of

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in Operation Management and Logistics

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Abstract

This master thesis project describes and models the relationship between life cycle costs and the state of a used capital good. This research contributes to the merge of life cycle cost and reprocessing costs. The model provides insights in the optimal reconditioning strategy and the costs necessary to start a project, and therefore the financial performance of the reuse of a used system can be evaluated. The model has been developed for the Posisorter, but which can also be applied to other kind of systems.
Acknowledgements

This report is the final work of a master thesis for my master Operations Management and Logistics at Eindhoven University of Technology. The master thesis project is executed at Vanderlande in Veghel.

First, I want to thank dr. M. Slikker for all his support, his guidance, his insights, and his patience with me. I enjoyed our cooperation and our frequent meetings. Second, I want to thank ir. dr. S.D.P. Flapper, my second supervisor for his feedback on my reports.

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Joke Jongen, also many thanks to you, for listening to all my stories about life cycle costs and helping me during the complete process. Moreover, I want to show my gratitude to Joost van Dommelen and Lucas Otten for their support and constructive criticism.

Finally, I would like to thank my family and friends for supporting me during my study period. A period which I certainly have enjoyed very much.

Luc Aangenendt
Vegehel, December 2017
Executive summary

This report presents the results of a Master thesis project at Vanderlande. Vanderlande is an internationally operating company that produces capital goods to automate material handling. Vanderlande wants to reduce material waste as resulting from the systems they produce. They want to achieve that by extending the life of the systems, by getting the systems back that are end-of-use, reprocess the systems and sell them to a new customer as a used system.

Reprocessing is defined as the value-adding activity to increase the value of a system. Reprocessing a particular component of a system to as good as new is called reconditioning for which three different strategies are identified:

- Reuse the system ‘As-Is’, add no additional value to the system by replacing nothing;
- Refurbish the system, add minimal additional value to make the system acceptable to sell to the customer, by only replacing some components;
- Remanufacture the system, add maximal additional value so the system is as good as new by replacing all important components.

Within Vanderlande and from the customers there is the demand for a life cycle costs (LCC) analysis for used systems. Customers are not only interested in the acquisition price, but also in the costs that appear after buying the system. Vanderlande wants to anticipate the demand of the customers, and it can use a proper LCC analysis to their own advantage by using the insights of the LCC analysis to:

- Support the estimation of a good sales and buy-back price;
- Facilitate the customer in choosing the best reprocessing strategy that results into the lowest expected LCC.

One of the challenges of the LCC analysis is that different disciplines are involved, for example R&D, service, sales, engineering and operations. Many new activities are included for which no information is known yet. For making prediction about future costs, information is necessary to make the right assumptions and to decrease uncertainty. Due to lack of this information, Vanderlande does not know what the life cycle costs will be for a system that is going to be reused. This research will focus on one system called the Posisorter (SPO), with the following research question:

What is the LCC for a reused Posisorter of Vanderlande in the parcel and postal market?

An LCC model is developed to determine the LCC a SPO which is not integrated with other systems. The SPO is bought from customer, say A, and will be sold to a new customer, say B. The cost perspective of the LCC is that Vanderlande and customer B are hypothetical one party, so the allocation of costs between Vanderlande and customer B is not important. The life cycle of the used SPO is defined as the moment Vanderlande buys the SPO until customer B disposes the system.

The action plan for this research is based on the LCC methodology of Woodward (1997) and is described as follows:
- Identify cost elements of interest by describing the related process for reusing a system;
- Construct a calculation model that incorporates the relation between the state of a component and the LCC. Based on this relation, decisions can be made about the reprocessing strategy and when to use preventive replacements;
- Build a tool that calculates the LCC for which different scenarios about the age of the system, length of the system, extension of the length, and other parameters can be tested.

The development of the model is summarized in Figure 1. Based on internal data, data extracted from conducted pilots and assumptions, enough input is provided to develop and use the LCC model. For internal data, existing calculation methods within Vanderlande are used, and a reliability analysis is conducted on internal data. The developed LCC model is used to identify opportunities by giving an estimation of all the costs. With the insights in the LCC, an estimation can be made about the market value of the used system, identify an opportunity if the market value is favorable, and supports the finding of the optimal reprocessing strategy by providing the LCC for the different strategies. Once the model is used for real projects, new data will become available by logging the costs and time duration of all activities. With this data the parameters of the model can be updated.

**Figure 1: Development of the LCC model**

A new category of cost elements is identified, called reprocessing costs, which include all new activities compared to the LCC of a new system. Moreover, the other cost elements, that were already identified by Vanderlande, are also updated so they have a better fit with the process for a used system.

Based on previous research within Vanderlande and the general literature about capital goods, maintenance and down-time costs are considered to be of great significance. Therefore, an essential element of this research is the description how the collected maintenance data of Vanderlande can be used to harmonize maintenance and reliability. Instead of analyzing the system as a whole, the system is analyzed by groups of components of the system, say component types. The reliability function of a component types indicates the probability of failure of the component type at a period \( n \). The reliability function can be influenced by environmental conditions such as temperature, average weight of the handling units, dust and moisture.

Based on this function, a maintenance policy can be chosen for a component type given the state of that component type, i.e. whether preventive maintenance or corrective maintenance will be executed and at what time. In general, corrective maintenance is more expensive because of downtime costs. The chosen policy and the reliability function, can be used to calculate the expected costs for a component type in state X in a system with n periods to go. Based on the expected costs for
each state of the component, an optimal reprocessing strategy can be chosen, which means whether to change the state of the component type to the state of a new component type by replacing it.

The mathematical model has been translated into an Excel tool that provides insights for different scenarios with other values for the scenario dependent input parameters. For this research one case study is conducted. A sensitivity analysis has been executed to test the robustness of the developed LCC model and provided insight in the sensitivity of the modeled relationships and the assumptions made in this research. The main results of this case study are:

- Depending on what reconditioning option is chosen, the reprocessing costs can vary significantly. However, the other reprocessing costs elements cannot be influenced but are smaller than expected. The reconditioning options also influences the maintenance costs, which is in general the largest cost element for capital goods. Cost of down-time is the biggest cost driver of the maintenance costs.
- Investing in reconditioning can earn itself back by savings on the maintenance costs. Although the savings are relatively small, compared with reusing the system “As-Is”. One should not choose the remanufacturing option, because more components are replaced than necessary. Using the right reprocessing strategy is therefore important.
- The model is very sensitive for changes in the reliability functions and the cost of down-time.
- The LCC is mostly dependent on the age of the system, the state of the component types, the environmental conditions (average weigh of handling units, temperature, dust, and moisture), the size of the system and what reprocessing strategy is used.

The main recommendations are as follow:

- Vanderlande should gather more failure data, in which components in the system are individually marked and the operation time of the system is logged so a more precise time to failure can be determined for each failed component.
- The set of components in a component type for which the reliability is determined, should be made smaller so less information about the failure behavior of the individual components is lost. This can only be done, when more data is collected.
- The environmental conditions of each systems should be determined, so the effect of these conditions on the failure behavior of the system can be analyzed and this knowledge can be used to improve the maintenance schedule or to support the decision to change the environmental conditions at the location of the system.
- Use the estimated reliability functions to calculate optimal spare-part levels for a customer, for a system with n periods to go.
- Conduct more research to create a better method to calculate the costs for operations and include these costs in the LCC.
## List of definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Condition based maintenance</td>
<td>A maintenance type that recommends maintenance decisions based on the information collected through condition monitoring.</td>
</tr>
<tr>
<td>Corrective maintenance</td>
<td>The maintenance that is performed after a component has broken down.</td>
</tr>
<tr>
<td>Down-time</td>
<td>The time that a system is out of operation resulting from the breakdown of a component, which may be either scheduled or unscheduled.</td>
</tr>
<tr>
<td>Life cycle cost</td>
<td>The sum of all costs associated with the system as applied to the defined life cycle.</td>
</tr>
<tr>
<td>Preventive maintenance</td>
<td>The maintenance that is performed to replace parts before failure occurs.</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>The reprocessing activity of replacing a component.</td>
</tr>
<tr>
<td>Refurbish</td>
<td>The reprocessing activity on a system at minimal cost, to ensure that the system performance is within the limits of what is considered acceptable for reuse.</td>
</tr>
<tr>
<td>Reliability</td>
<td>The probability that a component or system will perform a required function for a given period when used under stated operation conditions.</td>
</tr>
<tr>
<td>Remanufacture</td>
<td>The reprocessing activity on a system in such a manner that the quality is as good or better than new in terms of appearance, reliability, and performance.</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>The value-adding activity to a product.</td>
</tr>
<tr>
<td>Reuse ‘As-Is’</td>
<td>The reprocessing activity on a system in which minimal or no value-adding activities are performed.</td>
</tr>
<tr>
<td>State of a component</td>
<td>The total number of hours the component has operated.</td>
</tr>
<tr>
<td>TCO approach</td>
<td>A purchasing tool and philosophy to understand the relevant cost of buying a particular product or services from a specific supplier.</td>
</tr>
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## List of abbreviations

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<th>Description</th>
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<tr>
<td>CBS</td>
<td>Condition based maintenance</td>
</tr>
<tr>
<td>EOL</td>
<td>End-of-life</td>
</tr>
<tr>
<td>EOU</td>
<td>End-of use</td>
</tr>
<tr>
<td>LCC</td>
<td>Life cycle costs</td>
</tr>
<tr>
<td>ETO</td>
<td>Engineered to order</td>
</tr>
<tr>
<td>ETU</td>
<td>End-take-up</td>
</tr>
<tr>
<td>MTTR</td>
<td>Mean time to repair</td>
</tr>
<tr>
<td>SDP</td>
<td>Stochastic dynamic programming</td>
</tr>
<tr>
<td>SPO</td>
<td>Posisorter</td>
</tr>
<tr>
<td>TCO</td>
<td>Total cost of ownership</td>
</tr>
<tr>
<td>TICO</td>
<td>Toyota Industries Corporation</td>
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<td>UBM</td>
<td>Usage based maintenance</td>
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1. INTRODUCTION

It is believed by that each year, the current society consumes more resources than the Earth is capable of replenishing. With an increasing population, this can cause problems for the planet’s limited resources, such as energy, food, water, and raw materials (Fehrenbacher, 2016). Consumers are getting more aware of these problems and demand that companies take their responsibility for searching solutions. One important concept is circular economy, which is about the reuse or recycle of waste. If the end of a product life cycle is also the beginning of a new one, one can use the planet’s limited resources for an infinite time and the economy is able to continue to meet the needs of the society in a sustainable way. Following this trend, the number of executive managers that believe that circular economy will be important for their business in a few years, is only increasing (UPS/GreenBiz, 2016).

The idea of circular economy is also an opportunity for companies to make a profit. The “green image” can be used as a marketing tool, but it can also reduce costs. Being able to reuse or recycle your own products, results in not having to buy new resources. However, many new challenges arise for companies that want to implement the concept of circular economy. These challenges are: optimal transportation for new, used, and re-processed products across the supply chain, repairing or recycling in such a way that good quality is guaranteed, sale of the products on potential second-hand markets and involvement of consumers and local governments (Gupta and Pochampally, 2004). The companies that overcome these challenges and can keep the costs low, will stay competitive.

Because keeping costs low is so important to stay competitive, it is important for a company to be aware of all significant costs relating to their product, also in case of the product being reused or recycled. By mapping all life cycle costs (LCC), a company can analyze these costs and use this information for improvements and decision making with regard to the establishment of a circular economy. All abbreviations and their definitions are given in at the beginning of this report in chapter List of abbreviations.

This thesis aims at the development of an LCC model for an used system of Vanderlande for a new customer. By mapping all the relevant costs and researching how these costs are made, an LCC analysis can help Vanderlande to support their decisions concerning the reuse of their systems.
2. COMPANY DESCRIPTION AND PROBLEM FORMULATION

In this chapter, the situation and the problem formulation will be discussed.

2.1. Company description

A description of the company is provided in this section to provide more context for the problem formulation. First the history of the company is discussed. After that some insights in the company’s structure and the products that Vanderlande sells is provided.

2.1.1. History

Vanderlande is a manufacturer of capital goods that is specialized in automation of material handling. Vanderlande was founded in 1949 by E. van der Lande, and was at that time mainly concerned with the service and repair of machines for the textile industry. Now Vanderlande designs and implements innovative, automated material handling solutions for customers worldwide.

The mission of Vanderlande is to improve the competitiveness of its customers through value-added automated material handling solutions. Vanderlande wants to achieve that by designing innovative solutions and offering reliable systems and services for its customers (Vanderlande, 2015).

At this moment Vanderlande has more than 4,500 employees at a number of locations across the world and a consistently increasing turnover of more than one billion euros. Because of the consistent growth and a good future perspective, Toyota Industries Corporation (TICO) has bought Vanderlande recently but it promised that Vanderlande will stay an autonomous entity within TICO, i.e. TICO’s involvement will be limited to the business decisions of Vanderlande (Lindell, 2017).

2.1.2. Company structure

Vanderlande is active in three different markets: baggage handling system, parcel and postal, and warehouse distribution. The systems Vanderlande offers are different for each market, but within the market, the systems can also differ. Vanderlande offers systems ranging from small local sorting depots to one of the largest sorting and distribution facilities in the world. Because of the differences between the markets and the different solutions, each market is a different business unit within Vanderlande. Another business unit of Vanderlande, which is active in three described markets, is the business unit “Service”. Service involves performing maintenance activities and other related activities. For a customer, it is optional to make use of these services.

2.1.3. General product description

Each product of Vanderlande is engineered to order (ETO) and thus customer specific. Based on the customer’s order, Vanderlande designs products that automate the material handling. These products consist of different systems in order to achieve these automations. Each system consist of electrical and mechanical components for which each component has an item-number. For each
market Vanderlande is active in, Vanderlande offers different systems which have different functionalities. For the automation of material handling there are always three different steps that need to be taken, these steps are receiving, sortation and shipping.

Customers have an inflow of material which should be placed on the system. The material that must be processed are called handling units. This inflow of handling units can be received in many ways which is dependent on the amount and the kind of handling units. Once the handling units are received they must be transported to the right place. For the baggage handling and parcel and postal market this means that the handling units must be transported to the transportation unit stationed at the dock. This can only happen when the system knows where each handling unit should go to and is able to sort the handling units automatically. For the warehouse distribution market, the handling units also must go the right place in the warehouse, but in this case the handling units will be temporarily stored at their location before they are transported to the right truck. Also in this case, the handling units must be sorted automatically.

Once the handling units are sorted they must be transported and loaded into a specific load carrier, a medium to transport the handling units. Load carriers are for example: a pickup and delivery vehicle, line haul or roll container with bag. Note that the handling units can enter the system, the same as they would leave it: in diverse ways and in different amounts.

2.2. Problem formulation

In this section, the problem description is provided and previous research on the life cycle costs and total costs of ownership of the products of Vanderlande are discussed. Moreover, the problem definition is given and more information about the scope of the research is discussed.

2.2.1. Problem description

Vanderlande wants to reduce material waste as resulting from their systems by implementing the principles of circular economy. The way Vanderlande wants to establish this, is by extending the life of their systems. Once a customer does not use its system anymore, and the system is still suitable for use, Vanderlande wants to buy the system back and sell it on the second-hand market. The exact costs regarding the life cycle extension are currently unknown.

Because the costs are unknown, it is hard to make any decisions regarding the implementation of a circular economy. For example, it is hard to determine a buyback price and a selling price to ensure a positive financial performance on the projects. Moreover, the communication with the customers can be complicated if there is no insight in the cost structure which can lead to lost sales. In this case, there is also no support for continuous improvements because there is no understanding of the costs and performance cannot be compared (Ellram, 1994).

Vanderlande and the new customer of the used system have to make several decisions together. One of these decisions involves how they going to reprocess the system. According to Parkinson and Thompson (2003) reprocessing is a value-adding activity of a product. A convenient way, which is
technological achievable, is to add value to the product by replacing the old components of a product by new components, which is called reconditioning. Three different reconditioning options are identified as:

- Reuse the system ‘As-Is’;
- Refurbish the system;
- Remanufacture the system.

Reuse ‘As-Is’ means that a system will be reused with minimal or no value-adding activities. The system will be cleaned a bit and sold to the next customer, so no components are replaced. When a system is refurbished, the system will be reprocessed at minimal cost, but ensure that the system performance is within the limits of what is considered acceptable for reuse, so only components are replaced if it is necessary. In case the system is remanufactured, the product will be reprocessed in such a manner that the quality is as good or better than new in terms of appearance, reliability, and performance, which means that all components are replaced (Parkinson & Thompson, 2003). Thus, each strategy will influence the future maintenance costs and the reprocessing costs of the system, but the exact influence is unknown. What strategy is optimal is dependent on the state of the individual components. The state of a component indicates the chance of failure of that component. The state of the complete system is determined by the states of all individual components. By going from one state to another state with a lower chance of failure, a transition takes place for which an investment must be made.

2.2.2. Previous research on LCC within Vanderlande

Vanderlande already has been working on providing insights into the life cycle costs of a new system, these insights are used as input for this research. The first research developed a general method for life cycle costing and provided insight into models that could give more information about the availability of the systems of Vanderlande (Putten, 1999). Franssen (2006) went more into detail and identified main cost buckets. His findings showed that acquisition cost, maintenance costs, operational costs, and downtime costs are the main cost buckets and that 70% of the LCC consists of maintenance costs and downtime costs. See Appendix A for an overview of these cost buckets. A tool was constructed to determine the LCC of a specific system and the optimal spare-part inventory. Other research was conducted to develop a calculation model that models the relationship between technical system availability and life cycle costs. One of the findings was that more inspections of the system leads to a higher availability and that extra spare parts investment would not lead to a substantial improvement of the availability (Vlasblom, 2009). At the same time, other research provided insight into the way the number of technical failures and total relevant maintenance costs of a Vanderlande system is influenced by different maintenance strategies. Based on this research, the conclusion is drawn that pro-active strategies with increased commitment in terms of resources and inspection can lead to increased reliability and performance and thus a lower LCC (Stein, 2009).

2.2.3. Problem definition

Based on the problem description and the gap in the previous research, the following problem definition is defined:
Vanderlande does not know what the life cycle costs will be for a system that is going to be reused by a new customer.

2.2.4. Scope

This research solely focuses on costs, and not the impact on the environment. Because of time constraints and need for clarity, there is a necessity to further narrow down the research scope. This will be done in three ways; first by defining the life cycle of the used system for which costs will be included in the LCC, secondly by explaining whose problem it is and thus from what perspective the costs are determined, and thirdly by selecting a specific system. This section will provide further explanation of the scope in these terms.

Life cycle

As described earlier, Vanderlande designs a specific system for a customer, say A. Once the system is end-of-use (EOU), and customer A does not want to use the system anymore, Vanderlande will buy the used system back and will make the system ready for reuse. Parts that are not useful will be sent to the landfill. When the system is ready, it will be transferred to a customer, say B, for operation and Vanderlande will be in charge of the maintenance. The system will stay at customer B until the system is end-of-life (EOL), and thus customer B cannot use the system anymore. For this research it is assumed that a system can only be reused once. At this moment, the system will be moved to the landfill after customer A does not want the system anymore, which is not in line with the idea of circular economy.

For this research, the life cycle will be defined as the moment when the system is EOU until the system is EOL, see Figure 2. The blocks indicate a location and the arrows represent material going from one place to another. According to Product Engineers, the life of a system cannot be extended when the system is EOL. This is because the frame of the system would then need to be replaced and this would be too expensive compared to ordering a new system.

![Figure 2: The scope of the defined life cycle](image)

Perspective

Depending on the perspective, the perspective of Vanderlande or the perspective of the new customer B, different kind of costs are meaningful for the LCC. For this research, a combined
perspective of Vanderlande and customer B is used. So, all costs that are related to the system in this scope are important for both parties, but the allocation of the costs between Vanderlande and customer B is beyond the scope. Allocation of the costs can differ per customer, because Vanderlande can make different arrangements with each customer and thus this allocation is not included in the research. In other words, Vanderlande and customer B will be seen as one party instead of two different parties.

System
Vanderlande has a lot of different systems, too many to include them all in this research. This thesis will thus focus on only one kind of system. The Posisorter (SPO) has been chosen because Vanderlande believes it has the most potential in the second-hand market. The SPO is used in a dynamic market with customers that grow relatively fast because of the fast growing E-commerce. Fast growing customers are often in need of an SPO with more capacity and can prefer a used SPO over a new SPO because of the price advantages and shorter lead-times compared to a new SPO, because the system does not have to be produced. Another reason is that the SPO is one of the most sold systems of Vanderlande. This means that there is a relatively high probability that old SPO’s will become available for reuse in the near future. Moreover, some sites using an SPO, have a full-service contract. This means that the SPO’s are maintained by Vanderlande thus there is more data available about the maintenance and there is no maintenance conducted of which Vanderlande has no knowledge. The SPO is an expensive system and often the most critical system at the location of a customer. The maintenance strategy of the SPO is often the basis for the maintenance strategy for the entire site.

Another important aspect in the present study is that the SPO is treated as a stand-alone system. This means that the integration of the SPO with other systems is not taken into account. Hence, the costs for this integration depends on the actual systems the customer uses already and not on the used SPO. Last important aspect is that for this research one specific specification of the SPO will be fixed: the SPO will be a dual side SPO. The reason for this is that most SPO’s in the market are dual side and this choice of design does impact the LCC.

2.2.5. Research questions

In this chapter, the research questions are defined. As previously discussed, the costs for a reused system are unknown for Vanderlande and a future customer, which has led to the following main research question:

What is the LCC for a reused Posisorter of Vanderlande in the parcel and postal market?

With the corresponding sub-research sub questions:

1. What process flow is associated with reusing a system?
2. What are the various cost elements in the described process?
3. What components of the Posisorter should be included in the model?
4. What is the financial performance given the state of a Posisorter?
5. What are the reprocessing investments that could be used for the Posisorter?
6. How to quantify the reprocessing investments in monetary terms?
7. How to determine the optimal reprocessing investment?

2.2.6. **Deliverables**

This section discusses the deliverables involved in this thesis. The deliverables are determined from the point of view of Vanderlande and from an academic point of view.

**Deliverables for Vanderlande**
To help Vanderlande in being prepared for the future, the following deliverables of this research are important for Vanderlande:

1. A description of the process flow for a reused system;
2. An overview of all costs element relevant for the LCC of a used Posisorter;
3. A method to predict future costs based on the state of the system;
4. All necessary values for the input parameters of the LCC model;
5. A tool that can calculate the expected LCC of a used Posisorter for different scenarios.

**Academic deliverables**
The first academic deliverable is to enrich the available literature in the field of LCC and reprocessing used systems with insights from practice because there is a large cap in the literature about the reprocessing of used capital goods. By applying the models in practice and checking whether the models are realistic, insight are created. By indicating changes in case the model does not work in practice, the model is updated. By combining the literature of LCC and value recovery of used systems new insights can be provided.

The last deliverable is creating a model that should be easily converted to be able to use for other systems, so other capital goods manufacturers will be able to use the same model.

2.3. **Report outlines**

This chapter has provided an insight in the company, the problem, the scope, the research questions and its sub-questions. Based on the research sub-questions the report is structured as follows: **Chapter 3** provides background information about the LCC approach methodology. Moreover, background information is provided about replacement theory. **Chapter 4** focuses on explaining the process that Vanderlande should undertake when it wants to reuse its old systems. Each activity is described in detail for the identification of cost elements. Furthermore, the implementation of the LCC model is discussed. **Chapter 5** elaborates on the cost elements described in chapter 4. For each cost element, a formula is developed. Also, the added value of the model for Vanderlande is discussed and the categorization of the input parameters. The model is validated and verified. **Chapter 6** describes a case study in which the input parameters of the model described in chapter 5, are discussed for the reuse of a SPO. Next the developed tool is described, en the results of the case study and a sensitivity analysis are discussed. Finally, the main findings, limitations and recommendations are presented in **Chapter 7**.
3. SHORT LITERATURE REVIEW

This chapter will provide more background information about life cycle costs and will present an introduction into reliability theory and maintenance.

3.1. Life cycle cost approach methodology

A LCC approach was first applied in the mid-1960s by the US department of Defense in order to minimize the expenses of their equipment (White & Ostwald, 1997). Later it was also taken up by the capital goods industry and the construction industry to rank different investment options (Neugebauer et al., 2016). The LCC approach aims to go beyond the purchase price and wants to include all relevant costs in the decision to purchase something. Many different definitions for LCC can be found in literature, for this study a straightforward definition of LCC is used, which is the following: *Life-cycle cost refers to all costs associated with the system as applied to the defined life cycle* (Blanchard and Fabrycky, 1990).

The use of an LCC can have various goals (Barringer and Weber, 1996). The most important purposes of the present study are summarized below:

- Old measures on the LCC of existing system can help with the prediction of the LCC of used systems. This information can be used during selling to satisfy the customer and to convince the customer to choose a system with the lowest LCC, although the acquisition price is higher.
- Once the most important cost factors are identified, Vanderlande will have better insight in its processes and can better prioritize what operations should be improved first.

A methodology which is similar to the LCC approach is the total cost of ownership (TCO) approach. Also, the TCO approach focuses on more than the purchase price of a product and takes into account all the relevant costs of a product. The TCO approach is defined as: *TCO approach is a purchasing tool and philosophy to understand the relevant cost of buying a particular product or services from a specific supplier* (Ellram and Siferd, 1998).

The main difference between LCC and TCO is the perspective of the costs. For TCO the perspective of the buyer is used, while the LCC adopts the product perspective which means that different costs are important. When computing the total costs from a product perspective, this means that the costs related to creating the concept, designing, manufacturing, distribution, operating, and disposing of the product, are all taking into account. Furthermore, because of the difference in perspective, the time horizon over which the costs are included can also be different. For the TCO only the time horizon over which the buyer owns the product is relevant, while for LCC this time horizon could be extended to the defined life cycle of the product (Rapaccini et al., 2013). The defined life cycle can be adjusted to the extent in what is relevant for the manufacturer. For this research, the LCC approach fits best because of the cost perspective that is defined in section 2.2.4 and the time horizon of the LCC fits with the life cycle of the used product. Note that the life cycle of the used
product is defined as: the moment Vanderlande gets the products back from customer A until customer B disposes the product.

A good methodology helps to construct and analyze an LCC. To define the LCC of the system, the LCC procedure can be used (Woodward, 1997), shown in Figure 3.

![Figure 3: LCC procedure](image)

For the first step, the cost elements of interest are determined, which include all the cash flows that occur during the life of the assets that are considered important. The elements that are related to only a small amount of costs are not considered important. Also, a distinction should be made between the initial capital costs and the costs that are made during the life of the system. The first three research sub-questions will be answered with executing this step.

The second step defines what cost structure to be used for all the costs related to the system. The cost structure helps to identify potential trade-off relationships which will help to answer research sub-question 4. What structure is used depends on the required depth and breadth of the LCC study. The third step is to determine the mathematical relationship between the different costs, which will answer research sub-question 5, 6 and 7.

The fourth step is choosing an appropriate methodology that should evaluate the systems LCC. As suggested by Kaufman (1970), in this step all the cost parameters of the identified cost elements are calculated at current rates and all costs need to be projected forward at appropriate rates of inflation. Also, the cost should be discounted back to the base period to ensure comparability between different LCC’s. At last, all cost should be summed. By executing this step, the main research question can be answered.

3.2. Reliability and maintenance

Because Franssen (2006) discovered that maintenance costs and down-time costs cover 70% of the total LCC costs for one of the systems of Vanderlande, it is assumed that these costs will also be considerable for this research. To be able to answer sub-research question 5 and 7, more insight should be provided about an important concept relating to maintenance and down-time, which is reliability. Reliability is defined as: The probability that a component or system will perform a required function for a given period when used under stated operation conditions (Ebeling, 2010). In other words, the probability that the component or system will not fail for a time period. When the probability of failure is high, it may be beneficial to do preventive maintenance because preventive maintenance can be less expensive for an organization than corrective maintenance.
Preventive maintenance refers to replacement of a component before it fails because of the reliability of the component. There are two forms of preventive maintenance: usage based maintenance (UBM) and condition based maintenance (CBM) (Arts, 2017). UBM means that the replacement of a component is based on the total usage of a part. Examples of how usage is measured are mileages or time. CBM means that the replacement of a component is based on the measured condition, when the condition passes a previous established threshold the component will be replaced. The UBM and CBM are both maintenance policies that require information about the failure behavior of a component before one can use these policies. Obtaining this information and using this information correctly is therefore very important for determining the right policy and the associated cost with the policy. Different policies, results into different costs, which influences the LCC of a system.

The reliability of a component cannot only be used to determine the maintenance policy but it can also support the reliability improvement decision for a used system before selling it to a new customer. As shown in Figure 4, reliability improvement actions result into costs, but with the optimal decision, the future maintenance costs could decrease. So, there exist an optimum for the reliability improvement actions, which corresponds with sub-research question 7 (Saidi-Mehrabad et al., 2010).

![Figure 4: Block diagram of determining the optimal reprocessing level](image)

According to Saidi-Mehrabad et al. (2010) there are three interesting questions for a company, related to the concept of reliability improvement procedure for reprocessing, at that moment the company gets a system back:

1. Should reliability improvement actions be used for second hand products?
2. What improvement actions should be taken?
3. What should be the optimal reliability improvement level?

The outcome of these three questions can have a significant influence on the costs of a company and the LCC of a system and answer sub-research question 5 and 7.

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1 Figure 4 was inspired by Figure 3 of Saidi-Mehrabad et al. (2010), but has been altered to be consistent with the definitions in this research.
4. THE PROCESS FOR REUSE AND COST STRUCTURE

This chapter will discuss how the process of Vanderlande should look like when implementing the business idea of reusing systems and compare it with the process for a new system. Furthermore, it will be discussed when in the process the LCC model should be used and what the important cost elements are for the LCC model.

4.1. The process for the reuse of a system

This section will provide a process description regarding the reuse of an old system. The process flow regarding the reuse of a system consists of many different activities, which are executed by different stakeholders. An overview of the process is shown in Figure 5. First, the opportunity is spotted. The system will be inspected to check what the condition is. Then, a decision is made whether to buy-back the system. If the decision is to not buy back the system, the process is terminated. When the system is bought back, Vanderlande will start looking for a customer to buy the system. Immediately after that, the system needs to be disassembled, packed, documented, and transported to the new customer. When no customer is found yet, the system can be stored in a warehouse. The system will be engineered from scratch, to determine how the system should be built at the customers location. If a reconditioning strategy has been chosen, the necessary new components will be ordered and transported to the customer. When it is known what will be assembled at the customer location, the master data of the system will be created in the information system of Vanderlande. The system will be assembled and tested before the system will be operated and maintained. At last the system will be disposed when the system is EOL.

![Figure 5: Process description of the reuse of products](image-url)
The processes in the orange box are exactly the same as for the process of a new system. The process flow that is provided is based on the execution of the pilots of Vanderlande concerning the reuse of systems, and small revision projects of the service department. The process flow is validated by the project managers of the pilots and the revision projects. Detailed descriptions of the processes are provided in Appendix B. The process description will be used to derive the cost elements relating the life cycle cost for a reused system as described in the procedure of Woodward (1997) in the previous chapter.

4.2. The process for a new system

The original process flow that Vanderlande executes that is related to a project with a new system, has similarities with the process flow for a system that is going to be reused. In Figure 6 a general process overview is shown for a project with a new system. When a customer is found for a new system, the system will be engineered, so Vanderlande knows what they are going to build and creates the master data of this system in the information system. Then all components are manufactured in their own factory, and these components are packed, documented and transported. At last, the system is assembled, tested, operated, maintained and disposed.

Many processes in Figure 5 have the same name as the processes in Figure 6. However, this does not mean that the processes are the same. Vanderlande has relatively much information about the costs for this original process flow, mapping the similarities and differences makes it easier to find the LLC for this project. When processes are the same, the same costs can be used for the calculation of the LCC. The processes in the orange box of Figure 5 and Figure 6 are the same. The other processes with the same name differ from each other. How the processes differ is described in Appendix C.
4.3. Cost elements

The most recent cost break-down for a new system of Vanderlande is described by Franssen (2006), and consist of four main cost buckets: acquisition costs, maintenance costs, down-time costs and operation costs, see Appendix A. This cost break-down is from 11 years ago and not applicable for a used system. Based on the processes described in section 4.1, all relevant cost activities are identified in this section. All cost elements are divided over cost buckets, based on the LCC described by Franssen (2006) for Vanderlande. See Table 1 for the identified cost elements for a used system and see Appendix D for the lay-out of the new LCC. This section will elaborate the changes that needs to be made to the old cost break-down, to get the new cost break-down.

Table 1: Identified cost elements

<table>
<thead>
<tr>
<th>Main cost buckets</th>
<th>Sub cost bucket</th>
<th>Described in section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition costs</td>
<td>Project management</td>
<td>5.2.1</td>
</tr>
<tr>
<td></td>
<td>Finding a customer</td>
<td>Appendix E1</td>
</tr>
<tr>
<td></td>
<td>Buy-back</td>
<td>Appendix E2</td>
</tr>
<tr>
<td></td>
<td>Engineering</td>
<td>5.2.2</td>
</tr>
<tr>
<td></td>
<td>Site work at new customers location</td>
<td>Appendix E3</td>
</tr>
<tr>
<td></td>
<td>Master-data</td>
<td>Appendix E4</td>
</tr>
<tr>
<td>Reprocessing costs</td>
<td>Research</td>
<td>Appendix F1</td>
</tr>
<tr>
<td></td>
<td>Site work old customer</td>
<td>5.3.1</td>
</tr>
<tr>
<td></td>
<td>Transport</td>
<td>Appendix F2</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>Appendix F3</td>
</tr>
<tr>
<td></td>
<td>Reconditioning</td>
<td>5.3.2 and 5.4.2</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>Maintenance inspections</td>
<td>5.4.1</td>
</tr>
<tr>
<td></td>
<td>Replacements</td>
<td>5.4.2</td>
</tr>
<tr>
<td></td>
<td>Spare-parts</td>
<td>5.4.3</td>
</tr>
<tr>
<td>Operation costs</td>
<td>Operation personnel costs</td>
<td>5.5.1</td>
</tr>
<tr>
<td></td>
<td>Energy consumption costs</td>
<td>5.5.2</td>
</tr>
</tbody>
</table>

A summary of the relevant changes that are made to the LCC described by Franssen (2006) are:
- One main cost bucket is added, Reprocessing costs, with new sub cost buckets;
- The main cost bucket down-time costs, is made a sub cost bucket in Maintenance cost;
- Changes in the construction of the main cost buckets.

Figure 7 provides an overview of how the LCC break-down used by Franssen (2006) must be altered to get the LCC break-down for a used system as described by Table 1. The cost elements in red are removed from the old cost break-down, the cost element in dark blue are moved to the light blue cost elements with the same name, the yellow cost elements got a different more applicable name, the green cost elements are new, and the white cost elements stay the same. The changes will be elaborated below.

The first main bucket, acquisition costs, includes costs that are similar to the original distribution of acquisition costs. A new cost bucket master data is added. The project costs remain; however, the project costs are differently obtained. The cost elements project management and engineering stay the same for project costs, but equipment is changed to buy-back costs and consist of the cost...
elements initial spare-parts, purchasing process and the costs for the system that is bought back. Costs for site work is further specified to costs for site work at the new customers location. All identified activities in this cost bucket remain the same. Miscellaneous is removed because they cannot be predicted and are thus irrelevant for this LCC. Further, the sub-bucket sales charges is changed to finding a customer, which put more emphasis on the activity of finding a customer instead of selling the product. The cost bucket initial spare-parts is moved to the cost element equipment (buy-back costs). Next, the cost bucket cost of capital is removed.

Figure 7: Changes that are made to the original LCC structure

The second main bucket, maintenance costs, is also a restructured. The cost buckets are defined to describe the costs for regular maintenance actions, so the total costs can be calculated by finding how often the maintenance actions are conducted. So, the new sub cost buckets are maintenance inspections and replacements. Replacements can be divided into corrective and preventive replacements. For both actions labor costs and spare-part usage costs are included. For the element corrective replacements, a new cost element fee is included and the cost of down-time is moved to this cost bucket. This is because cost of down-time is directly related to corrective maintenance action, and influences the replacements by deciding to replace components preventively, or not. Preventive maintenance does not include down-time costs, because for this model it is assumed that preventive replacements always is done outside operation hours. The sub bucket spare-parts remains but is differently obtained. The cost for extending the initial spare-parts package is added, the cost of spare-part usage is removed to replacements, holding costs stays the same, and the spare-part fee is removed. The buckets RMR/additional work, helpdesk costs, subcontractor and miscellaneous are removed. These costs were not identified in section 4.1 and are also not discussed in detail by Vlasblom (2009) and by Franssen (2006) and are therefore removed from the new LCC break-down.
The third main bucket, operation costs, was not investigated in the previous researches because operation costs are mostly dependent on the customers. Almost no information is known about this, because the customers do not provide Vanderlande with this information. Because the focus of this research is about the costs that are directly related to the reuse of the used system, the cost buckets for operation management costs, facility space costs and other operating costs are removed for the new LCC break-down. Operation personnel costs and energy consumption costs are direct costs and will therefore be included in the LCC.

The fourth and new main bucket, reprocessing costs, is related with all new activities that need to be executed compared to the sale of a new system. For example, inspecting an old system and the evaluation of this system are research costs and are new activities. Work that must be done at the old customers location: disassembly, packing and documentation, are new activities. Next, transportation costs are not mentioned in Franssen (2006). Transportation costs are also included for a new system; however, transportation costs for a reused system are larger and are therefore mentioned in the LCC. Storage costs are completely new and directly linked with the reuse of a system because the storage of a complete system is never necessary for a new system. The last cost bucket within reprocessing costs is the reconditioning costs which is also a cost that is incurred because of the reuse of a system.

4.4. The LCC model applied in the described process

Before development of the LCC model, it should be clear when in the process, described in section 4.1, the LCC model must be used. Because the model can give helpful insights at multiple moments in the process, it is necessary for clarity reasons to specify one of these moments as the basis for this research. With this basis, it can be determined what cost elements are already sunk costs and known, and what costs still need to be made and thus can still be influenced.

The moment for which the LCC is developed is for when a potential buyer is found during the process ‘Finding a customer’. Vanderlande can use the model to discuss the reconditioning options with the customer and as a support tool to determine a sales price. If Vanderlande knows what the future costs are of the project and what the sunk costs are from the moment they are discussing with a potential customer, Vanderlande can construct a sales price which ensures a positive financial performance for Vanderlande. Concluding, the full cost price is calculated by the LCC model.
5. MODEL DEVELOPMENT

In this chapter, the identified cost element of Table 1 will be discussed together with the calculations for the LCC model. Each cost element and the corresponding calculations are discussed briefly.

5.1. LCC model

The summation of all the cost buckets leads to the LCC for a used system. This leads to the following general LCC formula:

\[ LCC^s = C_A^s + C_M^s + C_O^s + C_R^s \]  

(1)

Where

- \( LCC^s \) = Life cycle cost for a used system s (in euros).
- \( C_A^s \) = Cost related to the main cost bucket acquisition of system s (in euros).
- \( C_M^s \) = Cost related to the main cost bucket maintenance of system s (in euros).
- \( C_O^s \) = Cost related to the main cost bucket operation of system s (in euros).
- \( C_R^s \) = Cost related to the main cost bucket reprocessing of system s (in euros).
- s = Corresponds to system s.

For notational convenience, s will not be mentioned in the following formulas because when building an LCC it should be clear which system is meant.

**Level of detail**

All costs will be described in the following sections with such a level of detail that it is clear what is included in the cost and what is not. Also, the level of detail will match with the current detail of cost calculations of Vanderlande. This level of detail will result in many parameters, but most of them should only be determined once and can then be used for multiple systems. When information of future projects for used systems are logged well, it will be easy to update specific parameters. A reason to update the parameters would be that Vanderlande experiences a learning curve and can execute some activities more efficiently than before.

A high level of detail is necessary to determine the LCC as accurate as possible. Capital goods are expensive systems, a difference of a few percentages on the total cost will have a significant impact. Which costs will be more important than others is unknown, because it is a new business for Vanderlande and they do not have much experience with it. Especially, the acquisition and reprocessing costs are new for Vanderlande and directly influences the sales price for a used system and thus whether the system can be sold for a competitive market price. At last, some parameters will have a higher level of detail than Vanderlande and the customer can handle efficiently. However, this should identify improvement aspects in the information gathering process of Vanderlande and the customer.

The next section will discuss cost elements that are typical or representative for other cost elements, so it is clear how the formulas for the cost elements are constructed and this report does contain too
much detail. The description of the cost elements that will not be described in this chapter, are provided in Appendix E and F.

5.2. Acquisition cost

In this section, the acquisition cost and the corresponding costs will be discussed, as described in Table 1. For the acquisition costs, the following formula is used:

\[ C_A = C_PM + C_FC + C_BB + C_Eng + C_SWN + C_MD \]  

(2)

Where

- \( C_PM \): Cost related to project management for the used system (in euros).
- \( C_FC \): Cost related to finding a customer for the used system (in euros).
- \( C_BB \): Cost related to buying back an old system for the used system (in euros).
- \( C_Eng \): Cost related to engineering for the used system (in euros).
- \( C_SWN \): Cost related to site work at the new customer’s location for the used system (in euros).
- \( C_MD \): Cost related to creating the master data (in euros).

The cost elements that will be described in this section are \( C_PM \) and \( C_Eng \), the others are discussed in Appendix E.

5.2.1. Project management costs

It is assumed that the project management costs are independent of the length of the system and the type of system. Vanderlande claims that this is true for projects with a project value between zero and five million euro’s, which is the range for used SPO’s. The cost consists of the hours that the project manager spends on the project and the hourly rate of the project manager. For this research not the wage of the employee is taken, but the total costs per hour for the company, determined by Vanderlande, which includes for example the costs for insurances. The activities that a project manager do is described in Appendix B. However, when extra activities must be arranged, such as sending components to an external cleaning company or extending the system in length, extra time is added. Sometimes the location of the project must be visted. The number of visits depends on the total number of estimated hours that the project manager should spend on the project and the estimated minimum number of hours that should be worked to go on a visit. Vanderlande makes a distinction between short trips and long trips. Short trips mean that an employee goes to the customer and back, the same day. Long trips mean that an employee goes to the customer and stays the week in a hotel, and then goes back home. Each short trip has the same costs, and this is also the case for each long trip. Long trips are mostly used for employees that do site work at the location of a customer, see 5.3.1.

\[ C_PM = (T_PM + cl \cdot T_PMCL + ex \cdot T_PMEM) \cdot W_PM + C_ST \cdot \left( \frac{T_PM + cl \cdot T_PMCL + ex \cdot T_PMEM}{T_TPM} \right) \]  

(3)

Where

- \( T_PM \): Time that a project manager spends on the project (in hours).
- \( W_PM \): The hourly rate of a project manager (in euros/hour).
\(T_{PMCL}\) = Time spent by a manager to arrange cleaning (in hours).
\(T_{PMEX}\) = Time spent by a manager to arrange extension of the system (in hours).
\(cl\) = Binary variable whether components are cleaned. One means that components are cleaned and zero means that no components are cleaned.
\(ex\) = Binary variable whether the system is extended. One means that the system is extended and zero means that the system is not extended.
\(C_{ST}\) = Cost for a short trip (in euros).
\(TT_{PM}\) = Minimum budgeted work time for the project necessary to make one trip for a project manager (in hours).

5.2.2. Engineering costs

Engineering costs are dependent on the duration time that an engineer works on the project and the hourly rate of the engineer. The engineer starts from scratch, and cannot use the engineering work that was made for when the system was new. The time spend on engineering a new system depends on the length and type of the system.

As described in Appendix B, extra time needs to be spend on engineering when the used system does not qualify the current safety rules or old components are end of life and must be replaced by a new component. The time spent on re-engineering the system for the new safety rules dependents on the difference between the safety levels of the used systems and the current safety rules. Because there is no clear insight available in the changes of safety rules over time and how this affects the design of the systems, it is assumed that each year the safety rules changes and that for each year a system becomes older a constant number of hours is necessary to process the new safety rules into the used system. In case of re-engineering the system to replace old components, the old system can be defined as a set of components. In this set all components are counted that are EOL. For all these EOL-components, the engineer spends extra time to find a way to replace these components with new components without changing the system more than necessary. For each EOL-component a fixed constant will be assumed to indicate the time spend on engineering a replacement solution.

\[
C_{Eng} = T_{eng} \cdot W_{Eng} + C_{ST} \cdot \left(\frac{T_{eng}}{TT_{eng}}\right) \\
T_{eng} = T_{EN} + T_{ES} + T_{EOC} \\
T_{ES} = g \cdot ea \\
T_{EOC} = \sum_{i=1}^{d} EOL_i \cdot eoc
\]

Where
\(W_{Eng}\) = The hourly rate of an engineer (in euros/hour).
\(T_{eng}\) = Time spend the complete engineering process (in hours).
\(T_{EN}\) = Time spend engineering a new system (in hours).
\(T_{ES}\) = Time spend to engineer the new safety rule correctly (in hours).
\(T_{EOC}\) = Time spend to find a solution to replace old components (in hours).
\(TT_{eng}\) = Minimum work time necessary to make one trip for an engineer (in hours).
\( g \) = The age of the used system (in years).
\( e_a \) = Constant for engineering safety hours per year (in hours per year).
\( d \) = Total number of different components in the used system.
\( i \) = Component index of the used system, \( i = 1, \ldots, d \).
\( EOL_i \) = Binary variable whether a component \( i \) is EOL. Zero means that the component is not EOL and one means that the component is EOL.
\( eoc \) = Constant for replacing old components for engineering (in hours per old component).

5.3. Reprocessing costs

The reprocessing costs consist of five different elements, mentioned in Table 1. For reprocessing costs, the following formula is used:

\[
C_R = C_{Research} + C_{SWO} + C_{TR} + C_{ST} + C_{RC}
\]  

(5)

Where

\( C_{Research} \) = Cost for doing research for the system (in euros).
\( C_{SWO} \) = Cost for doing site work at the location of the old customer (in euros).
\( C_{TR} \) = Cost for transport of the system (in euros).
\( C_{ST} \) = Cost of storage of the system (in euros).
\( C_{RC} \) = Cost of reconditioning (in euros).

The cost elements described in this section are \( C_{SWO} \) and \( C_{RC} \). The other cost elements are discussed in Appendix F.

5.3.1. Site work at old customer costs

Costs for site work at the old customer’s locations consist of disassembly costs, packaging costs, documentation costs and travel costs of the employees to go to the customers location. Disassembly costs are made by the time duration and hourly rates of a supervisor and the operational employees.

The operational employees spend time on the mechanical and electrical disassembly of the system. The time duration of supervising and the disassembly is dependent on the system size. Next, often a forklift truck is necessary to move certain parts of the system, because they cannot be moved by hand. This forklift is not always present at the location and must be rented. It is assumed that this cost is always constant because all lifting can be done within one day. The total costs are obtained by:

\[
C_{SWO} = C_{dis} + C_{pack} + C_{doc} + C_{travel, swo} \\
C_{dis} = T_{SD} \times W_{supervisor} + (T_{DM} + T_{DE}) \times W_{employees} + C_{tools} \\
T_{SD} = SS \times dsh \\
T_{DM} = SS \times dmh \\
T_{DE} = SS \times deh
\]  

(6)

Packaging and material costs are dependent on the systems length. The length determines the time duration for packing, hours a supervisor is present and how much material is needed.
\[ C_{\text{pack}} = T_{\text{sp}} \cdot W_{\text{supervisor}} + T_{\text{packing}} \cdot W_{\text{employees}} + C_{\text{pm}} \] (7)

\[ T_{\text{sp}} = SS \cdot sp \]
\[ T_{\text{packing}} = SS \cdot pt \]
\[ C_{\text{pm}} = SS \cdot pm \]

Documentation is done by a supervisor and the time that it takes to document everything is also dependent on the size of the system.

\[ C_{\text{doc}} = T_{\text{doc}} \cdot W_{\text{supervisor}} \] (8)
\[ T_{\text{doc}} = SS \cdot doc \]

\[ C_{\text{travelSwo}} = C_{\text{LT}} \cdot \left[ \frac{\left( T_{\text{SD}} + T_{\text{DM}} + T_{\text{DE}} + T_{\text{sp}} + T_{\text{packing}} + T_{\text{doc}} \right)}{TT_{\text{sw}}} \right] \]

Where

- \( C_{\text{dis}} \) = Cost related to disassembly of the old system (in euros).
- \( C_{\text{pack}} \) = Cost related to the packing of the old system (in euros).
- \( C_{\text{doc}} \) = Cost related to the documentation of the old system (in euros).
- \( C_{\text{travelSwo}} \) = Cost related to the travel cost of the employees for site work at old customer’s location (in euros).
- \( C_{\text{tools}} \) = Cost related to renting a forklift (in euros).
- \( C_{\text{pm}} \) = Cost related to packing material (in euros).
- \( C_{\text{LT}} \) = Cost for a long trip (in euros).
- \( T_{\text{SD}} \) = Time of supervising the disassembly (in hours).
- \( T_{\text{DM}} \) = Time spent on disassembly of the mechanical parts (in hours).
- \( T_{\text{DE}} \) = Time spent on the disassembly of the electrical parts (in hours).
- \( T_{\text{packing}} \) = Time spent on the packing process (in hours).
- \( T_{\text{sp}} \) = Time spent by the supervisor on packing (in hours).
- \( T_{\text{doc}} \) = Time spent on the documentation (in hours).
- \( TT_{\text{sw}} \) = Minimum time necessary to make one trip for site work (in hours).
- \( W_{\text{supervisor}} \) = Hourly rate of the supervisor (in euros per hour).
- \( W_{\text{employee}} \) = Hourly rate of an operation employee (in euros per hour).
- \( SS \) = Size of the old system at the old customer (in meters).
- \( d_{\text{sh}} \) = Number of hours for supervising the disassembly per meter (in hours per meter).
- \( d_{\text{mh}} \) = Number of hours for mechanical disassembly per meter (in hours per meter).
- \( d_{\text{eh}} \) = Number of hours for electrical disassembly per meter (in hours per meter).
- \( sp \) = Number of hours supervising the packing process per meter (in hours per meter).
- \( pt \) = Number of hours for packing the system per meter (in hours per meter).
- \( pm \) = Packing material cost per meter system (in hours per meter).
- \( doc \) = Number of hours for documentation the system per meter (in hours per meter).

5.3.2. Reconditioning costs

As discussed in section 2.2.1, different reconditioning options can be chosen, not doing anything, clean the components, and replace some or all components. However, additional value for the customer can also be added differently. For example: changing the lay-out of the system in terms of
expansion. Because expanding the system is a decision that must be made almost simultaneously with the decision for the reconditioning option. In both cases new components must be produced and transported, and thus it is decided to grouped these cost activities together.

The cost for changing or adding components consist of the production price of the new components that are replaced and the delivery cost to bring them to the new customer. Because the components that are replaced are small items, it is assumed that the components can always be sent with one truck. For all reconditioning options cleaning the components extensively is also a choice that must be made by the customer. It is assumed that always the same set of components of the used system will be cleaned and cleaning will be done by an external cleaning company. New produced component do not need to cleaned. This means that the components need to be sent to this company and sent back to the new customer. In case the system is expanded, the cost will be the price of the new material for the extra meters and the delivery cost. The new parts will always come from the headquarters in Veghel. Note that no labor costs for assembly are included, or management or supervisor costs because these costs are added in other costs elements. In general, the costs for reconditioning can be expressed as follow:

\[
C_{RC} = C_{RP} + C_{RD} + C_{CL} + C_{EXT}
\]

\[
C_{RP} = \sum_{i=1}^{d} REC_i \cdot PR_i \cdot k_i
\]

\[
C_{RD} = rp \cdot TC + cl \cdot K \cdot 2 \cdot TC + ex \cdot TC
\]

\[
C_{CL} = SS \cdot CL
\]

\[
C_{EXT} = (SS' - SS) \cdot ext
\]

Where

\(C_{RP}\) = Cost replacing components (in euros).

\(C_{RD}\) = Cost for delivery of new components (in euros).

\(C_{CL}\) = Cost for cleaning components (in euros).

\(C_{EXT}\) = Cost for extending the system size (in euros)

\(REC_i\) = Binary variable for which one means that component \(i\) will be reconditioned and zero means that component will not be reconditioned.

\(PR_i\) = Production price for component \(i\) at the factory of Vanderlande (in euros).

\(K\) = The number of trucks necessary to calculate for transport.

\(TC\) = Cost for one truck within the assumed range (in euros)

\(k_i\) = The number of components that are present in the system which belong to component type \(i\).

\(rp\) = Binary variable whether one or more components are reconditioned. One means that components are reconditioned and zero means that no components are reconditioned.

\(CL\) = Constant for cleaning hours per meter system (in hours per meter).

\(ext\) = Constant for extending cost per meter system (in euros per meter).

\(SS'\) = Size of the system that will be delivered at the new customer (in meters).

Remark that the decision to replace a component \((REC_i)\) will be discussed Section 5.4.2.
5.4. Maintenance costs

The maintenance costs consist of three different elements, mentioned in Table 1. Maintenance costs, are costs that are made over different years and thus the net present value of these costs must be calculated. The maintenance costs can be expressed as follow:

\[ C_M = C_{IN} + C_{RE} + C_{SP} \]  \hspace{1cm} (10)

Where
\[ C_{IN} = \text{Cost related to inspections (in euros).} \]
\[ C_{RE} = \text{Cost related to the replacement of parts (in euros).} \]
\[ C_{SP} = \text{Cost related to spare-part (in euros).} \]

5.4.1. Maintenance inspection costs

Maintenance inspections are a part of maintenance and are different than the inspecting activity described in 4.1, which objective is to inspected what the condition is of the system before buying back the system of customer A. Maintenance inspections are done regularly and include investigation of the inside of the system. Based on these inspections a preventive maintenance action can be scheduled. The net present value of the cost maintenance inspection costs can be calculated with annuity. The nominal interest rate needs to be used because the costs that are used don’t include inflation (Berk et al., 2012). To calculate the net present value, following information need to be known: total inspection cost per year, the discount rate, and the remaining number of years that the system will be operating. The inspection costs per year are determined by the number of visits per year, the duration of an inspection, the hourly rate of the inspector and the travel expense. In the annuity formula the first year is not include, the cost of the first year is added in formula 11. The LCC is constructed from the moment the negotiations starts with the new customer. It is assumed that a used system will be ready for operation within a quarter of a year because the activities within the acquisition and reprocessing bucket can take a couple of months. Thus, in the remaining 3 quarters inspections can be performed. When the system is stored, it is assumed to be stored for half a year, thus the first inspections will start at the third quarter of first year. Note that inspection is always done with two inspectors.

\[ C_{IN} = \frac{C_{IN1}}{r} \times \left(1 - \left(\frac{1}{(1+r)^Y}\right)\right) + (1 - ST) \times \frac{1}{4} \times C_{IN1} + ST \times \frac{3}{4} \times C_{IN1} \]  \hspace{1cm} (11)

\[ C_{IN1} = 2 \times (T_{inspection} \times W_{inspector} + C_{ST}) \times I \]

\[ Y = A_{EOL} - g \]

Where
\[ C_{IN1} = \text{Cost for maintenance inspection for 1 year (in euros).} \]
\[ T_{inspection} = \text{Time spent on one inspection (in hours).} \]
\[ W_{inspector} = \text{The hourly rate of the inspector (in euros per hour).} \]
\[ ST = \text{Binary variable if storage is needed. One if no storage is needed, and zero of storage is needed.} \]
\[ I = \text{Average number of visits per year.} \]
\[ r = \text{Nominal interest rate (in percentage).} \]
\[ Y \] = Number of years that the system will be operating (in years).
\[ A_{EOL} \] = Age when a system is end-of-life (in years).

5.4.2. Replacements, reconditioning and down-time

For the cost of replacement, it is important to know how often what component fails and what the related costs are. Because this project is about the reuse of a system, in which it is assumed that a system can only be reused once, the system has a finite life and will not be repaired forever. This is important to notice for the description of the model because the literature describes multiple methods to calculate the future replacement cost, but it makes a distinction between finite and infinite lifetimes.

For this project, it is important to be able to represent the state of the components over a finite lifespan, because the state of a component influences the future replacement costs and the reconditioning decision. Most components experience wear which influence the failure behavior, which is related to the number of operated hours. Therefore, the state of a component will be defined as: The total number of hours the component has operated.

During the lifetime of a component two distinct types of replacements can take place: unplanned replacement and planned replacements, i.e. corrective and preventive maintenance. Planned maintenance is performed outside operation hours, and unplanned replacement can be performed the same day as the failure. When the costs for unplanned replacements are high, it can be smart to do planned replacements based on the state of the component. However, the optimal moment for planned replacements must be determined.

Concluding, the elements that should be considered in the model are:

- Replacement cost per component;
- Finite life of system;
- The current state of the component;
- Planned and unplanned replacements.

A method that fits these elements is the stochastic dynamic programming (SDP) solution, described by Arts (2017) and Kececioglu & Sun (1995). The replacement costs are given by:

\[ C_{RE} = \sum_{i=1}^{d} V_{N}^{i} (x) \]

\[ N = \left\lfloor \frac{b}{m} \right\rfloor \]

\[ b = Y \ast w \ast a \]

Where

- \( X_{i} \) = The state of the component \( i \) (in operated periods).
- \( N \) = Number of remaining periods before system is EOL (in periods).
- \( V_{N}^{i} (x) \) = The minimal expected discounted cost for component \( i \) in state \( X \) that will be incurred from zero to \( N \) periods to go (in euros).
- \( a \) = Average number of operation hours a day for the system (in hours).
\( m \) = Number of operation hours during a period for the system (in hours).
\( b \) = Remaining number of operation hours for the used system before EOL (in hours).
\( w \) = Number of working days within a year (in days).

**SDP explanation**

SDP is a versatile technique to optimize decisions made in systems that evolve over time in a stochastic (Markovian) manner. It calculates the minimal expected replacement costs for a component being in a state \( X \) with \( n \) periods of possible replacements moments to go. At the beginning of each period it can be decided to replace a component or not based on state \( X_i \in S \). Between the periods no decisions can be made. It is assumed that a component can only fail once between the periods, and once a component fails it will be replaced. The probability of going from state \( x \) to \( y \) given the replacement decision \( a \) is indicated by \( p_{xy}^a \). The replacement decision to not replace the component preventively is indicated with 0 and to replace preventively with 1. The probabilities can be derived from a reliability analysis, as described in section 6.4. Example of the probabilities are:

\[
p^0 = \begin{pmatrix}
p_{00} & p_{01} & p_{02} & p_{0L}
p_{10} & p_{11} & p_{12} & p_{1L}
p_{20} & p_{21} & p_{22} & p_{2L}
p_{L0} & p_{L1} & p_{L2} & p_{LL}
\end{pmatrix}
\quad \text{and} \quad
p^1 = \begin{pmatrix}
p_{00} & p_{01} & p_{02} & p_{0L}
p_{10} & p_{11} & p_{12} & p_{1L}
p_{20} & p_{21} & p_{22} & p_{2L}
p_{L0} & p_{L1} & p_{L2} & p_{LL}
\end{pmatrix}
\]

where \( L \) is the last state of a component. The last state indicates that if a component reaches that state, the component fails immediately and corrective maintenance need to be conducted. The remaining period the state of the component is as good as new, thus the first state. It is assumed that all spare-parts are available, and corrective maintenance can always be conducted the same day. When the replacement decision is made to replace a component preventively, the new state of the component will automatically be the first state. How many states a component has will be discussed later in this section. The SDP formula used for this research, for all \( i \) and for all \( n \), in which \( n = \{0, ..., N\} \), is given by:

\[
V_n^i(x) = \begin{cases}
V_n^i(0) = 0, & x < L_i \\
V_n^i(0) = C^i_u, & x = L_i \\
\min \left\{ \sum_{y \in S} p_{xy}^i \cdot V_{n-1}(y) / (1 + r)^{yrs}, \sum_{y \in S} p_{xy}^i \cdot V_{n-1}(y) / (1 + r)^{yrs} \right\} & x < L_i \\
(C^i_u + \sum_{y \in S} p_{xy}^i \cdot V_{n-1}(y) / (1 + r)^{yrs}, x = L_i.
\end{cases}
\]

Where

\( V_n^i(x) \) = The minimal expected discounted cost for component \( i \) in state \( X \) that will be incurred from period \( N-n \) up to and including period \( N \) (in euros).

\( C^i_p \) = Cost for preventive maintenance on component \( i \) (in euros).

\( C^i_u \) = Cost for corrective maintenance on component \( i \) (in euros).

\( yrs \) = Number of years in one period (in years).
$L_i$ = The last possible state which indicates that corrective maintenance must be conducted for component $i$ (in periods).

Thus, the SDP method calculates the replacement costs by backwards reasoning. Suppose that the system is in period N-1, thus the system has only one period to go before the system is EOL. When the component is not in its last state, the expected costs are calculated for the situation in which the component is replaced preventively and when the component is not replaced. This is done for every possible state, and the optimal decision is made for every state. When the component reaches its last state, the component fails immediately and the costs for this period will be the costs for corrective maintenance plus the expected maintenance costs for the remaining period, given that the state of the new component is the first state.

Now suppose that the system is in period N-2, the costs and the decisions made for period N-1 are used to calculate the costs and to make optimal decisions about whether to replace preventively yes or no for period N-2, for any possible state. These steps can be repeated until the costs are calculated for N periods. Because for the LCC the net present value must be calculated, the formula used by Arts (2017) has been altered so the costs that are used of the previous period are discounted with one period.

Notice that just like all the decisions are made at the beginning of each period, it is assumed that all costs are made at the beginning of each period. A calculation example is provided in Appendix V.

Figure 8: Visual representation the state of a component and the age of a system

Because the method works with periods, it is convenient to translate the state of the component also into periods. A graphical representation of the problem is shown in Figure 8. Assume a system with $n$ periods left before the system is EOL, with a component that survived $k$ periods already. Remark that $k$ is the total number of hours the component has operated divided by the number of hours in one period. This component has always two possibilities for the next period. The first possibility is that the component goes to the next state in the next period and thus the maximum number of periods before failure is one less and the number of remaining periods is one less. This is indicated with an arrow aimed obliquely upwards. The second possibility is that the component will fail during the period and will be replaced, which results that the next period will start with a new component with a state zero, indicated by the arrow aimed obliquely downwards. In both cases, the number of periods left for the system will be one less. Each period has a probability of $p(k)$ that the
component survives and goes to the next state, and there is a probability of $1 - p(k)$ that the component will fail. When a component is in state $L-1$, it will fail the next period with a 100% probability because both options for the component indicate failure. It is assumed a component will not fail two times within the same period.

However, to determine what value $L$ is for a component, the oldest age method will be used. In theory, the age of each component is a continuous variable, with the domain of $[0, \infty)$. To be able to use the stochastic dynamic programming solution, the life time of each component ($T$) should be treated as finite which indicate $L$, because calculating with infinite states is impossible and not realistic. The oldest age method defines the oldest age of a component type $i$ as the 99th percentile of its life ($T_{0.99}^i$) (Sun and Kececioglu, 1995). This means that the last state of a component is the first period when the reliability given $T(R(T))$ is 1% or less. Therefore,

$$L_i = T_{0.99}^i = T|R(T)=0.01$$  \hfill (14)

So, the set of states for a component is $\in \{0, 1, 2, ..., \lceil \frac{T_{0.99}^i}{m}\rceil \}$.

Concluding, given a fixed number of operated hours for a period, and the assumption that the last state is the period in which the reliability is 1% or less, the minimal expected replacement costs can be calculated for a component given the state of the component and the remaining number of periods of the system.

**Reconditioning decision**

With the SDP method the minimal expected costs can be determined for each component in one of the defined states. When all the states of the components of a system are known, one should make the trade-off whether replacing some components will save costs. Thus, the minimal expected costs of a component in state $k$ with $N$ periods to go, is compared with the minimal expected costs of a new component in state 0 with $N$ periods to go plus the costs for replacing this component. The option with the lowest expected costs is optimal. Thus, the total expected replacement costs plus reconditioning costs is provided by:

$$C_{RE}^i = \sum_{i=1}^d \min(V_N^i(k),V_0^i(0) + C_{RC}^i)$$  \hfill (15)

Where

- $C_{RC}^i$ = Cost of reconditioning component type $i$ (in euros).

Where it is natural to have $C_{RC}^i < C_p^i$ and $C_p^i < C_{UL}^i$, for preventive maintenance and reconditioning to be useful. For this research, the cost per component type are determined. So, the cost for maintenance is also determined per component type.

The cost for preventive maintenance consists of the travel cost, the price of the replaced component, the time of repair and the hourly rate of the engineer who does the replacements. The construction of the corrective replacements costs is almost the same as the preventive replacements. A first addition is that an extra fee is charged because the inspector must come immediately, and thus is not able to perform his planned activities. A second addition is that the
customer experiences down-time cost in this period and this should be added to the corrective maintenance cost. Another difference between preventive and corrective maintenance is that preventive maintenance is always done with two inspectors and corrective maintenance always with one. In section 5.3.2 the cost for reconditioning are determined, but now the reconditioning cost for a single component type are used. Therefore, the transport costs are changed for reconditioning to the same travel cost as for preventive maintenance. The costs are given by:

\[ C_p^i = 2 \times C_{ST} + PR_i + \frac{TR_i}{60} \times 2 \times W_{inspector} \]  \hspace{1cm} (16) \\
\[ C_u^i = C_{ST} + PR_i + \frac{TR_i}{60} \times W_{inspector} \times (1 + fe) + CDT_i \] \\
\[ C_{RC} = C_{ST} + PR_i \]

Where

- \( TR_i \) = Time spend on replacing component \( i \) (in minutes).
- \( fe \) = Percentage of fee over preventive maintenance (in percentage).
- \( CDT_i \) = Cost of down-time when component \( i \) fails (in euros).

The consequence of down-time on the cost is for each system type different. For each system type the cost of down-time can be constructed differently, therefore, no general method will be provided how to construct the cost of down-time, in section 6.5, assumes a method for one specific system.

### 5.4.3. Spare-parts costs

The costs for spare-parts consist out of two different elements, the cost for the initial spare-part package that the customers wants, and the holding cost, see formula:

\[ C_{SP} = C_{package} + C_{holding} \]  \hspace{1cm} (17)

Where

- \( C_{package} \) = Cost for the initial spare-part package (in euros).
- \( C_{holding} \) = Cost for holding the spare-parts (in euros).

The cost for the initial spare part package depends on the previous spare-part package that is bought back, which is included in the buy-back cost element, and the additional spare-parts that are considered necessary by the new customer. In case the system has changed a bit, new spare-parts are necessary because they are not included in the previous initial spare-part package. Also, it is possible that the new customers want to have extra spare-parts compared to the previous owner, because the system is of more importance to his operation than it was for the previous owner. It is assumed that always the whole spare-part package is bought back and the new customer is obligated to buy this spare-parts package with the system and can only add additional spare-parts to the package, and not remove them. In this thesis the goal is not to find the optimum stock levels for spare-parts, and thus the desired stock levels of the customer are used as input in the model. The costs for the extra spare-part package are thus:

\[ C_{package} = \sum_{i=1}^{d^t} \max(k_{i,2} - k_{i,1}, 0) \times PR_i \]  \hspace{1cm} (18)

Where
The amount of spare parts of component \( i \) that is desired by customer \( c \), \( c=1,2 \) (1, old customer; 2, new customer).

\( d' \) = Total number of different components in the adjusted used system.

The spare part holding cost are calculated as a yearly percentage of the new spare part package. This should cover all costs the customer makes for storing these spare-parts. Examples of these costs are the cost of the space used including rent, maintenance and heat. The spare part package reflects the average inventory levels of the spare parts because inventory is always replenished after consumption. The replenishment costs are included in section 5.4.2. The costs for holding spare-parts are thus constructed the same as formula 11:

\[
C_{holding} = \frac{C_{CSP}}{r} \left( 1 - \frac{1}{(1+r)^T} \right) + ST \cdot C_{CSP} \cdot r_s \cdot \frac{3}{4} + (1 - ST) \cdot r_s \cdot \frac{1}{4} \cdot C_{CSP}
\]

Where

- \( C_{CSP} \) = The value of a complete spare-part package (in euros).
- \( r_s \) = Yearly percentage of the value of the spare-parts package that covers the costs that the customers make for storing spare-parts.

### 5.5. Operation costs

In this section, the cost elements regarding the operation cost is discussed. These cost elements are the costs for operational personnel and the costs for energy consumption, as described in Table 1. The general formula for operation cost is the following:

\[
C_O = C_{OP} + C_{En}
\]

Where

- \( C_{OP} \) = Cost related to operational personnel (in euros).
- \( C_{En} \) = Cost related to energy consumption (in euros).

For both elements a general and simplified cost function is presented to estimate the expected cost. Although, these elements could be a significant part of the LCC, the focus of this LCC model is on the cost that are originated or affected by the reuse of a system, which is not the case for the operation costs. For both cost elements relatively, few information is known and gathering this information is time consuming and could be another separate research.

#### 5.5.1. Operational personnel

Cost for operational personnel is based on the wages of the personnel. Depending on the number of personnel necessary each day and the number of hours they work each day, the total cost can be computed. Just like the costs for inspection, the cost for operational personnel is made over multiple years and thus the net present value must be calculated. It is assumed that the hourly rate that the customer pays their employees is the same as Vanderlande pays their employees.

\[
C_{OP1} = w \cdot a \cdot q \cdot W_{employees}
\]
\[ C_{OP} = \frac{C_{OP1}}{r} \left( 1 - \left( \frac{1}{1+r} \right)^Y \right) + ST * \frac{3}{4} * C_{OP1} + (1 - ST) * \frac{1}{4} * C_{OP1} \]

Where

- \( C_{OP1} \) = Cost for operational personnel for 1 year (in euros).
- \( q \) = number of needed personnel per day.

### 5.5.2. Energy consumption

For the cost of energy, the power consumption of the system, the use per day and the cost for one kilowatt-hour must be taken into account.

\[
C_{EN} = \frac{C_{EN1}}{r} \left( 1 - \left( \frac{1}{1+r} \right)^Y \right) + ST * \frac{3}{4} * C_{EN1} + (1 - ST) * \frac{1}{4} * C_{EN1}
\]

Where

- \( C_{EN1} \) = Cost of energy consumption of one year (in euros).
- \( C_{kwh} \) = Cost for one kilowatt-hour (in euros).
- \( PC \) = Power consumption per hour (in watts per hour).

### 5.6. Formation of the LCC model

In this section, the formation of the LCC in discussed by explaining the regulation of LCC model and the categorization of the parameters presented in this chapter.

#### 5.6.1. regulation of the model

Implementing the LCC model will make it possible for Vanderlande to better identify and utilize opportunities for reusing used systems. Next, the LCC model makes it possible to determine the market value of the system. Further, the model supports the reprocessing strategy by calculating the LCC for all options. However, this LCC model needs input to be used, as shown in the overview in Figure 9.

![Figure 9: Contribution of the model to the organization](image)

The LCC model and the processes are new for Vanderlande, thus most input should be extracted from internal data, conducted pilots, and assumptions. Once the model is used for real project, the LCC model can be improved with the gathered data from the projects. The LCC model supports Vanderlande with:
1. Providing insight into the cost break-down structure and thus indicates what data Vanderlande should gather;
2. Determining the cost for a reuse project;
3. Time gain in determining the cost for a reuse project.

5.6.2. Categorization of the input parameters

To use the model correctly, all the input parameters should be known. Because the model and the activities are new for Vanderlande, not all input parameters are known. It is important to make a distinction between the known and unknown input parameters and to identify the decision variables. To determine the unknown input parameters, another distinction is made. Some unknown input parameters are dependent on the case, while others are the same for each system within a type. Also, there are general parameters that are the same for each system type. The project dependent input parameters and decision variables shall only be filled in the model in consultation with the new customer. The distinction of the parameters is shown in Table 2. What parameter belongs to what category is determined by interviews with managers and general knowledge.

<table>
<thead>
<tr>
<th>Case dependent known parameter values</th>
<th>Case dependent unknown parameter values</th>
<th>Decision variable</th>
<th>General known parameters values</th>
<th>General unknown parameters values</th>
<th>System type dependent known parameters values</th>
<th>System type dependent unknown parameters values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>$V_m$</td>
<td>$SS'$</td>
<td>$C_{kwh}$</td>
<td>$fe$</td>
<td>$T_{EN}$</td>
<td>$PC$</td>
</tr>
<tr>
<td>$T_{FC}$</td>
<td>$V_{fcf}$</td>
<td>$U$</td>
<td>$W_{PM}$</td>
<td>$sc$</td>
<td>$T_{JM}$</td>
<td>$T_{inspecting}$</td>
</tr>
<tr>
<td>$T_{FCS}$</td>
<td>$g$</td>
<td>$I$</td>
<td>$W_{CS}$</td>
<td>$T_{IR}$</td>
<td>$ea$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$d$</td>
<td>$RECI_i$</td>
<td>$W_{Eng}$</td>
<td>$T_{Testing}$</td>
<td>$T_{PM}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$i$</td>
<td>$rp$</td>
<td>$W_{employee}$</td>
<td></td>
<td>$CL$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$SS$</td>
<td>$cl$</td>
<td>$W_{software}$</td>
<td></td>
<td>$PS$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Z$</td>
<td>$ex$</td>
<td>$W_{SE}$</td>
<td>$T_{Inspection}$</td>
<td>$T_{Neg}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K$</td>
<td>$W_{supervisor}$</td>
<td>$EOL_i$</td>
<td>$T_{discuss}$</td>
<td>$T_{searching}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$X_i$</td>
<td>$W_{inspector}$</td>
<td>$T_{Inspection}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$r_k$</td>
<td>$TC$</td>
<td>$T_{SA}$</td>
<td>$CDT_i$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k_{i,c}$</td>
<td>$C_{CT}$</td>
<td>$ext$</td>
<td>$A_{EOL}$</td>
<td>$m$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$ST$</td>
<td>$C_{ST}$</td>
<td>$TM_{MCL}$</td>
<td>$m$</td>
<td>$dmh$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$r_i$</td>
<td>$TT_{PM}$</td>
<td>$TP_{MEX}$</td>
<td>$dmh$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k_i$</td>
<td>$TT_{eng}$</td>
<td>$TR_{i}$</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>$a_i$</td>
<td>$TT_{sw}$</td>
<td>$deh$</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>$w$</td>
<td></td>
<td>$sp$</td>
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<td></td>
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<tr>
<td></td>
<td>$d'_i$</td>
<td></td>
<td>$pt$</td>
<td></td>
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<tr>
<td></td>
<td>$q$</td>
<td></td>
<td>$pm$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$doc$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$C_{tools}$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$p_{kj}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$L_i$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.7. Validation

A common type of validation of the tool is to compare the output with the reality, however because the model can make a prediction over 20 years and it includes activities that have not happened before, comparing the output with reality is rather difficult. Therefore, this model will not be validated in a quantitative way, but in a qualitative way. Aken et al. (2007) describes three different validation types that should be justified: construct validity, internal validity and external validity.

Construct validity checks whether the concept is covered completely and if the measurement has parts that do not fit the meaning of the concept. Chapter 2, 4 and 5 describes the concepts that are covered in this study. Some concepts are not taken into account. However, these decisions are well thought over and in agreement with the opinion of all approached experts. The construct validity is therefore deemed sufficient.

Internal validity is concerned with the conclusion about the relationship between the different cost elements in the proposed LCC model. Internal validity is high when almost all the actual causes of the business problem are found. Studying the problem from different perspectives will increase the internal validity. Relationships between the cost elements are discussed with multiple employees with diverse backgrounds and some relations are also determined by literature. It does not guarantee that all actual causes are found, but it can be assumed that most are.

External validity checks how generalizable or transferable the results of the research are to other systems or organizations. Because the LCC model is designed to solve a project problem, the external validity is less important. However, when data for the other system types are collected, the parameter values can be easily adjusted so it can be applied for those system types as well.
6. THE POSISORTER

This chapter will discuss the application of the LCC model as described in chapter 5 for the Posisorter (SPO). The SPO is a horizontal sorting system that sorts handling units by pushing them of the carrier at the exact right time which is done by shoes. See Figure 10 for how an SPO looks like. The aim of this chapter is to make the LCC model ready for use by finding all necessary input parameters, so it is applicable to use when an SPO will become available for reuse in the future. Next, this chapter will discuss the tool that is developed, how it can be implemented, the verification of the tool and a case study with the find values.

Figure 10: Posisorter (Mu, 2011)

In section 5.6.2 all input parameters are categorized into parameter types. By finding the values for all input parameters, with the exception of decision variables and case dependent parameters, the LCC model can be easily used in the future. Five different methods of finding the values for the input parameters are identified:
- Vanderlande already knows the value;
- The value can be obtained from performing analysis with existing cost calculation tools, for Vanderlande this tool is called CAP8;
- Use data from pilots;
- Execute a reliability analysis;
- Assumptions.

Table 3 provides an overview of which methods can be used to find the values for the input parameter types, and Appendix G provides an extensive overview for each input parameter. The methods will be thoroughly discussed one-by-one and for each method at least one example will be provided. The focus will be put on the input parameters concerning the maintenance cost bucket. These costs are estimates by Öner et al. (2007) to be one of the most important cost elements in the LCC analysis for a capital good.

Table 3: Distinction of input parameter types and what method is used to find the values for the input parameters. The “X” indicates what method can be used.

<table>
<thead>
<tr>
<th>Input parameter type/ Method to find the values</th>
<th>Internal information</th>
<th>Analysis with an existing cost calculation tool</th>
<th>Extract data from pilots</th>
<th>Reliability analysis</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>General known</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General unknown</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System type dependent known</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System type dependent unknown</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

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6.1. Internal information from Vanderlande

For many input parameters, the values are already known within Vanderlande, but the question is where the values can be found. Vanderlande is in possession of a few databases in which information is stored. The values for the input parameters regarding the hourly rates and travel costs can be found in CAP8 or separate documents managed by the Pricing department. General information about components can be found in Straitweb. SmarTeam provides information about the system of a customer. Where to find the values for the different input parameters of this type and what the values are, is depicted in Appendix H.

Example

$T_{\text{inspection}}$ is an input parameter for which the value is obtained by a method constructed by the Pricing department. The following formula is used to calculated the maintenance inspection time:

$$T_{\text{inspection}} = 2 \times \left( \frac{1}{2} + k_1 \times SS' \right)$$

This formula assumes that two inspectors need half an hour to make the system ready for inspection, by stopping the system and opening the SPO. Per meter the duration of inspection is $k_1$ minutes. The value of $k_1$ can be found in Appendix H. This formula is not included in CAP8, and is therefore included in this section.

6.2. Analysis with an existing cost calculation tool

CAP8 is the pricing tool Vanderlande uses to determine the cost-price for each individual project. The values that can be obtained by a CAP8 analysis are values of parameters of activities that match with the activities for a new system and are related with the installation of an SPO. Also, the pricing tool includes the information for extending an SPO and for cleaning the SPO as part of reconditioning.

For the installation activities, the calculation rules described in Chapter 5 are a bit different from the calculation rules described in CAP8. This is because CAP8 uses many input parameters and using them all would provide more detail than necessary. Especially when the described model is implemented in CAP8, then the original calculation rules of CAP8 can be used. For now, simpler calculation rules with less input parameters are used that only depends on the length of a system and for which the costs per meter can be extracted from CAP8.

Two fictive test cases are used to calculate the costs for all activities regarding the installation of a new SPO. By estimating the number of hours increasing from the first case ($H_{\text{case 1}}$) to the second case ($H_{\text{case 2}}$), divided by the difference in meters of the cases ($L_{\text{case 1}}$ and $L_{\text{case 2}}$), the variable costs and the fixed costs can be estimated. For the test cases, an SPO of 60 meters and an SPO of 100 meters are used. Both SPO have a different number of exit lanes because when an SPO is longer, more exit-lanes can be installed. The number of exit-lanes is determined by a Pricing Consultant. The third and fourth test cases shows what the costs are when an SPO is extended and cleaned. The costs for these activities will be divided by the size of the SPO to determine the cost per meter. It
was determined that these costs had no fixed costs, and therefore only 1 test case is used. The cleaning case is based on removing all the carriers and send them to an external party to clean the carriers thoroughly, so not the whole SPO is cleaned. The input values for these test cases are found in Table 4 and are formulated with the help of a Pricing Consultant by suggesting what values are normal for an SPO. The results of these test cases are shown in Appendix I. Based on these results the values of the input parameters are estimated.

Table 4: Input parameter for the test cases in CAP8

<table>
<thead>
<tr>
<th>Input values</th>
<th>Case 1 new</th>
<th>Case 2 new</th>
<th>Case 3 extending</th>
<th>Case 4 cleaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size SPO</td>
<td>60 meter</td>
<td>100 meter</td>
<td>40 meter</td>
<td>60 meter</td>
</tr>
<tr>
<td>Number of exits-lanes</td>
<td>20</td>
<td>30</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>System runs on</td>
<td>FSC</td>
<td>FSC</td>
<td>FSC</td>
<td>FSC</td>
</tr>
<tr>
<td>Range transport</td>
<td>&lt;250 km</td>
<td>&lt;250 km</td>
<td>&lt;250 km</td>
<td>&lt;250 km</td>
</tr>
<tr>
<td>Safety nets included</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Continent</td>
<td>Europe</td>
<td>Europe</td>
<td>Europe</td>
<td>Europe</td>
</tr>
<tr>
<td>Length infeed</td>
<td>3 meters</td>
<td>3 meters</td>
<td>No</td>
<td>3 meters</td>
</tr>
<tr>
<td>Dual or single</td>
<td>Dual</td>
<td>Dual</td>
<td>Dual</td>
<td>Dual</td>
</tr>
</tbody>
</table>

**Example**

To calculate the number of engineering hours for a system, the results of case 1 and case 2 are used. CAP8 provides multiple cost activities related to engineering and therefore the sum of the hours of the following activities are used: Project Leader Engineering Project, Mechanical Engineering and Mechanical Specifications. The following formula is used:

\[ \text{Engineering hours per meter} = \left( H_{\text{case } 2} - H_{\text{case } 1} \right)/(L_{\text{case } 2} - L_{\text{case } 1}) \]  
\[ \text{Fixed engineering hours} = H_{\text{case } 1} - L_{\text{case } 1} \times (H_{\text{case } 2} - H_{\text{case } 1})/(L_{\text{case } 2} - L_{\text{case } 1}) \]  

For which \( L_{\text{case } 1} \) is 60, \( L_{\text{case } 2} \) is 100 and \( H_{\text{case } 2} \) and \( H_{\text{case } 1} \) can be found in Appendix I.

**6.3. Pilots**

For this research, information can be extracted from one of the few pilots that Vanderlande has executed with the reuse of a SPO. The pilot that had the most reliable data is a pilot of, say Customer 1. The lay-out of this system is shown in Appendix J. This system was only five years old, with a length of 89-meters, had 35 exit-lanes (only one side) and only carried very light items.

The actual costs of the pilot and the values for the input parameters can be found in Appendix J. The results are obtained by the project manager and the supervisor. The results for this pilot are based on an SPO with exit lanes on only one side of the system. Because in section 2.2.4 it is stated only dual sided SPO’s are discussed, an assumption must be made about the proportion of extra work. According to a Service Project Manager, these exit-lanes are easily disassembled, and took \( \frac{1}{4} \) of the mechanical disassembly time, \( \frac{1}{2} \) of the freight and packing time, \( \frac{1}{2} \) of the packing material, and no extra hours for the electrical disassembly and the supervisor. These proportions are not included in
the results of Appendix J. Because there was only one pilot with this information available, there is no distinction between fixed costs and variable costs.

One input parameter, time spent on inspecting the system, is found with the help of another pilot. The inspection of a SPO from, say Customer 2, took place in 2014, see Appendix J for the lay-out of the system.

**Example**

For the Customer 1 pilot, the package material costs are used for a SPO of 89 meters with only exit-lanes on one side of the SPO, thus the factor 1.5 is used. This results into:

\[
\text{Package material per meter} = \text{Package costs Customer 1 pilot} \times 1.5 \quad (25)
\]

The results are shown in Appendix J.

6.4. **Reliability analysis**

To find the probabilities necessary for the SDP method, a reliability analysis must be executed for which the research methodology, described in Figure 11\(^2\), is used. First, the components must be identified for which the reliability analysis is done. Second, the data that is available should be decomposed and prepared to use for the analysis. Third, the data must be checked for correlation. Then, the right reliability assessment method should be chosen and executed. These steps will be discussed below in the following sections.

![Research methodology for conducting a reliability analysis](Demirel and Gölbasi, 2016)

\(^2\) Figure 11 was inspired by Figure 1 of Demirel and Gölbasi (2016). The mentioning of the dragline and failure modes are removed. Also, the trend analysis is removed because it adds no value in this research. Also the lifetime parameter estimations is changed to the estimation of probabilities of going to the next state. At last, the preventive replacement analysis from the methodology is removed because that is out of scope.
To find the set of components \((i)\) that are relevant for this research, the SPO is split up into different sections. Next, the variation between SPO’s is discussed and how this influences the set of components.

As shown in Figure 12, the SPO can be split into five different sections. Each section has a different functionality and consists of various components. First section is the entry, second section is where the shoes got sorted, third section is the sortation of the handling units, fourth section is the exit and the fifth section is the computer of the SPO. Based on maintenance manual, created by the Product Engineers of Vanderlande, component types are identified, that are important for this research. These component types are identified by the Product Engineers as spare-parts, which means that there is probability that they will fail during the life time of a system. Each component type is a set of item-numbers. In Appendix K more information is provided about the functionalities of each section of the SPO with a list of component types and the set of item-numbers for each component type.

Each SPO is ETO, and therefore each SPO is different from one another. The demands of the customer can influence the following:

- Whether the output lanes are placed on one or two sides of the SPO and thus what kind of merge is necessary;
- The length of the SPO and thus the number of carriers and shoes;
- The angle of the output lane, 20 or 30 degrees, which influences the switch-frames;
- The number of output lanes and thus also the number of switch-frames;
- What motor is necessary to reach the required power.

Another reason that the SPO differ from one another is the development of the SPO over time, which means that certain sections of the SPO did get some updates and new item-number are used. These updates are applied to the new sold SPO’s but not to the SPO already installed. This results into that almost every SPO having different item-numbers. To get a better understanding of this development process, see Appendix L.
6.4.2. Data decomposition

In this section, the maintenance data of Vanderlande and how it is prepared for analysis, is discussed. The available data set contains the maintenance data of 17 different locations which each an SPO, and the start of measuring is 2009. The 17 locations all have a different start date and most locations were already operating before 2009. The data consist of three individual sheets, each with its own information. One sheet contains the records of all the dates and unique maintenance number for the corrective maintenance actions with a problem description, the second sheet contains the records of all the dates and unique maintenance number for the preventive maintenance actions with a problem description, and the third sheet indicates which components (indicated by item-number), how many are ordered or used on what date, and for what unique maintenance number. The information on all sheets is thus linked by this unique maintenance number. To use this data of Vanderlande, 10 steps are taken and described below.

**Step one:** filter the first and second sheet on the mark code “SPO” and use the remaining unique maintenance numbers to find all ordered and used spare-parts in the third sheet.

**Step two:** remove all spare-parts that are only ordered and not installed in the system. Only the used spare-parts are interesting because these indicate a failure.

**Step three:** translate all Italian to English, so the item descriptions and the problem descriptions can be read.

**Step four:** check for any big revisions on the systems that have taken place and are not mentioned in this maintenance data. A revision could indicate that components are replaced. Revisions are done as a separate project and therefore not recorded in this data sheet. In our case, no revisions have taken place at any location concerning the SPO’s.

**Step five:** combine all item-numbers for which the components are similar in function and failure behavior. Within the remaining data set, there are now more than 500 different item-numbers. The reason there are so many, is partly because of updates the SPO received over the years in which items were changed a little and got another item-number. Another reason is because every small item in the system gets an item-number, even if the subsystem in which they are present, has an item number of its own. A problem that arises is that not all these item-numbers are identified in Appendix K, and thus not all item-numbers have a component type to which they belong. The item-numbers are combined based on expected failure behavior, however, because the exact failure behavior is unknown, assumptions must be made about what item-numbers have the same failure behavior. The table with all identified component types are shown in Appendix M. Internal documents and a senior R&D engineer are used to combine the item-numbers and provide them with a component type name. In total, there are 42 different component types left. Not all new components could be assigned to a single section in the SPO, so some component types are assigned to a new section: Others (O).
Step six: the dates of all preventive replacements are changed to a date two month later as failure. This so failure behavior of the component types can be analyzed, and a preventive replacement is not a failure of a component. A preventive replacement is only conducted because a maintenance engineer estimates during regular inspection that the component will fail within two months, based on his experience.

Step seven: the number of operation hours between installation of a component and the failure needs to be determined for each installed component. In the maintenance data, only the visit date is recorded in which a component type is replaced. To determine the exact operated time before failure, there are some issues:

A. It is known what component type is replaced, in a system there could be multiple components with the same name. So, it is unknown what specific component is replaced. If a component type is replaced, and later it is replaced again, it is unknown if it is the same component that was replaced before, or another component.

B. The starting age of all component types for each system is unknown. This is because some systems were already active before Vanderlande was recording this maintenance data.

C. The exact number of operated hours between dates is unknown.

To deal with issue A, it is assumed that the oldest component is always the one that fails. Because the components experience wear, the oldest component has experienced the most wear and has therefore the highest chance of failure. It is necessary to know the number of the same components within one type are present in one system. Because each SPO is different and there is incomplete and cluttered information about the set of component types present in each system, it is assumed that a system only contains a component type if that component type has failed in that system. However, for some systems it is known how many components of one component type are present and for other systems it is not. For the systems for which the number of components are unknown, the average number of components will be taken, calculated from the systems for which the number of components is known. For the component types in which no information about the quantity is known in any system, the number of components is estimated by a Product Engineer. This to not ignore the cost for replacing these components, but to approximate them.

To deal with issue B, a distinction is made between component types that are known to fail often and component types that are known to fail not often. The decision about when a component type fails often is based on the expert opinion of a Product Engineer. Based on this opinion and a ratio of the number of all recorded failures from 2009 till 2017 and the number of components present in all systems, it is assumed whether a component type is assumed to fail often or not. If the ratio is less than 0,2 the component type does not often fail, and when the ratio is above or equal to 0,2 the component type is assumed to fail often. This ratio is only constructed to be able to make an assumed difference between component types. For components that do not fail often, the starting age will be set to zero from the moment the system is installed and it is assumed that they have never failed before the first known failure. For the components that do fail often it is unknown when they have failed before, but there is a high probability that they have failed before. Therefore, it is assumed that the starting age of each component was zero from the moment Vanderlande started
measuring the failures. An overview of which component types belong in what category is shown in Appendix M.

For issue C, the average number of operation hours per day are required from the maintenance manager that is in charge of all locations. Based on the number of days between two dates, the number of workdays in a year and the average number of working hours per day, the number of operation hours between events can be calculated. When the system is operating, it can be assumed that all component types are also operating.

**Step eight:** the data set that is provided is ungrouped censored data, which means that the failures are not grouped into time intervals and the data set contains censored data. Censored data is data that is incomplete because units are removed from consideration prior to their failure or the measuring is stopped before all units could fail (Ebeling, 2010). For this research the measuring is stopped while all systems were still operating. Because all components are replaced after failure, the remaining operation time until the stop of measurement can be determined for each component. These times are logged separated from the operation time to failures. Other types of censoring are not included in this research.

**Step nine:** Calculate the time to failures for each component. Remark that some replacements are done before the installation date of the system. It is assumed that these are typos, and they were removed from the dataset. A general description of how the time to failures are calculated and the remaining operation hours without failure are shown in Appendix W.

**Step ten:** Compare the various locations on the operation conditions. For all locations, a general description of the dust and moisture levels and minimum and maximum temperature over the year is requested. All locations were described as: “General dusty, no heater and no air conditioning”. Also, the temperature for all locations are assumed to be the same. The weight of the handling units that is being processed is also an operation condition. Heavy handling units will result into more wear of the components than light handling units. All locations deal with a large variety of handling units between 2kg and 20 kg. It can be assumed that the conditions for all locations are the same.

6.4.3. **Correlation**

By checking whether there is correlation between the failures of the component types, it is checked whether the failure of one component type leads to the failure of another component type. When this is the case, the second component type must be removed from the analysis to prevent misleading results. To determine whether there is correlation between the failure of components the Pearson product-moment correlation coefficient is used (Puth et al., 1993). For information about the formula used to calculate the correlation coefficient, see Appendix N. Only combinations that have a correlation coefficient of 0.5 or higher are interesting to discuss. The results of the correlation are shown and discussed in Appendix O.

Appendix N shows that there are four possible combinations of component types that are possibly correlated. In Appendix O is concluded that only component type C18 and C4 are correlated, and
that C16 and C17 are correlated. Thus, components C18 and C17 will not be further analyzed, and
the costs of these components will be added to C4 and C16.

6.4.4. Reliability assessment method

Most literature about reliability analyzing methods are about the reliability of one item or one
system as a whole. The statistical power of an analysis will improve if more items, which are the
same, are measured because more data will be available (Button et al., 2013). For this research the
system is divided in 42 different component types for which the reliability should be determined.
Each component type consists of multiple item-numbers, with the same expected failure behavior.
Even though the component types consist of multiple item-numbers, there are still component types
with only one or two failures per SPO. A reliability analysis with only a few failures is less valuable.
Because all SPO are essentially the same and the environmental conditions are the same, the data of
all SPO’s is combined for the reliability analysis.

Because the data set contains multiple systems and component types can appear multiple times in
the same system, the method that will be used to determine the reliability, should also represent
the number of components at risk. This number will change over time due to the different ages of
the SPO’s (Trindade and Nathan, 2006).

Next, because the method discussed in Section 5.4.2 uses periods, and the state of the component
types are based on those periods, the original ungrouped censored data set is changed to a grouped
censored data set. This is convenient, because the sample size is large in terms of time and for some
components also in number, by using intervals the data is more accessible. Calculating the reliability
with the original ungrouped censored data will provide more reliable results, however, because the
data set contains more than 20.000 failures and more than 300.000 unique components, calculating
the reliabilities would be too much work, given the time limit of this research.

When using grouped censored data, choosing the right length of the time interval is important. If the
length is too big, useful information can be lost. If the time interval is too small, the determined
probabilities for each period can be over fitted and the model described in Section 5.4.2 would get
too many periods to keep the model user friendly. Overfitting means that the production of a
function corresponds too closely to the used data set, and may therefore fail to fit additional data or
predict future observations reliable, and results into poor generalization (Lawrence & Giles, 2000).

Also, when the model is used on a system, the state of the component must be estimated, which
cannot be estimated so precisely that smaller intervals would add more value to the model. Based
on the expert’s opinion of a Product Engineer, and the fact that the model should not contain too
many described states, a good interval would be 4000 operation hours. This number of hours
between periods approximately matches with the number of operation hours per year. When more
failure data is available and better estimations can be made about the state of a component type
within a system, the time intervals can be made smaller if deemed necessary.
Ebeling (2010) describes a method that determines the reliability for grouped censored data. This method helps with constructing a life table that summarizes the survival experiences of the units that are subject to failure. The $i$ is not included in the following notation that is necessary for the life table, but it should be clear that every component typed is treated separately. The life table is constructed with the following data:

- $F_k$ = Number of failures in the $k$-the interval.
- $C_k$ = Number of removals (censored) in the $k$-th interval.
- $H_k = H_{k-1} - F_{k-1} - C_{k-1}$ = Number of components at risk at time $t_{k-1}$.
- $H'_k = \frac{C_k}{2}$ = Adjusted number at risk assuming that the censored times occur uniformly over the interval.
- $H_0$ = Total number of observed component.
- $p_{k-1,k} = 1 - \frac{F_k}{H_k}$ = Conditional probability of surviving the $k$-th period giving survival to time $k - 1$th period, with no preventive replacement.
- $R_k = \left(1 - \frac{F_k}{H_k}\right) * R_{k-1}$ = The reliability of a unit surviving beyond the $k$-th interval.

6.4.5. Estimation of the probability of going to the next state

With the method described above, all reliabilities can be determined for the periods of which data is available. However, not all reliabilities can be determined until the last estimated period, because of a lack of data. A general reliability function needs to be determined for each component type, to predict the reliabilities for periods in which the reliability is unknown and to prevent reliability values that are over fitted with the data set. The general reliability functions will be used to calculate all the necessary probabilities.

For all components types, first three-different trend-lines are fitted with the ordinary least square approach in Excel: linear, exponential and logarithmic. The reason that these three trend-lines are chosen is because they represent three totally distinct kinds of failure behavior and they are easily checked in Excel. For all components it is assumed that $R_0 = 1$, because the testing activity before installing ensures that systems always work properly after they are installed.

The trend-lines are compared with the coefficient of determination ($R^2$), which indicate the proportion of the variance that can be explained by the trend-line and thus what the chance of success is of predicting the dependent variable from the independent variable (Nagelkerke, 1991). The trend-line with $R^2$ closest to one, is assumed to be de best predictor and will be used for this research.

If the three trend-lines do not provide a fit that is judged plausible by the other or had an $R^2$ lower than 0.8, other trend-lines should be considered that should result into a reliability function. The results for each component type are shown in Appendix P. For some component types, there was no good fit with the linear, exponential and logarithmic trend-line. Based on the available data points, a Weibull fit has been selected for fitting. The parameters of the Weibull fit are determined by the least square approach described by Ebeling (2010). For some these component types with a low $R^2$, the Weibull fit resulted into a higher $R^2$. Also, according to the opinion of the author, the Weibull fit
provided more plausible trend-lines for some components. However, for some components types with a low $R^2$, the $R^2$ was even lower for the Weibull fit. These cases had only a few failures, for which it is difficult to make an estimation about what fit is the most plausible one. Subsequently, the trend-line that provided the highest $R^2$ was selected.

Each chosen fitted trend-line describes the reliability function for that component type. With the help of the reliability function, the probability of going from one state to another state can be calculated with:

$$ p_{k-1,k}^0 = \frac{R_k}{R_{k-1}} \quad \forall k = 1, \ldots, L - 1 $$

For $p_{k-1,k}^1$, the probabilities are the same as the first row of $p^0$ as described in 5.4.2.

**Environmental conditions**

Because the $p_{k-1,k}^0$ are all based on a reliability analysis of 17 SPO’s that are operating with the same environmental conditions, the impact on $p_{k-1,k}^0$ when these environmental conditions change is unknown. However, because of the expert opinion of Project Managers and Product Engineers, it is strongly believed that the environmental conditions do have a tremendous influence on the reliability of a component. Therefore, three different scenarios for the environmental conditions of a location are identified. For each scenario, it is assumed that a different factor $ef$ influences the reliability function by multiplying the $ef$ factor with the independent variable $k$. As a result, the probabilities of surviving the $k$-th period giving survival the time $k-1$-th period, will be changed. So, the same reliability will be reached sooner or later than the original situation.

**Linear:** $R'(k \cdot m) = ef \cdot a \cdot k \cdot m + b$

**Exponential:** $R'(k \cdot m) = e^{-a \cdot k \cdot m \cdot ef}$

**Logarithmic:** $R'(k \cdot m) = ef \cdot a \cdot \ln(ef \cdot k \cdot m + 1) + b$

**Weibull:** $R'(k \cdot m) = e^{-\left(\frac{k \cdot m \cdot ef}{\theta}\right)^\beta}$

Where

- $R'(k \cdot m) = $ The adjusted reliability at $k \cdot m$ number of operation hours.
- $ef = $ Factor that translate the environmental conditions.
- $a = $ The slope parameter of the function.
- $b = $ A constant value of the function.
- $\theta = $ The scale parameter of the Weibull distribution.
- $\beta = $ The shape parameter of the Weibull distribution.
- $m = $ Number of operation hours during a period (in hours)

Three different environmental conditions are assumed for this research, see Table 5. The environmental condition of the 17 locations that are used for the reliability analysis belong to group 2.
Table 5: Environmental conditions

<table>
<thead>
<tr>
<th>Environmental condition group</th>
<th>Environmental condition description</th>
<th>ef Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clean environment, temperature controlled area and low weight handling units (&lt;10 kg)</td>
<td>0,9</td>
</tr>
<tr>
<td>2</td>
<td>General dusty, minimum temperature changes and average weight handling units (between 10 and 20 kg)</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Very dusty, large temperature changes and heavy handling units (&gt;20 kg)</td>
<td>1,1</td>
</tr>
</tbody>
</table>

6.4.6. Example DS component type

This example will focus on the reliability analysis of component type DS. First, all times to failure and the remaining operated hours are calculated and grouped into time intervals of 4000 hours. These are the input for $F_k$ and $C_k$ as described in 6.4.4, the failures and the censored data. Second, based on the times to failure, it is concluded that the DS component type had no correlation with other components types, and thus the reliability of the DS component can be calculated as described in 6.4.4. The number of components at risk at period zero, $H_0$, is determined by summing the total number of failures and the total number of present components. In Figure 13 the results are shown from the reliability analysis. Each point in Figure 13 is thus not a failure, but the determined reliability level.

A trend-line is fitted so the reliability function could be determined. Of the three-described trend-lines, the linear trend-line had the highest $R^2$ value of 0,9256. The exponential trend-line had a $R^2$ value of 0,8707 and the logarithmic trend-line had a $R^2$ value of 0,8047. Because of the high $R^2$, the Weibull fit is not checked. Note that an ef value of 1 is used in this reliability function.

With the oldest age method is determined that the last state is at period 21, because the reliability for component type DS is 0,01 or lower after 21 periods. The probabilities for component type DS are shown in Table 6. The probabilities for the other component types will not be presented in this research, but can be calculated with the help of the determined reliability functions.
Table 6: Result of the conditional probability of surviving the k-th period giving survival to time \( k - 1 \)th period, with no preventive replacement for component type DS

<table>
<thead>
<tr>
<th>Periods passed</th>
<th>( p_{k-1,k}^0 )</th>
<th>Periods passed</th>
<th>( p_{k-1,k}^0 )</th>
<th>Periods passed</th>
<th>( p_{k-1,k}^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>8</td>
<td>0,925505</td>
<td>16</td>
<td>0,815623</td>
</tr>
<tr>
<td>1</td>
<td>0,951037</td>
<td>9</td>
<td>0,919508</td>
<td>17</td>
<td>0,773943</td>
</tr>
<tr>
<td>2</td>
<td>0,948516</td>
<td>10</td>
<td>0,912462</td>
<td>18</td>
<td>0,707916</td>
</tr>
<tr>
<td>3</td>
<td>0,945722</td>
<td>11</td>
<td>0,904064</td>
<td>19</td>
<td>0,587402</td>
</tr>
<tr>
<td>4</td>
<td>0,942607</td>
<td>12</td>
<td>0,893884</td>
<td>20</td>
<td>0,297589</td>
</tr>
<tr>
<td>5</td>
<td>0,939112</td>
<td>13</td>
<td>0,881287</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0,935165</td>
<td>14</td>
<td>0,865296</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0,93067</td>
<td>15</td>
<td>0,844326</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.5. Assumptions

Many input parameters are determined by expert’s opinion or an assumed function. Assumptions about the time duration of a certain activity are always based on the input of a manager that is involved with that activity. Other assumptions are based on discussions with an expert and on logical reasoning of the author and the experts. Some assumptions only involve a single value, other assumptions involve a complete calculation method to determine the value for the input parameter. The values, or calculation methods for all input parameters that need to be determined by assumptions are described in Appendix Q. In this section two examples will be provided, both input parameters are related to the maintenance cost bucket. The two-input parameter are: time of replacing component type \( i \) and the cost of down-time for component type \( i \).

Time of replacing component type \( i \)

Vanderlande already determined the mean time to repair (MTTR) for all component types that were already identified by them. In section 6.2.2 it is explained that some new component types are identified. For the component types for which no MTTR is determined the following method is assumed to calculate the MTTR: \( MTTR = TR_i = 30 \text{ min} + tr \text{ min\textdegree} SS' \), for which \( tr \) is a constant that indicates the number of minutes an inspection is for one meter. See Appendix R for an example of all MTTR’s for a SPO of 80 meters.

Cost of down-time for component type \( i \)

Previous research stated that down-time costs can be 70% of the total LCC, and the assumption that down-time costs are dependent on the customer, a cost function is assumed to calculate the down-time cost for the failure of component type \( i \) \( (CDT_i) \). The biggest cost drivers for \( CDT_i \) are the costs made due to extra hours of work to finish all orders \( (COT_i) \), and the costs for the extra truck that must be arrange unexpectedly \( (CPU_i) \).

\[
CDT_i = COT_i + CPU_i
\]

Because Vanderlande and the customer are described as one entity, compensation of Vanderlande to the customer for down-time costs is not included. Based on Vlasblam (2009), the cost drivers are dependent on: moment of failure, system capacity \( (cap) \), system throughput \( (th) \), system availability \( (av) \), and the importance of each handling unit to arrange extra transport.
In a situation without failure, all handling units are processed at the end of a shift and will be immediately be shipped by a pick-up truck. When the system fails, which is assumed to be always during operation, a service engineer is called and comes directly to the system to repair it, this takes a fixed number of hours \((dt_i)\), depending on the mean time to repair of component type \(i\) \((TR_i)\) and the travel time of the service engineer, which is assumed to be two hours.

\[
d t_i = 2 + TR_i/60
\]  

(29)

In the meantime, handling units will be buffered in front of the system. If the system is repaired, all buffered handling units can be processed. If the regular throughput is lower than the maximal capacity of the system, the system can process all buffered handling units with the maximal capacity until the buffer is empty. So, depending on the moment of failure, the remaining operation time after repair, and the difference between the regular throughput and capacity, the number of handling units that arrive too late can be reduced. Thus, two periods are identified during the shift of a time duration of \(s hi\), say period 1 and period 2. See Figure 14 for a representation of the situation. The line indicates the number of handling units that arrive too late given the time of failure in the shift.

![Figure 14: Representation of the number of handling units that arrive too late. The intercept with the y-axis depends on the difference between the capacity of the system and the average throughput of the customer.](image)

When a component type fails in period 1, the system is repaired before the end of the shift and in the remaining operation time after repair, the system will operate at full capacity to reduce the number of handling units that will miss the truck. It is assumed that no extra personnel are needed to reach this capacity. If not, all handling units can be processed before the end of the shift, the personnel will work over-time until all handling units are processed. When the component type fails in period 2, no remaining operation time is left in the shift after repair. The number of handling units that arrive too late can be calculated by the throughput rate and the remaining duration time of the shift at the moment of failure. It is assumed that the remaining handling units will be processed before the next shift starts. Moreover, it is also assumed that every handling unit is important enough to arrange an extra pick-up truck for which a fixed price is paid per handling unit \((cm)\). Because of the small-time frame of a shift, it is assumed that the moments of failure are distributed uniformly over the shift and therefore the availability of the system can be calculated. Availability is defined as the probability that a system is performing its required function at a given point in time when used under stated operating conditions (Ebeling, 2010).

\[
av = \frac{s hi - dt_i}{s hi}
\]  

(30)
The average number of handling units that arrive to late due to failure of component type \( i \) \( (B_i) \) can be calculated by multiplying the probability of having a failure in period 1 and 2 with the average number of handling that will miss the regular pick-up truck when the failure occurs in that period.

This is provided by the formula:

\[
B_i = av \times \frac{\max(0, th \times shi - cap \times shi \times av + (th \times dt_i))}{2} + (1 - av) \times \frac{(th \times dt_i)}{2}
\]  

(31)

The total costs related to the extra pick-up track can then be calculated by multiplying the number of handling units that arrive too late with the fixed price that paid per handling unit, given by:

\[
CPUi = B_i \times cm
\]  

(32)

The total cost for extra hours of work is determined by the multiplying the hours of work that is necessary to process all handling units that arrived too late, with the cost of all the personnel present per hour.

\[
COT_i = \frac{B_i \times cap}{W_{employee}}
\]  

(33)

Notice that \( th, shi, cap \) and \( q \) are case dependent input variables and it is not possible to determine them beforehand. Parameter \( cm \) is classified as system type dependent unknown parameter, for which a value of 40 euros per parcel is assumed. This is based on the parcel domestic express prices of PostNL.

6.6. Tool description

This section describes the basics of the tool that is created for this research. The tool is developed to calculate the LCC of a used system. The tool is built with the formulas described in Chapter 5 and further information of Chapter 6 is used to make the tool ready for calculating the LCC for used SPO’s.

The tool provides the user with an input sheet in which all decisions variables are shown and the case dependent input parameters, as described in Chapter 5. All input parameters are used to calculate the LCC for the three possible reconditioning options. Next to the LCC, also the division of the LCC over the cost elements is shown in the tool, so the user can make a distinction between acquisition costs, reprocessing costs and maintenance costs.

The platform used to build the tool is Microsoft Excel and R. Microsoft Excel is the interface of the tool in which all input parameters should be filled in and in which most calculations can be done. An indication how the tool looks like is shown in Appendix U. The Microsoft Excel tool also includes a sheet with the values of the other parameter types, however these values need to be changed when the tool is used to calculate another system than the SPO. Before changing the values, the right values needs to be determined.
The dynamic programming solution described in 5.4.2 is used for the replacement, down-time and reconditioning costs and are not calculated in Excel or with Excel VBA because R provides more online support and is better in error finding. The R script uses the Excel file as an input file. The input that the R scripts requires are:

- Cost for corrective and preventive maintenance of each component type;
- Cost for reconditioning of each component type;
- Remaining operation periods;
- State of the component types and the number present in the system;
- The probability of survival for each period.

R creates an output of another Excel file with four columns of information for each component types. These columns should be copied to the tool in Excel. When all input parameters are filled in, the LCC is automatically calculated for the three reconditioning options.

6.7. Implementation

Fitting the described model into the current business processes of Vanderlande is an important aspect of implementing this model. Section 4.4 already discussed how the model, fits within the business process. In this section, the best department within the organization that should manage the model is discussed.

As described before, a goal of this research is to create a model that support steering LCC at the beginning of a project that involve reusing a system and deciding what reconditioning option should be chosen. The model deals mostly with aspects from the customer service, but it needs also input of other departments. It is suggested to manage the model by a department that has experiences with LCC tools and has an overview of the entire process. For Vanderlande this means the Pricing department. The pricing department was already involved in the development of this model and informed over all assumptions that are made. Also, some assumptions of the pricing department are used.

6.8. Verification of the tool

The objective of verifying the tool means the process of confirming the correct implementation of the model with respect to the model described in Chapter 5. However, the described model has too many cost elements to verify them all individually. However, because most cost elements follow additive and multiplicative relations, these cost elements are not difficult to implement correctly. Therefore, most focus was put in the cost element replacement, down-time and reconditioning, as described in section 5.4.2.

By using a well-structured example, the computerized model for this cost element is verified. First it is ensured that the code for this model has no errors. Furthermore, the calculations for the simple example are checked by hand, so it is assured that the model as described in section 5.4.2 is correctly modelled. After that, some changes are made in the input and it is checked whether the change in results follow the expected behaviour. Consequently, it can be assured that the computer
programming and implementation of the model are correct, also for other problems. The result of this verification is shown in Appendix V.

At last, the Excel tool is checked for weird outcomes by changing the length of the system, the reconditioning options, the storage options, the desired and initial spare-part packages, and the number of inspections. All outcomes were logical.

6.9. Case study

By providing the results of the LCC model for one fictive scenario, insights will be created about what cost elements are important to focus on for improvements and future research. Based on these insights assumptions can be tested to see how robust the LCC model is. First, a base case is constructed that should be the input for the parameters that are case dependent. The values for the other input parameter were given in sections 6.1, 6.2, 6.3 and 6.4.

6.9.1. Case description

Based on an SPO of a real customer, a fictitious scenario has been constructed in which that system is being reused by another customer. By using the case dependent parameter values of a real customer, the results of the case will be representative for other cases. The parameter values that are based on the real SPO are the length, the capacity, throughput, average duration of a shift, age of the system, number of components, state of components and environmental conditions.

All component types that are identified in this research are used in this scenario. Further, the number of components within each component type, and the number of spare-parts in the spare-part package is based on the bill of materials of the real SPO. Next, the states of the component types are based on the age of the system, the assumption whether a component type fails often or not (see Appendix M), and the maintenance data of this customer. Although the LCC model needs one definition of state of each component type, the items within a component type do not all have the same state. During operation some of the item-numbers within a component type could be replaced already, which results into items with a different state. In this case, expert's opinion is used to estimate the overall state of the component type. The expert takes the number of replacements and the date of the replacements into account in estimating the overall state of the component type. If only a few items, or none, have been replaced during operation, the state can be determined by the start age of the component type, as described in Section 6.4.2.

Further, for the construction of the case, from the three reconditioning options that are possible, the new customer chooses to refurbish the system, by only replacing the component types that decreases the expected LCC. Also, it is assumed that the new customer does not want any extension of the SPO and does not want the system to be cleaned thoroughly, and the system should be put into storage for half a year in an external warehouse because the new customer is not able to use the system immediately.
The costs for operation and energy will not be included in this case. In Section 5.5 it is explained why these cost elements are not elaborated extensively and thus why no data is gathered in Chapter 6 for these input parameters. By excluding the operation costs element, the effect of the other relevant cost elements on the LCC becomes clearer. All values for the input parameter that are case dependent for this case can be found in Appendix S.

**Remark that the results of this base case, that will be described in the next section, are based on fictive system type dependent input values and values determined by assumption. This means that the exact values of the results will not match with reality, but the proportions between the number and the order of magnitude will be representative.**

### 6.9.2. Results

For the described case, the LCC is estimated to be between one and two million euros, Figure 15 shows the split up of the costs. Acquisition and reprocessing costs are the costs that are made at the beginning of the project and influences the sales price of the used system. The acquisition costs cover 26% of the total LCC and the reprocessing costs only 4%. The maintenance costs, good for 70% of the total LCC, are costs that are made over the remaining six years the system is operating. This percentage of maintenance costs on the total LCC is in line with the percentage of maintenance cost described by Öner, Franssen, Kiesmüller, & Van Houtum (2007).

**Figure 15: Pie-chart of the total LCC with a general overview**

So, the maintenance costs are by far the largest costs in the LCC. A closer look on the maintenance costs, shown in Figure 16, shows that replacement costs are 96% of the maintenance costs, inspection costs are 4% and the spare-parts costs are 0%. The reason why spare-parts costs are that low is because the cost of replenishments is included in the cost of replacements. However, in contrast with the inspection costs and spare-parts costs, the level of accuracy of the replacement and down-time costs is more uncertain. Many assumptions are made for this cost element, which is 68% of the total LCC.

**Figure 16: Pie-chart of the maintenance costs**
In appendix T the results are shown for the replacement and down-time costs for component type DS, which are calculated with the dynamic programming solution described in 5.4.2. For this case, the minimal expected costs for component type DS are €74,731,171 (based on fictive input parameters) and no preventive maintenance is expected to be necessary. So, all expected costs are due to corrective maintenance for which 84% is down-time costs. Thus, the total expected costs for component type DS is largely due to down-time costs. These costs for the other components are of the same magnitude.

The acquisition cost is more diverse, see Figure 17. The buy-back cost are 60% of the total acquisition costs, which is mostly the market value of the system and not the process of buying the system. Next, site work at the new customer is 29% of the acquisition costs and engineering costs 9%. These costs are still significant on the total LCC. However, the cost for project management and finding customer is only 1%. The cost for creating the master data is not even significant on the total LCC. The cost for site work at the new customer is the most accurate one, because these costs are the same for a new system. The other cost elements do have a level of uncertainty because of assumptions. For this case an assumption is made for the buy-back costs, however in reality the buy-back costs are known because of the timing the model is used, as described in section 0.

The reprocessing costs are relatively small, see Figure 18 for a division of the costs. The biggest costs within the reprocessing cost bucket is the site work at the old customer with 53%. For this scenario all components of 13 component types are replaced, which leads to a reconditioning cost of 21%. For this scenario external storage is needed and transport, which are 15% and 8% of the total reprocessing costs. Research cost is the smallest cost, 3%. Reconditioning, storage and site work old customer, are cost elements that are small but significant in the LCC.
So, it can be concluded that cost of replacement is the most important element in the LCC model. Further, when looking solely at the start costs of a project, the costs for buy-back, engineering, site work at the old customer and the reconditioning costs, are important. The results are close to what was expected. The maintenance costs are higher than expected for a system that only operates for 6 years. This is because of the high down-time costs that is assumed. Further, the fact that assembly is much more expensive than disassembly is surprising. Some Operation Managers expected that they would be almost the same. In the next section, the most important assumptions will be tested. Cost for spare part is lower than expected, but this is due to the fact that the use of spare-parts is included in the replacement and down-time costs. Other costs are as expected.

6.10. Sensitivity analysis

To test the robustness of this model, the sensitivity of the most important assumptions is tested. The most important assumptions are determined based on the expected influence of the assumption on the cost element it belongs to, the certainty that the assumption matches with the reality, and the proportion of that cost element on the total LCC. This sensitivity analysis compares the outcomes of different modeled relationships. The sensitivity of the model is tested for the following assumptions:

- Reliabilities based on field data.
- Down-time:
  - Changing the cost per bag;
  - Changing the type of relation.
- Age
  - The age of the system that is returned;
  - State of the component types.
- Recondition option.
- Engineering.

6.10.1. Reliability obtained by field data

Currently Vanderlande is collecting failure data for which many assumptions must be made to use the data for a reliability analysis. The assumptions have a direct effect on the time to failure of components, the shape of the reliability function, and the slope of the reliability function. To test the sensitivity of the model on these assumption, a comparison is made between the LCC outcomes of a system with the reliability functions based on the assumptions used in this research, and reliability functions that have slopes with different level of steepness. This can be represented by changing the environmental condition factor value. In this way, not all assumptions have to be tested individually. The data preparation that is necessary to test all assumptions, is a time-consuming activity, and it is therefore not possible to test all assumptions one by one for this research. The results are shown in Figure 19.

Figure 19 shows that the model is very sensitive to deviations in the $e_f$ value, and thus the impact of the assumptions regarding the reliability functions is high, as expected. Therefore, it is highly recommended to replicate the failure-time measurements, data preparation and the reliability analysis in the future in order to establish more reliable reliability functions. Furthermore, the
relationship between the environmental condition factor value and the LCC seems linear, however it is not. The steepness of the line is slowly increasing. Because the steepness is that slowly increasing, it is not useful to test more values of the environmental condition factor.

![Sensitivity of variation of the environmental condition factor value](image1)

**Figure 19**: Sensitivity of the reliability function by varying the EF value

### 6.10.2. Down-time costs

This study assumed that down-time cost is a consequence of the number of missed bags which causes over-time and a penalty for delivering the handling units that missed the pick-up truck. So, by changing the penalty costs per handling unit that arrives too late, the sensitivity of this relationship with the LCC is tested. See Figure 20 for the results.

![Sensitivity of variation in the penalty for missed handling units](image2)

**Figure 20**: Sensitivity of variation in the penalty for missed handling units

The results of Figure 20 show that the model is sensitive for the deviations in the penalty cost. A slight change in the penalty, already has a large impact on the LCC, which is expected because of the large number of handling units that arrive too late when a failure takes place. The relationship between the penalty costs and the LCC also looks linear, but it is not linear. The steepness decreases when the penalty costs increases. Thus because of the sensitivity of this assumption, it is recommended to discuss the value of the penalty with the customer.

A second analysis is conducted to test the sensitivity of the number of missed handling units on the LCC. For this research a trivial method has been adopted to determine the number of handling units that arrive too late if a component type fails. So, it is very likely that this method does not provide the right number of too late handling units. In order to test how sensitive the model is to the number of too late handling units, a comparison is made between the LCC with the determined number of handling units that arrives too late when a component type fails, and the number of
handling units that are too late multiplied by a factor between 0,5 and 1,5. Results are shown in Figure 21.

![Sensitivity of variation of the number of missed handling units](image)

**Figure 21: Sensitivity of variation of the number of missed handling units**

Figure 21 shows that changing the number of missed handling units, has a significant impact on the LCC and thus that the model is sensitive as expected. The sensitivity is less compared to the sensitivity for the penalty cost for missed handling units, but it is still significant. Again, the relationship seems linear, but it is not. If the number of too late handling units increases, the steepness of the lines decreases. It is recommended to replicate the function for cost of down-time and its parameter values.

6.10.3. **Age**

Age can impact two parameters, the age of the returned system, and the age of component types what can be translated to the state of the component types. The age of a returned system impacts the LCC because it influences the number of remaining operation periods and thus also the number of inspections, the spare-parts costs and the replacement and down-time costs. A system can only operate for 20 years, no matter if it is reused. This is because of the frame of the SPO that experiences wear, but is too expensive to replace. In order to test the sensitivity of the model on the age of the returned, a comparison is made between the LCC outcome of the base case and scenario’s where the age of the returned system is different and thus also the remaining operating years. Results are shown in Figure 22.

![Sensitivity of variation of the age of the returned system](image)

**Figure 22: Sensitivity of variation of the age of the system**

A smooth decreasing line is expected in Figure 22, because the maintenance costs should decrease when the system has to operate for fewer years. However, at the age of 10 and 11, and 15 and 17, the LCC costs are almost the same. This is because although the number of remaining operation
years is different, the number of operation periods is the same. One period has a length of more than one year, and therefore the expected replacement and down-time costs are the same.

Thus, the age of a returned system has a large impact on the LCC, but this is mainly because the time period for maintenance is shorter. Further it is also expected that the number of operated period for the component type has a significant impact on the LCC. When a system is returned, an engineer has to make an estimation of the state of a component type based on the number of operated hours, environmental condition and the time and number of conducted replacements. By changing the number of operated hours for each component type, the impacted on the LCC is measured. The results are shown in Figure 23.

![Sensitivity of variation of the number of operated periods of each component type](image)

**Figure 23: Sensitivity of variation of the state of the component types**

Figure 23 shows that the state of the components has a small impact on the total LCC. This is because that the probabilities of failure are all similar and small during the life time of the system. A smooth increasing line was expected. However, between -4 and -2 periods, the cost does not increase. This is because some components have a Weibull distribution which indicate that the probability of failure direct after installation is higher than a couple of periods past installation.

6.10.4. **Reconditioning options**

For this research three different reconditioning options are described: reuse “As-Is”, refurbish and remanufacture. For the base case the refurbishment option is chosen, in which only the components are replaced that should result into a lower LCC when compared to not replacing the component. In section 5.3.2, also other options are included to the reconditioning costs, and sometimes desired by the customer although the LCC is higher. These options are extensive cleaning and extending the system in length. Note that the LCC model assumes that cleaning has no effect on the maintenance costs. A comparison is made between the LCC of the different reconditioning options as described here. The results are shown in Figure 24.

The results in Figure 24 show that the impact of some recondition options on the LCC are lower than the other elements tested already. For example, if the base case is compared with another case in which the new customer chooses to remanufacture the system, all components are preventively replaced, the total LCC increases to 154% of the base case. Some Product managers preferred this option at the beginning of this research, because it would ensure that the system would be of high
quality. However, this analysis shows that the costs are much higher than when the system is refurbished.

![Sensitivity of the reconditioning options](image)

**Figure 24: Sensitivity of the reconditioning options**

In case nothing is replaced, the LCC increases with two percent. Note that by investing less than 1% of the base LCC, a 2% increase in the total LCC is prevented. Thus, the rate of return for this investment is high. The case in which the system is also cleaned has a small increase in the LCC. This is because the costs for cleaning are expensive and it results in no savings on the maintenance costs but sometimes cleaning can be desired by the new customer. For the case in which the system is extended, it can be concluded that the costs for extending are significant.

**Engineering**

For engineering two big assumptions are made, the time it takes to engineer the new safety rules in the used systems, and the time to reengineer the system to replace components that are end-of-life. Both assumptions were discussed with a Product Manager, but in both cases, the Product Manager, he had no clue about what the values of the parameters should be.

First, the assumption for the number of hours spend on implementing the new safety rules is changed from zero to eight hours per year. For the second assumption, the number of hours spend on replacing an EOL component, is also changed from zero to eight hours per component. For both cases there was no significant impact on the LCC or the acquisition costs. If the parameter values do not take extreme values, or the number of components that are EOL increases extremely, then the model is robust for this assumption.
7. CONCLUSIONS

This chapter describes the main findings of this study. Next to the main findings, also the limitations and the recommendations.

7.1. Main findings

Based on the sub-research questions, the following findings are presented:

7.1.1. What process flow is associated with reusing a system?

Based on the process flow of a new system, the new activities present in the process flow for a used system are: checking the system, evaluation of the system, buying back the system, finding a customer, disassembly, packing, documentation, warehousing and reconditioning. Processes that are completely the same for both systems are: assembly, testing, maintaining, operating and disposal. At last, there are some processes that are essentially the same, but because the process is done for a used system, the process differs a bit: transport, engineering and creating master data.

7.1.2. What are the various cost elements in the described process?

The cost elements are based on the described process flow, but in general the main cost elements are: acquisition costs, maintenance costs, operation costs, and reprocessing costs. Compared to the cost elements for a new system, the reprocessing costs are completely new and include almost all new processes described in the process flow. Depending on what reconditioning option is chosen, the reprocessing costs can vary significantly. However, the other reprocessing costs elements cannot be influenced but are smaller than expected. The reconditioning option also influences the maintenance costs, which is in general the largest cost element for capital goods. Cost of down-time is the biggest cost driver of the maintenance costs. For acquisition costs the buy-back costs and site work are the biggest cost drivers. Operation costs are completely dependent on the customer and therefore not included in this research.

7.1.3. What components of the Posisorter should be included in the model?

Based on nine years of failure data, 42 different component types are identified that are replaced in practice. Not all these components were already identified by Vanderlande.

7.1.4. What is the financial performance given the state of a Posisorter?

The financial performance given the state of a Posisorter can best be defined as the expected future maintenance costs given the state of a Posisorter. A system is a collection of components, thus the state of system is dependent on the state of the components within that system. The state of a component is in this research defined as the number of operated hours. With the help of stochastic dynamic programming the minimal expected future costs for each component type given their state,
can be calculated. With the expected costs for each component type, the total expected cost of the system can be calculated.

7.1.5. *What are the reprocessing investment options that could be used for the Posisorter?*

Three different options can be executed because they are technological achievable for most system, which are all based on the replacement of component types. The first option, Reuse ‘As-Is’, does not replace any component types at all. The second option, ‘Remanufacturing’, replaces all component types, and the third option, ‘Refurbishing’, only replaces the components that will decrease the LCC upon replacement.

7.1.6. *How to quantify the reprocessing investments in monetary terms?*

The reprocessing investment is mostly based on the prices of the component types, the number of items present in the system, the transport costs and the decision to replace what component types.

7.1.7. *How to determine the optimal reprocessing investment?*

When replacement costs during reprocessing are cheaper than replacing during operation, replacing components preventively in this stadium can be beneficial, dependent on the present state of the component types. The replacement decision is made by comparing the expected costs for the component type in its present state with the expected costs for the component type in its youngest state plus reconditioning costs. A case study indicated that for the pilot case there is a small difference in LCC between the reuse ‘As-Is’ option and the ‘Refurbishing’ option, and one should not choose the remanufacturing option because more components are replaced then necessary. The model described in this research is able to identify all component types that would decrease the LCC upon replacement compared to the situation in which the component is not replaced.

The sub-research questions are used to answer the main research question: *What is the LCC for a reused Posisorter of Vanderlande in the parcel and postal market?* The LCC is mostly dependent on the age of the system, the state of the component types, the environmental conditions (average weigh of handling units, temperature, dust, and moisture), the length of the system and what reconditioning option is used. With the help of the described model the LCC can be calculated for each individual case.

7.2. *Limitations*

Based on the sensitivity analysis, it is shown that the determined reliability functions have a great influence on the LCC, therefore limitation concerning the reliability functions are discussed in this section. Moreover, other limitations will also be discussed.

7.2.1. *Reliability function*

The failure data that is used to determine the reliability function is tracked over a short-time span, compared to the life-time of a system. This resulted into not enough data for all component types,
to fit for all component types an appropriate trend-line with a high coefficient of determination. Also, because the data set was incomplete, the determined reliability functions are constructed with the help of assumption, which makes the reliability function less reliable. Further, the reliability functions are based on grouped data which results into a loss of information. When better estimations can be made about the overall state of a component type, it would be useful to decrease the length of the time interval in which the data is grouped. Next, only a limited set of trend-lines have been used to fit the data. This means that maybe probably not all component types have the best fitted trend-line.

7.2.2. Information component types

Due to the large amount of different item-numbers, the relatively few failures per item-number, the lack of an individual identification number per item, it was difficult to determine the failure behavior of each item-number or the failure behavior of individual items. Therefore, item-numbers needed to be combined into sets called component types, based on the expected failure behavior determined by an expert. As a result of this action, a lot of useful information is lost. Further, the lack of information about the quantity of each item-number present in the systems made it difficult to determine the reliabilities for the component types.

7.2.3. Environmental conditions

The recorded 17 locations all have the same environmental conditions. For this reason, the influence of the environmental conditions on the reliability function could not be measured. Thus, it is assumed that a factor between the 0.9 and the 1.1 must be multiplied with the independent variable (the number of operated hours) of the reliability functions to mimic the effect of the environmental conditions on the reliabilities. However, it is unknown whether this is a good representation.

7.2.4. Others

The cost functions for the cost elements within the bucket operations are not extensively been developed and tested. Developing a cost function for these elements could be a separate research. However, these cost elements will probably be a large part of the LCC and could be important to know for the customer. The last limitation is that many assumptions are made about the value for activities that have almost never been done before. Often these values are based on the opinion of only one expert, which can give a biased estimation of the values.

7.3. Recommendations

In this section recommendation will be discussed how to improve the model, for further research and for the implementation of the model.

7.3.1. Recommendations to improve the model

Vanderlande should make the group of item-numbers in each component type smaller, so less information about the failure behavior of the individual item-numbers will be lost. Further, the
failures of all locations should be tracked and Vanderlande should be able to measure how many hours a specific component has operated before it fails. By providing a unique identification number for each item and recording the number of hours a system operates, more useful information can be obtained from the failures. Next, the set of used trend-lines to determine the reliability functions of the component types can be expanded.

To improve other estimated values of the input parameters, the Delphi technique can be used to estimate the values for the assumptions. The Delphi technique requires the opinion of more than one expert. Also, after each project that involves a used system, the time duration and the costs of all activities should be logged properly so the values in the model can stay up to dated. Further, because the down-time costs have a big impact on the LCC a more reliable method should be determined to predict the number of handling units that arrive too late for pick-up.

7.3.2. Recommendations for further research

The model can be extended by measuring the effect of the described environmental conditions, on the reliability function. By identifying the environmental conditions for each measured system, the right value for the environmental condition factor can be determined. This knowledge can be used to improve the maintenance schedule or to support the decision to change the environmental conditions at the location of the system.

Next, the cost elements of the operation costs should be better specified and values should be found for these parameters, so the customer can have a more complete view on the LCC of the system. Further, an optimal spare-part policy can be determined that incorporates the state of the component present in the used system and the number of remaining operation periods. Moreover, Vanderlande should investigate other options to reduce the state of a component, instead of replacement with a new component. Other option could be replacement by another used component.

7.3.3. Recommendations to implement the model

The tool must be incorporate with the existing pricing tools within Vanderlande, so information of these tools can be used. In this way a more accurate estimation can be made about the costs of activities that are the same as for a new system. Moreover, when Vanderlande want to use the model for other systems, they should determine the values of all parameters in a systematic way and they should know components are in each system and how many. They should keep track of all failures and the operated time of the components before failure. Further, they should group the right components in same set. People should be instructed about the value of collecting the right information and how Vanderlande can benefits from that.
8. REFERENCES


9. SYMBOLS AND DEFINITIONS OF THE VARIABLES

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{EOL}$</td>
<td>Age when a system is end-of-life (in years).</td>
</tr>
<tr>
<td>$BBP$</td>
<td>The buy-back price for the system (in euros).</td>
</tr>
<tr>
<td>$C_{dis}$</td>
<td>Cost related to disassembly of the old system (in euros).</td>
</tr>
<tr>
<td>$C_{doc}$</td>
<td>Cost related to the documentation of the old system (in euros).</td>
</tr>
<tr>
<td>$C_{pack}$</td>
<td>Cost related to the packing of the old system (in euros).</td>
</tr>
<tr>
<td>$C_A$</td>
<td>Cost for cleaning components (in euros).</td>
</tr>
<tr>
<td>$C_{ESP}$</td>
<td>The value of a complete spare-part package (in euros).</td>
</tr>
<tr>
<td>$CDT_i$</td>
<td>Cost of down-time when component $i$ fails (in euros).</td>
</tr>
<tr>
<td>$C_{EN1}$</td>
<td>Cost of energy consumption of one year (in euros).</td>
</tr>
<tr>
<td>$C_{EXT}$</td>
<td>Cost for extending the system size (in euros).</td>
</tr>
<tr>
<td>$C_{En}$</td>
<td>Cost related to energy consumption (in euros).</td>
</tr>
<tr>
<td>$C_{Eng}$</td>
<td>Cost related to engineering for the used system (in euros).</td>
</tr>
<tr>
<td>$C_{FC}$</td>
<td>Cost related to finding a customer for the used system (in euros).</td>
</tr>
<tr>
<td>$C_{IE}$</td>
<td>Cost related to the electrical installation for the used system (in euros).</td>
</tr>
<tr>
<td>$C_{IM}$</td>
<td>Cost related to the mechanical installation for the used system (in euros).</td>
</tr>
<tr>
<td>$C_{IN}$</td>
<td>Cost related to inspections (in euros).</td>
</tr>
<tr>
<td>$C_{IN1}$</td>
<td>Cost for inspection for 1 year (in euros).</td>
</tr>
<tr>
<td>$C_{IS}$</td>
<td>Cost related to the software installation for the used system (in euros).</td>
</tr>
<tr>
<td>$C_{LT}$</td>
<td>Cost for a long trip (in euros).</td>
</tr>
<tr>
<td>$C_{MD}$</td>
<td>Cost related to creating the master data (in euros).</td>
</tr>
<tr>
<td>$C_M^s$</td>
<td>Cost related to the main cost bucket maintenance of system $s$ (in euros).</td>
</tr>
<tr>
<td>$C_{OP}$</td>
<td>Cost related to operational personnel (in euros).</td>
</tr>
<tr>
<td>$C_{OP1}$</td>
<td>Cost for operational personnel for 1 year (in euros).</td>
</tr>
<tr>
<td>$C_O^s$</td>
<td>Cost related to the main cost bucket operation of system $s$ (in euros).</td>
</tr>
<tr>
<td>$C_{PM}$</td>
<td>Cost related to project management for the used system (in euros).</td>
</tr>
<tr>
<td>$C_{RC}$</td>
<td>Cost of reconditioning (in euros).</td>
</tr>
<tr>
<td>$C_{RD}$</td>
<td>Cost for delivery of new components (in euros).</td>
</tr>
<tr>
<td>$C_{RE}$</td>
<td>Cost related to the replacement of parts (in euros).</td>
</tr>
<tr>
<td>$C_{RP}$</td>
<td>Cost replacing components (in euros).</td>
</tr>
<tr>
<td>$C_{Research}$</td>
<td>Cost for doing research for the system (in euros).</td>
</tr>
<tr>
<td>$C_R^s$</td>
<td>Cost related to the main cost bucket reprocessing of system $s$ (in euros).</td>
</tr>
<tr>
<td>$C_{SA}$</td>
<td>Cost related to the supervision during the assembly process (in euros).</td>
</tr>
<tr>
<td>$C_{SP}$</td>
<td>Cost related to spare-part (in euros).</td>
</tr>
<tr>
<td>$C_{ST}$</td>
<td>Cost of storage of the system (in euros).</td>
</tr>
<tr>
<td>$C_{ST}$</td>
<td>Cost for a short trip (in euros).</td>
</tr>
<tr>
<td>$C_{SWN}$</td>
<td>Cost related to site work at the new customer’s location for the used system (in euros).</td>
</tr>
<tr>
<td>$C_{SWO}$</td>
<td>Cost for doing site work at the location of the old customer (in euros).</td>
</tr>
<tr>
<td>$C_{TR}$</td>
<td>Cost for transport of the system (in euros).</td>
</tr>
</tbody>
</table>
\( C_{\text{Tr.direct}} \) = Cost of transport directly from customer A to B (in euros).
\( C_{\text{Tr.indirect}} \) = Cost of transport from customer A to warehouse, and to customer B (in euros).
\( C_{\text{transport}} \) = Cost related to transport of the system (in euros).
\( C_{\text{eval}} \) = Cost related to the evaluation of the system (in euros).
\( C_{\text{inspection}} \) = Cost related to the inspection of the system (in euros).
\( C_{\text{kwh}} \) = Cost for one kilowatt-hour (in euros).
\( C_{p} \) = Cost for preventive maintenance on component \( i \) (in euros).
\( C_{\text{pm}} \) = Cost related to packing material (in euros).
\( C_{\text{tools}} \) = Cost related to tools (in euros).
\( C_{\text{travelresearch}} \) = Travel cost of the employees to the old customer for research (in euros).
\( C_{\text{travelswm}} \) = Cost related to the travels that the employees make for the site work at the new customer (in euros).
\( C_{\text{travelswmo}} \) = Cost related to the travel cost of the employees for site work at old customer’s location (in euros).
\( C_{\text{ci}} \) = Cost for corrective maintenance on component \( i \) (in euros).
\( CL \) = Constant for cleaning hours per meter system (in hours per meter).
\( EOL_{i} \) = Binary variable whether a component \( i \) is EOL. Zero means that the component is not EOL and one means that the component is EOL.
\( K \) = The number of trucks necessary to calculate for transport.
\( I \) = Number of visits per year.
\( L \) = The last possible state which indicates that corrective maintenance must be conducted (in periods).
\( L_{i} \) = The last state of component \( i \).
\( LCC_{s} \) = Life cycle cost for a used system \( s \) (in euros).
\( PC \) = Power consumption per hour (in watts per hour).
\( PR_{i} \) = Production price for component \( i \) (in euros).
\( R(T) \) = The reliability at \( T \) (in percentage).
\( REC_{i} \) = Binary variable for which one means that component \( i \) will be reconditioned and zero means that component will not be reconditioned.
\( S \) = Size of the old system at the old customer (in meters).
\( SS' \) = Size of the system that will be delivered at the new customer (in meters).
\( ST \) = Binary variable if storage is needed. One if no storage is needed, and zero if storage is needed.
\( STC \) = Cost for one truck within the assumed range (in euros).
\( T_{DE} \) = Time spent on the disassembly of the electrical parts (in hours).
\( T_{DM} \) = Time spent on disassembly of the mechanical parts (in hours).
\( T_{EN} \) = Time spend by an engineer for engineering a new system (in hours).
\( T_{EOC} \) = Time spend to find a solution to replace old components (in hours).
\( T_{ES} \) = Time spend to engineer the new safety rule correctly (in hours).
\( T_{FC} \) = Time spend by a sales manager for finding a new customer (in hours).
\( T_{FCS} \) = Time spent by a Service department for finding a new customer (in hours).
\( T_{IE} \) = Time duration of the electrical installation by an operation employee (in hours).
\( T_{IM} \) = Time duration of the mechanical installation by an operation employee (in hours).
\( T_{IS} \) = Time duration of the software installation by an operation employee (in hours).
\( T_{MD} \) = Time for creating master-data for the used system (in hours).
\( T_{Neg} \) = Time spend on negations with the client (in hours).
\( T_{PM} \) = Time that a project manager spends on the project (in hours).
\( T_{PMCL} \) = Time spent by a manager to arrange cleaning (in hours).
\( T_{PMEX} \) = Time spent by a manager to arrange extension of the system (in hours).
\( T_{PS} \) = Time spend on creating a purchase strategy (in hours).
\( TR_i \) = Time spend on replacing component \( i \) (in minutes).
\( T_{SA} \) = Time duration of the supervision (in hours).
\( T_{SD} \) = Time of supervising the disassembly (in hours).
\( TT_{PM} \) = Total work time necessary to make one trip for a project manager (in hours).
\( TT_{Eng} \) = Total time necessary to make one trip for an engineer (in hours).
\( TT_{sw} \) = Total time necessary to make one trip for site work (in hours).
\( T_{discuss} \) = Time spent on discussing the system (in hours).
\( T_{doc} \) = Time spent on the documentation (in hours).
\( T_{eng} \) = Time spend by an engineer for the complete engineering process (in hours).
\( T^i \) = The life time of component \( i \) (in hours).
\( T_{inspecting} \) = Time spent on inspecting the system (in hours).
\( T_{inspection} \) = Time spent on one inspection (in hours).
\( T_{packing} \) = Time spent on the packing process (in hours).
\( T_{searching} \) = Time spent on searching internal information of the system (in hours).
\( T_{sp} \) = Time spent by the supervisor on packing (in hours).
\( T_{travel.loc} \) = Time spent on travelling from Veghel to the old customer’s location (in hours).
\( U \) = Number of new components that must be added to the used system by change in lay-out.
\( V_fcf \) = The net present value of the future cashflow that are contractual committed for the system (in euros).
\( V_m \) = The market value of the system (in euros).
\( V^i_n(x) \) = The minimal expected discounted cost for component \( i \) in state \( X \) with \( n \) periods to go.
\( V^{i}_n(x) \) = The minimal expected not discounted cost for component \( i \) in state \( X \) with \( n \) periods to go.
\( W_{CS} \) = The hourly rate of a sales manager from the customer center (euros/hour).
\( W_{Eng} \) = The hourly rate of an engineer (in euros/hour).
\( W_{PM} \) = The hourly rate of a project manager (in euros/hour).
\( W_{SE} \) = Hourly rate of service engineer (in euros per hour).
\( W_{SE} \) = The hourly rate of service engineer (in euros per hour).
\( W_{employee} \) = Hourly rate of an operation employee (in euros per hour).
\( W_{inspector} \) = The hourly rate of the inspector (in euros per hour).
\( W_{software} \) = Hourly rate of a software installer (in euros per hour).
\( W_{supervisor} \) = Hourly rate of the supervisor (in euros per hour).
\( X_n \) = The state of the component in operation hours at period \( n \).
\( Y \) = Number of years that the system will be operating (in years).
\( Z \) = Binary variable that indicates with one, whether an external warehouse is used and with zero that the direct route must be chosen.

\( a \) = Average number of operation hours a day for the system (in hours).

\( b \) = Remaining number of operation hours for the used system before EOL (in hours).

\( cl \) = Binary variable whether components are cleaned. One means that components are cleaned and zero means that no components are cleaned.

\( d \) = Total number of different components in the used system.

\( d' \) = Total number of different components in the adjusted used system

\( deh \) = Number of hours for electrical disassembly per meter (in hours per meter).

\( dmh \) = Number of hours for mechanical disassembly per meter (in hours per meter).

\( doc \) = Number of hours for documentation the system per meter (in hours per meter).

\( dsh \) = Number of hours for supervising the disassembly per meter (in hours per meter).

\( ea \) = Constant for engineering safety hours per year (in hours per year).

\( eoc \) = Constant for replacing old components for engineering (in hours per old component).

\( ex \) = Binary variable whether the system is extended. One means that the system is extended and zero means that the system is not extended.

\( ext \) = Constant for extending cost per meter system (in euros per meter).

\( f \) = Binary indicator variable of whether service department finds a customer for system. Zero means that service department did find a customer and one means that the sales department must search for a customer.

\( fe \) = Percentage of extra cost of preventive maintenance (in percentage).

\( g \) = The age of the used system (in years).

\( i \) = Component index of the used system, \( i = 1, \ldots, d \).

\( j \) = End of use option index, \( j = 1,2 \) (1, disposal and replacement; 2, do nothing).

\( k_i \) = The number of components that are present in the system which belong to component type \( i \).

\( k_i, c \) = The amount of spare-parts of component \( i \) that are desired by customer \( c \), \( c=1,2 \) (1, old customer; 2, new customer).

\( m \) = Number of operation hours between periods for the system (in hours).

\( ms \) = The duration of replacing one component in the master-data (in hours).

\( n \) = Number of remaining periods before system is EOL (in periods).

\( p_{xy} \) = The probability going from state \( x \) to \( y \) at the next period given decision \( j \).

\( pm \) = Packing material cost per meter system (in hours per meter).

\( pt \) = Number of hours for packing the system per meter (in hours per meter).

\( q \) = Number of needed personnel per day.

\( r \) = Nominal interest rate (in percentage).

\( r_s \) = yearly percentage paid for storing the spare-parts.

\( rp \) = Binary variable whether components are replaced. One means that components are replaced and zero means that no components are replaced.

\( s \) = Corresponds to system \( s \).

\( sc \) = Cost for storage for half a year per square meter (euros per m\(^2\) per half year).

\( sp \) = Number of hours for supervising the packing process per meter (in hours per meter).
\( w \) = Number of working days within a year (in days).
Appendix A: Cost break-down structure

The cost break-down structure used in the previous researches on TCO and LCC within Vanderlande. This LCC was created for Vanderlande for a baggage handling system. Based on this cost break-down for a used system is made. See Appendix D.

Figure 25: Cost break-down structure (Franssen, 2006)
Appendix B: Reuse process descriptions

This appendix will discuss all process activities of the process flow for a used system described in Figure 26, this figure is used below again for clarification.

1. Spot opportunity
The process starts with a system that becomes available. The service department of Vanderlande will be the first ones to notice because they are in direct connection with the customers. The service department is not searching for these systems actively, but is waiting until a customer contacts them. Once the service department knows about an available system, they will assign a project manager to this new project, who will be responsible for the coordination of this project. Next, they will notify a service engineer to check whether the system is suitable for reuse.

2. Inspecting system
The system of the customer must be inspected first. The service engineer will visit the location where the system is located. There he will perform different kind of tests. First a visual inspection
will be done. The service engineer notes the general impression of the different sections of the
system and whether there are any remarks. Second, the engineer will measure the tension of the
chains in the system and compare them. Third, gears in the system must be checked on wear.
Fourth, the power of the drivers will be measured with different system settings. Fifth, resistance of
certain parts can be measured. The last test measures the noise level of the system when it is
operating. With these tests, the service engineer has an idea about the status of the system. Based
on these tests together with the current operation hours of the systems and the expected failure rate of the components, a decision can be made whether it is worth it to buy the system back. the
service engineer will report to the customer center if the system is worthwhile for reuse or not.
When the system is not worthwhile, then the process will be terminated, otherwise the evaluation
process will start.

3. Evaluation
In the evaluation process the report of the service engineer is discussed by the customer center. The
customer center consists of two different departments: sales and service. For the evaluation,
someone from both departments is necessary. Not only the report will be evaluated, but also all the
internal information for the system that is available within Vanderlande. This information includes
the maintenance data, the technical drawings and all the specifications. It is possible that not all
information is available, especially if it is an old system. This will influence the evaluation. Next, the
market value of the system will be estimated, which means an evaluation of the possibilities to sell
the system. At last, a decision will be made to engage with the project of reusing that system, or not.

Buying back system

4. Buying back system
The customer center will start the buying back process in case the system is suitable for reuse. In this
process, the customer center will determine a purchase strategy and negotiate with the customer.
The purchase strategy will be dependent on what kind of contracts about future cash flows of
Vanderlande with the customer. Examples of these contracts concern service that Vanderlande still
will execute, or the spare parts arrangements. Further, the customer center will maybe have to
compete with other companies that want to buy the system. This process can take some time
because of the negotiations.

5. Finding a customer
If Vanderlande succeeded in buying back the system, Vanderlande will search for a buyer. The
service department has connections with all the existing customers and can easily contact them and
ask them whether they have interest in a used system. If no existing customer wants to buy the
system, the sales department helps the service department with selling the system by contacting
potential new customers. The duration of this part of the process and the steps taken, will be
different for each system. Together with the new customer, the requirements and specifications of
the used system are discussed. If the new customers want to change somethings about the system
this can lead to new requirements and specifications. Before a customer is found, the next process
can already start.

6. Disassembly
In the meantime, the disassembly process already begins because the old customer often wants the system gone as soon as possible. The disassembly process should be executed very carefully so the system is not damaged and nothing gets lost. The disassembly process will be done by operation employees from an external party which are familiar with the system and received training to disassembly the system. Also, one supervisor of Vanderlande should be present to coordinate the process at site.

7. Packing and documentation
After the disassembly process, everything should be packed and properly documented. For new systems, manuals are available with instructions how to pack all components of the system properly in the factory before it send to the customers. These manuals can also be used for the packing of a used system. The right equipment is necessary for this and should be sent to location. The equipment will be sent from the factory to the location of the old customer.

8. and 9. Storage and Transport
Often the system cannot immediately be sent to the new customer and therefore must be stored. This storing can be done at the location of the old customer, but is also possible that the system will be stored in an external warehouse. In that case, the system must be transported to this external warehouse and be stored there until the system can be transported to the new customer. It is also possible that the system will not be sold, and the service department decides to dispose the system because is it not worthwhile to keep the system. Moreover, when the system is sold immediately, the system should be transported to the new customer.

10. Engineering
In case a customer is found, all specifications and requirements of the used system will be transferred to the engineering department. These requirements and specification are drawn up by the customer and the project manager. These specifications are related to the length of the system, the speed, the kind of material, and the amount of output lanes. If the customer has other wishes, these specifications will be noted. The complete system will have to be engineered from scratch, so the mechanical part, the electronic part, and the software part. When the system contains some old components, this can cause much extra work for the engineering department because old components are not integrated in the engineering software and it is not always clear how to replace certain old components by new components. Further, safety rules change overtime because of changing legislation and the used system should meet all safety requirements, which can lead to a change in design. It is not always clear which new safety rules have to be added to an old system, what also leads to extra time.

11. Transport to new customer
In this process the system is transported to the new customer from the external warehouse, or directly from the old customer.

12. Reconditioning
Vanderlande and the new customer should make an agreement about what value-adding activities should take place on the system. As described in section 2.2.3, three different options are available
on system level: reuse ‘As-Is’, refurbishing and remanufacturing. Because the system is large and unnecessary changes are expensive, a component level view will be used for the value-adding activities.

For the reuse “As-Is’ option, this means that nothing is done, or only clean the components. For the refurbish option, it is checked what components should be reprocessed. Reprocessing a component to as good as new is called reconditioning (Parkinson and Thompson, 2003). In this case reconditioning means the replacement of used components by new components. For the remanufacture option, all components are replaced by new components.

To achieve agreement on the components to be replaced, the opinion of the service engineer that inspected the system is important as well as the involvement of the engineering department that engineered the system. The components that should be replaced are disposed and new components are ordered. These components will be installed in the assembly process, together with all the other components. The components will be made in the factory and transported from there to the new customer.

13. Creating master-data
The next step is that the service engineer will have to create the master-data of the system in the information system of Vanderlande. All item numbers should be stored in the information system so Vanderlande knows exactly what the new customer gets. Depending on whether this is a new customer, and whether the system is re-engineered, creating the master-data will take more time than when the system stays the same.

14. Assembly process
After this process, and once the used system is delivered to the new customer, the assembly process can start, in which the system is build up. This means that first the mechanical installation should be build up. After that there will be an electrical installation, which means that all the cables will be installed. The last step in the installation of the software. For the process, a site supervisor will be present and operation employees of a third party.

15. Cleaning
When the system is assembled and ready to be tested, the complete workplace will be cleaned first.

16. Testing the system
The next process is testing if the system is installed correctly and is ready for operation. By letting the system run, the service engineer can check whether everything goes correctly. For example, if something is wrong with the software it could be that the wrong decisions are made by the system. A service engineer will perform multiple test and if necessary make changes in the system.

17. Maintaining
After testing, the system is ready for operation and the customer will be responsible for these operations. Depending on the service contract with Vanderlande, the system will be maintained by the customer or Vanderlande. It is assumed that this process will take place until the system is end-
of-life and the system needs to be disposed. Vanderlande has a maintenance manual for all their systems. Some parts should be cleaned and checked every week, other parts should be checked every three months and replaced if necessary. The activities that should be performed weekly are done by the customer, and that the activities that should be done every three months are done by Vanderlande. In case that there is an unexpected failure, the service department of Vanderlande is notified and a service engineer will be send to the customer as soon as possible. Moreover, often the failed component can be replaced by a component in the spare part package of the customer. Customers buy also a spare-part package when they buy a system. Depending on the customer, all necessary parts are included in this spare-part package. For this research, it is assumed that all repairs can be done with the spare-part package.

## 18. Disposal

When the system is declared EOL, a company that collects and trades steel will be called, which will disassemble the system and take all steel in the system. It is assumed that a system has a fixed number of years before it is EOL, independent whether is the system is reused.

### Project management

The project management process is not present in the process flow because it is a continuous process in which the project manager is responsible for the complete project. The project manager is responsible for the communication with the customer during the entire process and arranging the right people for all the processes. The project manager drafts the specification with the customer which should be transferred to the engineering department. Also, the project manager arranges the employees on site and arranges transport and storage, if necessary.
Appendix C: The comparison of processes from both process flows

In this section, all the processes for a new system will be discussed and compared to the process flow for a used system. The process is described in Figure 27.

1. Finding a customer
The process starts with finding a customer that wants to buy a system. For a new system, only the sales department is responsible for this task. They will discuss all systems that Vanderlande can offer and will draw some simple system designs to convince the customer. Now the customer often contacts Vanderlande first, and Vanderlande does not actively approach new customers.

2. Engineering
When a customer is found, the specifications for the system should be discussed and written down. The specifications are about what the customer wants and how. The specifications are about the size of the system, the speed, the lay-out, what kind of materials and how many exits. Once all these specifications are clear, the engineer can start making the drawings. For a new system, more specifications have to be discussed compared to a used system. For a used system, the basic specifications are already determined because the system returned that way. However, for a new system no extra time must be included for the changing old components and new safety rules.

3. Creating master-data
Creating master-data for a new system is much easier and less time consuming than for a used system. The master-data for a new system can be automatically created with some input from the engineering process. No adjustments must be made, with is not the case for the used system.

4. Manufacturing
Once the system is engineered, the complete system must be manufactured in the factory. In case of a used system, this process only happens for the reconditioning process, and then not the complete system is manufactured, but only a couple of components.
5. **Packaging and documentation**
When all the components of the system are manufactured, they must be made ready for shipment. All components should be packed and properly documented. Compared to the packaging and documentation process for a used system, no package material must be sent from the factory to the location of the old customer. All the other activities in this process are the same.

6. **Transportation to new customer**
This process is almost the same as for a used system, only the start of the transport differs. Instead the system is transported from Veghel to the new customer, it will be transported from the old customer to the new customer.

The processes Assembly, Testing, Maintaining and operating and disposal, are the same for both process flows.
Appendix D: New cost break-down for the reuse of a system

This appendix shows the new LCC cost break-down for a used system, based on cost break-down of Appendix A and the process description in Appendix B and C. It was checked whether the cost break-down had an appropriate match with the described activities described in the process description. If not, the cost break-down of Appendix A was changed.

Figure 28: LCC break-down for the reuse of a system
Appendix E: Other acquisition cost description

This appendix will describe the cost elements of the acquisition costs that are not discussed in the report.

E1. Finding a customer

The cost for finding a customer depends on the number of hours spent on finding a customer and the hourly rate of the manager. It is assumed that the service department does not spend much extra time on finding a customer compared to the sales department, this is because they know the existing customers very well and can easily find out if the existing customers are interested in the system. For the sales department, the time spent on finding a new customer can vary per project. Sometimes a new customer is found quickly, but other times a potential customer can have much interest, but decides not to buy the system at the end. In this last case, a sales person can have invested already a significant amount of time in this customer, which is lost if the potential customer does not buy the system. The model is used for the situation where a potential customer is already found, and thus the hours spent on the project are also known.

\[ C_{FC} = f \cdot T_{FC} \cdot W_{CS} + (1 - f) \cdot W_{CS} \cdot T_{FCS} \]

where

\[ T_{FC} \] = Time spent by a sales manager for finding a new customer (in hours).
\[ T_{FCS} \] = Time spent by a Service department for finding a new customer (in hours).
\[ W_{CS} \] = The hourly rate of a manager from the customer center (euros/hour).
\[ f \] = Binary indicator variable of whether service department finds a customer for system. Zero indicates that service department did find a customer and one indicates that the sales department must search for a customer.

E2. Buy-back costs

The buy-back costs consist of the time that the customer center spends on creating a purchase strategy, negotiation with the customer and the wage of the customer center. Also, the buy-back price for the system of the customer must be considered. The back price is based on the value of the used system minus the value of the contractual future cash flows. The value of the contractual future cash flows is different for each customer. The value of the used system depends on the market value of the system, i.e. does Vanderlande believes they can easily sell the system and what would the customer pay for the system. This is dependent on the state of the system and the demand for such a system. This is value that Vanderlande should determine themselves for each system.

\[ C_{BB} = (T_{PS} + T_{Neg}) \cdot W_{CS} + BBP \]

\[ BBP = V_m - V_{fcf} \]

where

\[ T_{PS} \] = Time spend on creating a purchase strategy (in hours).
\[ T_{Neg} \] = Time spend on negations with the client (in hours).
\[ BBP \] = The buy-back price for the system (in euros).
\( V_m \) = The market value of the system (in euros).

\( V_{f/cf} \) = The net present value of the future cash flow that are contractual committed for the system (in euros).

### E3. Site work at new customer

The cost for site work at new customer is divided into three different cost elements: assembly, testing, and travel. This cost element is the same for new system of Vanderlande and therefore based on the pricing method of Vanderlande. As described in section 4.12, the assembly process is split into three different activities. These activities lead to the following costs: cost for mechanical installation, electrical installation costs, and the costs for software installation. The costs for these three activities consist of the time the activity takes and the hourly rate of the employee that executes the activity. The hourly rate for mechanical installation and electrical installation are the same, but for the software installation it is different. Also, the time durations of all activities are different, but they are all dependent on the size of the system. The cost for testing is also dependent on the time duration of the activity and the hourly rate of a service engineer. In this case, also the time duration is dependent on the size of the system. At last, travel cost for the employees included in the total cost for site work at the new customer’s location. It is assumed that everyone works eight hours a day and everyone travels alone to the location of the new customers. The travel cost consists of the number of times someone needs to travel, the time duration of the travel, the compensation per kilometer and the hourly rate of the person that is traveling.

\[
C_{SWN} = C_{Assembly} + C_{Testing} + C_{travel_{swn}}
\]

\[
C_{Assembly} = C_{SA} + C_{IM} + C_{IE} + C_{IS}
\]

\[
C_{Testing} = T_{Testing} * W_{service\_eng}
\]

\[
C_{SA} = T_{SA} * W_{supervisor}
\]

\[
C_{IM} = T_{IM} * W_{employee}
\]

\[
C_{IE} = T_{IE} * W_{employee}
\]

\[
C_{IS} = T_{IS} * W_{software}
\]

\[
C_{travel_{swn}} = C_{LT} * [(T_{SA} + T_{IM} + T_{IE} + T_{IS}) / TT_{sw}]
\]

Where

- \( C_{IM} \) = Cost related to the mechanical installation for the used system (in euros).
- \( C_{IE} \) = Cost related to the electrical installation for the used system (in euros).
- \( C_{IS} \) = Cost related to the software installation for the used system (in euros).
- \( C_{travel_{swn}} \) = Cost related to the travels that the employees make for the site work at the new customer (in euros).
- \( C_{SA} \) = Cost related to the supervision during the assembly process (in euros).
- \( T_{SA} \) = Time duration of the supervision during the complete process (in hours)
- \( T_{IM} \) = Time duration of the mechanical installation of the system (in hours).
- \( T_{IE} \) = Time duration of the electrical installation of the system (in hours).
- \( T_{IS} \) = Time duration of the software installation of the system (in hours).
- \( W_{software} \) = Hourly rate of a software installer (in euros per hour).
E4. Master-data

The cost for creating the master-data for the new customer is build up by the time duration of creating the master-data and the hourly rate of the service engineer doing it. In case nothing is changed in the system, the system can be easily copied from the old customer to the new customer in the database of Vanderlande. It is assumed that the data in the data-base is correct for the old customer. However, when new components should be added in the database, this will influence the time duration. New components have to be added because the lay-out of the system is changed, or some components are end-of-life and are substituted by new components. Each item that must be processed, is added in the database by hand which costs a fixed number of minutes. For this cost element, a distinction is made between the set of components of the used system that Vanderlande got back and the set of components of the used system that Vanderlande will deliver to the new customer. The sum of

\[ C_{MD} = T_{MD} * W_{SE} \]
\[ T_{MD} = ms * (U + \sum_{i=1}^{d} EOL_i) \]

where

- \( T_{MD} \) = Time for creating master-data for the used system (in hours).
- \( W_{SE} \) = Hourly rate of service engineer (in euros per hour).
- \( U \) = Number of new components that must be added to the used system by change in lay-out.
- \( ms \) = The duration of replacing one component in the master-data (in hours).
- \( EOL_i \) = Binary variable whether a component type \( i \) is EOL. Zero means that the component type is not EOL and one means that the component is EOL.
Appendix F: Other reprocessing cost descriptions

This appendix will describe the cost elements of the reprocessing cost element that are not discussed in the report.

F1. Research

Research cost are all costs related to determining whether a used system is suitable for reuse or not. This means that the activities in the inspection process and evaluation process, as described in section 4.2 and 4.3, result into two cost elements: inspection costs and evaluation costs. Inspection costs consist of the time duration of the tests and writing the report, and the hourly rate of the service engineer executing the tests. It is assumed that tests and the time duration stay the same no matter what kind of system. Also, the size of the system is not relevant. The costs for evaluation consist of the number of hours that a sales manager and a service manager have to discuss, the time spent on searching for internal information of the system, and the hourly rates of the managers.

\[
C_{\text{Research}} = C_{\text{inspection}} + C_{\text{eval}} + C_{\text{travel research}}
\]

\[
C_{\text{inspection}} = T_{\text{inspecting}} \times W_{SE}
\]

\[
C_{\text{eval}} = (T_{\text{discuss}} \times 2 + T_{\text{searching}}) \times W_{CS}
\]

\[
C_{\text{travel research}} = C_{ST}
\]

Where

\[C_{\text{inspection}}\] = Cost related to the inspection of the system (in euros).
\[C_{\text{eval}}\] = Cost related to the evaluation of the system (in euros).
\[C_{\text{travel research}}\] = Travel cost of the employees to the old customer for research (in euros).
\[T_{\text{inspecting}}\] = Time spent on inspecting the system (in hours).
\[T_{\text{discuss}}\] = Time spent on discussing the system (in hours).
\[T_{\text{searching}}\] = Time spent on searching internal information of the system (in hours).

F2. Transport

The total transport cost is dependent on whether the system is transported from customer A to customer B directly, or that the system is transported from customer A to a warehouse and from that warehouse to customer B. For this model, it is assumed that the transport can be done with trucks and that the range will be 250 km for the headquarters in Veghel. Within this range, the cost for transport of one truck is always approximately the same. Vanderlande outsources transport to external parties. Because transportation is a very competitive market, the prices of the external parties are all close to each other. Therefore, a fixed cost for transport can be used. The number of trucks can be calculated by Vanderlande, the Pricing department has a tool for that.

\[
C_{\text{Transport}} = (1 - Z) \times C_{\text{Tr.direct}} + Z \times C_{\text{Tr.indirect}}
\]

\[
C_{\text{Tr.direct}} = K \times TC
\]

\[
C_{\text{Tr.indirect}} = K \times 2 \times TC
\]

Where

\[C_{\text{Transport}}\] = Cost related to transport of the system (in euros).
\[C_{\text{Tr.direct}}\] = Cost of transport directly from customer A to B (in euros).
\[C_{\text{Tr.indirect}}\] = Cost of transport from customer A to warehouse, and to customer B (in euros).
Z = Binary variable that indicates with one, whether an external warehouse is used and with zero that the direct route between customer A and B is be chosen.

**F3. Storage**

The storage costs are based on the number of square meters of the system it will occupy in a warehouse and the duration the system is stored. It is assumed that when storage is needed, the system will be stored for half a year because it is assumed that new customer can be found within a half year. Further the rent should be paid in advance. The system can be stored in a warehouse, as it is packed for transport, thus the number of trucks necessary indicates the number of square meter necessary. Vanderlande always uses 40 feet trucks, which equals 27.85m². The price for storage is the same whether the storage is at an external warehouse, at the customer’s location or at a warehouse of Vanderlande.

\[
C_{storage} = (1 - ST) \times K \times 27.85m^2 \times sc
\]

where

- \( sc \) = Cost for storage for half a year per square meter (euros per square meter per half year).
Appendix G: All defined Input parameters for the LCC model

In table 7 all input parameters are shown with the related cost bucket, description, distinction and method of finding the value of the parameter. The table is classified on distinction and on method of finding.

<table>
<thead>
<tr>
<th>Cost bucket</th>
<th>Parameter</th>
<th>Description</th>
<th>Distinction</th>
<th>Method of finding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replacement</td>
<td>$th$</td>
<td>Throughput through the system</td>
<td>Case dependent known parameter</td>
<td>Vanderland &amp; customer</td>
</tr>
<tr>
<td>Replacement</td>
<td>$shi$</td>
<td>Average length of a shift</td>
<td>Case dependent known parameter</td>
<td>Vanderland &amp; customer</td>
</tr>
<tr>
<td>Finding</td>
<td>$f$</td>
<td>Binary variable of whether service department finds a customer.</td>
<td>Case dependent known parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Replacement</td>
<td>$cap$</td>
<td>Capacity of the system</td>
<td>Case dependent known parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Finding</td>
<td>$T_{FC}$</td>
<td>Time spend by a sales manager for finding a new customer</td>
<td>Case dependent known parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Finding</td>
<td>$T_{FCS}$</td>
<td>Time spend by a Service department for finding a new customer</td>
<td>Case dependent known parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>$k_i$</td>
<td>The number of items that are present in the system of i</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Engineering</td>
<td>$g$</td>
<td>The age of the used system</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Engineering,</td>
<td>$i$</td>
<td>component index of the used system</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>master-data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replacement</td>
<td>$X_i$</td>
<td>The state of the component in operation hours at period n</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Buy back</td>
<td>$V_m$</td>
<td>The market value of the system</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Engineering,</td>
<td>$d$</td>
<td>Total number of different components in the used system.</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>master-data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$SS$</td>
<td>Size of the old system at the old customer</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Transport</td>
<td>$K$</td>
<td>The number of trucks necessary to calculate for transport</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Spare parts</td>
<td>$r_s$</td>
<td>yearly percentage paid for storing the spare-parts</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande &amp; customer</td>
</tr>
<tr>
<td>Spare parts</td>
<td>$k_{i,c}$</td>
<td>The amount of spare-parts of component i that are desired by customer c</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande &amp; customer</td>
</tr>
<tr>
<td>Storage</td>
<td>$ST$</td>
<td>Binary variable if storage is needed</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande &amp; customer</td>
</tr>
<tr>
<td>Transport</td>
<td>$Z$</td>
<td>Binary indicator whether external warehouse is needed</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande &amp; customer</td>
</tr>
<tr>
<td>Inspections</td>
<td>$r$</td>
<td>Nominal interest rate</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande &amp; customer</td>
</tr>
<tr>
<td>Replacement</td>
<td>$w$</td>
<td>Number of working days within a year</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande &amp; customer</td>
</tr>
<tr>
<td>Replacement</td>
<td>$a$</td>
<td>Average number of operation hours a day for the system</td>
<td>Case dependent unknown parameter</td>
<td>Vanderlande &amp; customer</td>
</tr>
<tr>
<td>Spare parts</td>
<td>$d'$</td>
<td>Total number of different</td>
<td>Case dependent</td>
<td>Vanderlande &amp;</td>
</tr>
</tbody>
</table>
components in the adjusted system | unknown parameter | customer
--- | --- | ---
operations | $q$ | number of needed personnel per day. | Case dependent unknown parameter | Vanderlande & customer
Buy back | $V_{f_{cf}}$ | The net present value of the future cashflow with old customer | Case dependent unknown parameter | Vanderlande & customer
Engineering & SWN | $SS'$ | Size of the system that will be delivered at the new customer | Decision variable | Vanderlande & customer
Master-data | $U$ | Number of new components | Decision variable | Vanderlande & customer
Project management | $cl$ | Binary variable whether components are cleaned | Decision variable | Vanderlande & customer
Project management | $ex$ | Binary variable whether the system is extended | Decision variable | Vanderlande & customer
Reconditioning | $REC_i$ | Binary indicator whether component $i$ is reconditioned | Decision variable | Vanderlande & customer
Reconditioning | $rp$ | Binary variable whether components are replaced | Decision variable | Vanderlande & customer
Reprocessing | $I$ | Number of visits per year | Decision variable | Vanderlande & customer
Engineering | $W_{Eng}$ | The hourly rate of an engineer | General known parameters | Vanderlande
Finding | $W_{CS}$ | The hourly rate of a sales manager from the customer center | General known parameters | Vanderlande
Project management | $W_{PM}$ | The hourly rate of a project manager | General known parameters | Vanderlande
Site work at new customer | $W_{employee}$ | Hourly rate of an operation employee | General known parameters | Vanderlande
Site work at new customer | $W_{software}$ | Hourly rate of a software installer | General known parameters | Vanderlande
Site work at new customer | $W_{supervisor}$ | Hourly rate of the supervisor | General known parameters | Vanderlande
Master-data, Research | $W_{SE}$ | Hourly rate of service engineer | General known parameters | Vanderlande
Inspections | $W_{inspector}$ | The hourly rate of the inspector | General known parameters | Vanderlande
Power | $C_{kwh}$ | Cost for one kilowatt-hour | General known parameters | Vanderlande
Transport | $TC$ | Cost for one truck within the assumed range | General known parameters | Vanderlande
Replacement | $C_{ST}$ | Cost of short trip | General known parameters | Vanderlande
Replacement | $C_{LT}$ | Cost of Long trip | General known parameters | Vanderlande
Project management | $TT_{PM}$ | Total work time necessary to make one trip for project manager | General known parameters | Vanderlande
Engineering | $TT_{eng}$ | Total time necessary to make one trip for an engineer | General known parameters | Vanderlande
Site work | $TT_{sw}$ | Total time necessary to make one trip for site work | General known parameters | Vanderlande
Replacement | $fe$ | Percentage of extra cost of preventive maintenance | General unknown parameters | Assumption
Storage | $sc$ | Cost for storage for half a year per square meter | General unknown parameters | Assumption
Master-data | $ms$ | The duration of replacing one | General unknown parameters | Assumption
<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Description</th>
<th>Type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>$T_{EN}$</td>
<td>Hours engineering new system hours per meter</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Site work at new customer</td>
<td>$T_{IM}$</td>
<td>Time duration mechanical installing</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Site work at new customer</td>
<td>$T_{IE}$</td>
<td>Time duration electrical installing</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Site work at new customer</td>
<td>$T_{IS}$</td>
<td>Time duration for software installing</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Site work at new customer</td>
<td>$T_{Testing}$</td>
<td>Time duration of testing system</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Site work at new customer</td>
<td>$T_{SA}$</td>
<td>Time duration of the supervision</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>$CL$</td>
<td>Constant for cleaning hours per meter system</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>$ext$</td>
<td>Constant for extending cost per meter system</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Project management</td>
<td>$T_{PMCL}$</td>
<td>Time spend by a manager to arrange cleaning</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Project management</td>
<td>$T_{PMEX}$</td>
<td>Time spend by a manager to arrange extension of the system</td>
<td>System type dependent known parameters</td>
<td>Analyse CAP8</td>
</tr>
<tr>
<td>Inspections</td>
<td>$T_{inspecting}$</td>
<td>Time spent on inspecting the system</td>
<td>System type dependent known parameters</td>
<td>Case study</td>
</tr>
<tr>
<td>Engineering, Master-data</td>
<td>$EOL_i$</td>
<td>Binary variable whether a component i is EOL</td>
<td>System type dependent known parameters</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>$PR_i$</td>
<td>Production price for component i</td>
<td>System type dependent known parameters</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Inspections</td>
<td>$T_{inspection}$</td>
<td>Time spent on one maintenance inspection</td>
<td>System type dependent known parameters</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Replacement</td>
<td>$TR_i$</td>
<td>Time spent on replacing component i</td>
<td>System type dependent known parameters</td>
<td>Vanderlande</td>
</tr>
<tr>
<td>Replacement</td>
<td>$dt_i$</td>
<td>Downtime caused by failure of component i</td>
<td>System type dependent known parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Buy back</td>
<td>$T_{PS}$</td>
<td>Time spend on creating a purchase strategy</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Buy back</td>
<td>$T_{Neg}$</td>
<td>Time spend on negotiations with the client</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Engineering</td>
<td>$ea$</td>
<td>Constant for engineering safety hours per year</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Engineering</td>
<td>$eoc$</td>
<td>Constant for replacing old components for engineering</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Project management</td>
<td>$T_{PM}$</td>
<td>Time that a project manager spends on the project</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Replacement</td>
<td>$CDT_i$</td>
<td>Cost of down-time when component i fails</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>$A_{EOL}$</td>
<td>Age when a system is end-of-life</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Research</td>
<td>$T_{discuss}$</td>
<td>Time spent on discussing the system</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Research</td>
<td>$T_{searching}$</td>
<td>Time spent on searching internal information of the system</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Replacement</td>
<td>$m$</td>
<td>Number of operation hours between periods for the system</td>
<td>System type dependent unknown parameters</td>
<td>Assumption</td>
</tr>
<tr>
<td>Replacement</td>
<td>$cm$</td>
<td>Fixed price for each parcel that</td>
<td>System type dependent</td>
<td>Assumption</td>
</tr>
<tr>
<td>Parameter</td>
<td>Formula</td>
<td>Description</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>---------</td>
<td>-------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$d_{sh}$</td>
<td>Number of hours for supervising the disassembly per meter</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$d_{mh}$</td>
<td>Number of hours for mechanical disassembly per meter</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$d_{eh}$</td>
<td>Number of hours for electrical disassembly per meter</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$s_{p}$</td>
<td>Number of hours for supervising the packing process per meter</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$p_{t}$</td>
<td>Number of hours for packing the system per meter</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$p_{m}$</td>
<td>Packing material cost per meter system</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$d_{oc}$</td>
<td>Number of hours for documentation the system per meter</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Site work old</td>
<td>$C_{tools}$</td>
<td>Cost related to tools</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Replacement</td>
<td>$p_{X,Y}$</td>
<td>Probability of component with state X surviving the next period</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Replacement</td>
<td>$L_{i}$</td>
<td>The last possible state of a component before failure</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>$P_{C}$</td>
<td>Power consumption (in watts).</td>
<td>System type dependent unknown parameters</td>
<td></td>
</tr>
</tbody>
</table>

Case study
**Appendix H: Input parameter known by internal information**

This appendix describes what values are used for the input parameters that are determined by internal information of Vanderlande. Table 8 shows all input parameters for which the value can be determined by internal information of Vanderlande. Further Table 8 indicates what the value is, and how it is determined.

**Remark that because of confidentiality these values in the Value column are fictive.**

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary variable whether a component i is EOL.</td>
<td>Does not apply</td>
<td>Does not apply</td>
<td>This information can be found in SmarTeam.</td>
</tr>
<tr>
<td>Binary indicator variable of whether service department finds a customer for the system.</td>
<td>Does not apply</td>
<td>Does not apply</td>
<td>This value is dependent on the case. When the LCC model is constructed for a project, a customer has already been found.</td>
</tr>
<tr>
<td>The hourly rate of a manager from Customer center.</td>
<td>55</td>
<td>Euros per hour</td>
<td>CAP8</td>
</tr>
<tr>
<td>The hourly rate of a project manager.</td>
<td>66</td>
<td>Euros per hour</td>
<td>CAP8</td>
</tr>
<tr>
<td>The hourly rate of an operation employee.</td>
<td>26</td>
<td>Euros per hour</td>
<td>CAP8</td>
</tr>
<tr>
<td>The hourly rate of a software installer.</td>
<td>53</td>
<td>Euros per hour</td>
<td>CAP8</td>
</tr>
<tr>
<td>The hourly rate of a supervisor.</td>
<td>51</td>
<td>Euros per hour</td>
<td>CAP8</td>
</tr>
<tr>
<td>The hourly rate of a service engineer.</td>
<td>54</td>
<td>Euros per hour</td>
<td>CAP8</td>
</tr>
<tr>
<td>Power consumption.</td>
<td>Does not apply</td>
<td>Kilowatt</td>
<td>This value is case dependent. Depending on the size, speed and type of driver in the system, a number of kilowatt is necessary. Information about this can be find in the Product database.</td>
</tr>
<tr>
<td>The number of items that are present in the system which belong to component type i.</td>
<td>Does not apply</td>
<td>Does not apply</td>
<td>This value is case dependent, but this information should be known within the master-data of the system.</td>
</tr>
<tr>
<td>Production price for components.</td>
<td>Does not apply</td>
<td>Does not apply</td>
<td>Known within SmarTeam.</td>
</tr>
<tr>
<td>Total work time necessary to make one trip for a project manager.</td>
<td>160</td>
<td>Hours per trip</td>
<td>Pricing department</td>
</tr>
<tr>
<td>Total work time necessary to make one trip for an engineer.</td>
<td>400</td>
<td>Hours per trip</td>
<td>Pricing department</td>
</tr>
<tr>
<td>Total work time necessary</td>
<td>50</td>
<td>Hours</td>
<td>Pricing department</td>
</tr>
</tbody>
</table>
to make of one trip for employees that do site work.

<table>
<thead>
<tr>
<th>Cost for a Long trip.</th>
<th>760</th>
<th>Euros</th>
<th>Pricing department</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>0.08</td>
<td>Hours</td>
<td>Pricing department</td>
</tr>
</tbody>
</table>
Appendix I: Input parameters determined by CAP8 analysis

Results of the CAP8 analysis summarized in Table 9.

Remark that because of confidentiality these values are fictive.

Table 9: Results CAP8 analysis

<table>
<thead>
<tr>
<th>Case/ Cost activity</th>
<th>60 meters</th>
<th>100 meters</th>
<th>Extra 40</th>
<th>Cleaning 60 meter</th>
<th>Variable hours per meter</th>
<th>Fixed hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering (hours)</td>
<td>428</td>
<td>559</td>
<td></td>
<td></td>
<td>3,275</td>
<td>231,500</td>
</tr>
<tr>
<td>Mechanical installing (hours)</td>
<td>628</td>
<td>1.035</td>
<td></td>
<td></td>
<td>10,175</td>
<td>17,500</td>
</tr>
<tr>
<td>Electrical installing (hours)</td>
<td>164</td>
<td>250</td>
<td></td>
<td></td>
<td>2,15</td>
<td>35</td>
</tr>
<tr>
<td>Software installing (hours)</td>
<td>216</td>
<td>228</td>
<td></td>
<td></td>
<td>0,3</td>
<td>198</td>
</tr>
<tr>
<td>Testing (hours)</td>
<td>94</td>
<td>144</td>
<td></td>
<td></td>
<td>1,25</td>
<td>19</td>
</tr>
<tr>
<td>Supervising (hours)</td>
<td>169</td>
<td>279</td>
<td></td>
<td></td>
<td>0,25</td>
<td>154</td>
</tr>
<tr>
<td>Cleaning (euros)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13586</td>
<td>226,43</td>
</tr>
<tr>
<td>Extending (euros)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>88.233</td>
<td>2205,83</td>
</tr>
<tr>
<td>Manager cleaning (hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Manager extension (hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56</td>
<td>56</td>
</tr>
</tbody>
</table>

The general formula for the input parameters described in Table 9 is: $\text{cost activity} = \text{size of the system} \times \text{variable hours per meter} + \text{fixed hours}$.

The lay-out of Table 8 is not an exact representation of the lay-out of CAP8, because CAP8 sometimes provides a more detailed distinction of more activities, which are added here together for clarity and simplicity reasons. The cost activities which are represented differently in CAP8 than in Table 8 are:

- **Engineering hours**: consist of the following cost elements of CAP8: Project leader engineering project, mechanical engineering en mechanical specifications.

- **Software installing**: consists of the following cost element of CAP8: Project leader Engineering software, function specification software, controls hardware specification, FSC programming and SCADA programming.

- **Testing**: consists of the following cost elements in CAP8: Site engineer and commissioning, FSC commissioning and SCADA commissioning.

CAP8 also provided insight in the cost for transportation and travel expenses. Transportation cost per truck are 750 euros. Vanderlande does not use a standard transportation company, but for every project they search for the lowest bidder. With the changing fuel prices, the real prices can differ a bit. However, the Pricing department chose for fixed value 750 euro per truck load, based on their experiences. For travel expenses, Vanderlande identified who (function related) makes short trips and who needs to make long trips.
Appendix J: pilot projects

This appendix will provide information about the lay-outs of the systems installed at Customer 1 and Customer 2. Also, more information will be provided about the cost of the pilots.

Lay-out Customer 1

Figure 29: Lay-out Customer 1

Lay-out Customer 2

Figure 30: Lay-out Customer 2

Cost of pilots

The cost of the pilot that are documented are shown in Table 10.

Remark that because of confidentiality the values for these cases are scaled and thus fictive.

Table 10: Cost of pilot

<table>
<thead>
<tr>
<th>Activity name</th>
<th>Number of employees</th>
<th>Number of hours</th>
<th>Total cost</th>
<th>Hours per meter</th>
<th>Cost per meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supervisor (hours)</td>
<td>1</td>
<td>50</td>
<td>-</td>
<td>0,56</td>
<td>-</td>
</tr>
<tr>
<td>Mechanical disassembly (hours)</td>
<td>4</td>
<td>60</td>
<td>-</td>
<td>3,37</td>
<td>-</td>
</tr>
<tr>
<td>Electrical disassembly (hours)</td>
<td>1</td>
<td>15</td>
<td>-</td>
<td>0,17</td>
<td>-</td>
</tr>
<tr>
<td>Freight and packing (hours)</td>
<td>2</td>
<td>30</td>
<td>-</td>
<td>0,61</td>
<td>-</td>
</tr>
<tr>
<td>Packing material (€)</td>
<td>-</td>
<td>-</td>
<td>750</td>
<td>-</td>
<td>12,64</td>
</tr>
<tr>
<td>Tools (€)</td>
<td>-</td>
<td>-</td>
<td>550</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Inspecting (hours)</td>
<td>1</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The cost for supervising still needs to be determined. This cost was not split into supervising the disassembly part and the packing part. The disassembly process took 75 hours and the freight and packing process took 18 hours, the supervisor hours are divided with the same ratio. This results into 40 hours for disassembly and 10 hours freight and packing. Calculating the hours per meter is 0,45 hours per meter and 0,11 hours per meter.

The cost for documentation was not documented properly and still needs to be determined. In this pilot the documentation was done by a trainee. He claimed that the documentation took 2 hours a day. The total duration time was 93 hours. According to the Project Manager, the employees worked 10 hours a day. This results into a 0,21 hour per meter.

The number of hours an inspection takes of this system took 8 hours, which is independent of the systems length. All the activities that took place during this inspection, are also the activities that should take place for inspecting an SPO to see whether the SPO is fit for reuse. So 8 hours can be used as value for the parameter.
Appendix K: Description SPO sections

In this section, all the relevant components of the SPO are mentioned divided per section so one can have a better idea what component type does what. Section A: The entry of the SPO, the place where handling units enter the SPO. This section consists of a charge belt and an end-take-up (ETU). The handling units are loaded on the SPO by the charge belt, which is a separate belt in front of the SPO. The ETU is responsible for the return of the carriers from the bottom deck to the upper deck of the SPO, on which the handling units are placed. The return is done by a rotating rod which guides the carriers.

Table 11: Components section A

<table>
<thead>
<tr>
<th>Pos. Nr.</th>
<th>Item description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Bearing Block flange 1</td>
</tr>
<tr>
<td>A2</td>
<td>PPI Sensor Assy</td>
</tr>
<tr>
<td>A3</td>
<td>Tension wheel</td>
</tr>
<tr>
<td>A4</td>
<td>Timing belt 1200</td>
</tr>
<tr>
<td>A5</td>
<td>Pulley TB TL 1</td>
</tr>
<tr>
<td>A6</td>
<td>Pulley TB TL 2</td>
</tr>
<tr>
<td>A7</td>
<td>Block pillow</td>
</tr>
<tr>
<td>A8</td>
<td>Timing belt 920</td>
</tr>
<tr>
<td>A9</td>
<td>Shaft ETU combination incl. wheels, taperlock, keys</td>
</tr>
<tr>
<td>A10</td>
<td>Pulley TB 3</td>
</tr>
<tr>
<td>A11</td>
<td>Prox. Switch 1</td>
</tr>
<tr>
<td>A12</td>
<td>Prox. Switch 2</td>
</tr>
<tr>
<td>A13</td>
<td>SCU hardware and software</td>
</tr>
<tr>
<td>A14</td>
<td>SPO Charge belt</td>
</tr>
<tr>
<td>A15</td>
<td>Bearing Block Flange 2</td>
</tr>
<tr>
<td>A16</td>
<td>Belt 1</td>
</tr>
<tr>
<td>A17</td>
<td>Antistatic brush connector 1</td>
</tr>
</tbody>
</table>

Section B: This section is responsible for getting the divert shoes to the right side of the sorter at the beginning of the SPO. The divert shoes are used to push the products of the carrier. If the product must leave the belt at the left side, the shoe will be placed on the right side, and the other way around. A pre-sort or a shoe merge is responsible for this job. The difference between these two parts is the fact that a pre-sort can be used to place the shoes on the left and on the right of the carrier, and a shoe merge can only place the shoes on one side of the carrier. A shoe merge is thus used when all the handling units must leave the sorter on one side.

Table 12: Components section B

<table>
<thead>
<tr>
<th>Pos. Nr.</th>
<th>Item description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Merge right 30º</td>
</tr>
<tr>
<td></td>
<td>Merge left 30º</td>
</tr>
<tr>
<td>B2</td>
<td>Divert right 30º</td>
</tr>
<tr>
<td></td>
<td>Divert left 30º</td>
</tr>
<tr>
<td>B3</td>
<td>Merge right 20º</td>
</tr>
<tr>
<td></td>
<td>Merge left 20º</td>
</tr>
</tbody>
</table>
Section C: The actual sortation of the handling units is done in section C. This section consists of multiple switch-frames, carriers and chains. The carriers are from aluminum which carry the handling units. Divert shoes are attached to the carriers, which are responsible for pushing the product of the carriers by sliding over the carrier. These divert shoes are also guided by the switch-frame which are placed below the upper deck. The switch-frames are steel plates with slots and they are placed at every exit lane. A metal pin of the divert-shoe follows the slot in the switch-frames. Divert-switches, crossings and divert-mergers are installed in the switch-frames to control what slots should be followed. If the exit lane is not the right exit lane for the parcel, then the divert-switch allows the divert-shoes to go straight instead of going to the exit lane. The carriers are attached to two chains which are used to move the carriers.

Table 13: Components section C

<table>
<thead>
<tr>
<th>Pos. Nr.</th>
<th>Item description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Subassy Carrier</td>
</tr>
<tr>
<td>C2</td>
<td>Divert shoe</td>
</tr>
<tr>
<td>C3</td>
<td>Special screw</td>
</tr>
<tr>
<td>C4</td>
<td>Standard Side plate</td>
</tr>
<tr>
<td></td>
<td>Brush for SPO, left</td>
</tr>
<tr>
<td></td>
<td>Brush for SPO, right</td>
</tr>
<tr>
<td>C5</td>
<td>Special/optional Subassy Side Plate Right (shown) Subassy Side Plate Left Subassy Side Plate Right Brush Subassy Side Plate Left Brush</td>
</tr>
<tr>
<td>C6</td>
<td>Ring Ret Shaft 1</td>
</tr>
<tr>
<td>C7</td>
<td>Special Washer</td>
</tr>
<tr>
<td>C8</td>
<td>Subassy Guiding Wheel</td>
</tr>
<tr>
<td>C9</td>
<td>Pair of detection blocks (right shown) (For plastic side plate)</td>
</tr>
<tr>
<td>C10</td>
<td>Divert right 20°</td>
</tr>
<tr>
<td></td>
<td>Divert right 30°</td>
</tr>
<tr>
<td></td>
<td>Divert left 20°</td>
</tr>
<tr>
<td></td>
<td>Divert left 30°</td>
</tr>
<tr>
<td>C11</td>
<td>Crossing 20° SPO</td>
</tr>
<tr>
<td></td>
<td>Crossing 30° SPO</td>
</tr>
<tr>
<td>C12</td>
<td>Merge right 20°</td>
</tr>
<tr>
<td></td>
<td>Merge right 30°</td>
</tr>
<tr>
<td></td>
<td>Merge left 20°</td>
</tr>
<tr>
<td></td>
<td>Merge left 30°</td>
</tr>
<tr>
<td>C13</td>
<td>Bridge-profile assy</td>
</tr>
<tr>
<td>C14</td>
<td>Nord-lock ring</td>
</tr>
<tr>
<td>C15</td>
<td>-</td>
</tr>
<tr>
<td>C16</td>
<td>Divert shoe</td>
</tr>
<tr>
<td>C17</td>
<td>Lock plate</td>
</tr>
<tr>
<td>C18</td>
<td>Washer wide</td>
</tr>
<tr>
<td>C19</td>
<td>Ring ret shaft 2</td>
</tr>
<tr>
<td>C20</td>
<td>Adaptor for prod. carrier link</td>
</tr>
<tr>
<td>C21</td>
<td>Wheel with adapter</td>
</tr>
</tbody>
</table>
Section D: The end of the SPO. In section D, a drive is placed which is responsible for the chains to move. Handling units that are not sorted on the SPO must leave the SPO at the end, and will be placed on a discharge belt. The discharge belt is mechanical connected to the SPO, so the speed of the belt is the same as the speed of the carriers. This same principle is also used for the charge belt and the ETU in section A. Also, an oil pump is present in this section. The oil pump makes sure that the chain has enough oil on it to operate smoothly.

Table 14: Components section D

<table>
<thead>
<tr>
<th>Pos. Nr.</th>
<th>Item description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Motor reducer</td>
</tr>
<tr>
<td>D2</td>
<td>Special tension BBlock</td>
</tr>
<tr>
<td>D3</td>
<td>Assy drive shaft SPO2</td>
</tr>
<tr>
<td>D4</td>
<td>Timing belt 2</td>
</tr>
<tr>
<td>D5</td>
<td>Assy end wheel support drive SPO</td>
</tr>
<tr>
<td>D6</td>
<td>Pulley TB TL 4</td>
</tr>
<tr>
<td>D7</td>
<td>BBlock pillow</td>
</tr>
<tr>
<td>D8</td>
<td>Timing belt 3</td>
</tr>
<tr>
<td>D9</td>
<td>Pulley TB TL 5</td>
</tr>
<tr>
<td>D10</td>
<td>Pulley TB TL 6</td>
</tr>
<tr>
<td>D11</td>
<td>Pulley TB TL 7</td>
</tr>
<tr>
<td>D12</td>
<td>Bearing Block Flange 3</td>
</tr>
<tr>
<td>D13</td>
<td>Drive pulley</td>
</tr>
<tr>
<td>D14</td>
<td>Take up pulley 1</td>
</tr>
<tr>
<td>D15</td>
<td>Take up pulley 2</td>
</tr>
<tr>
<td>D16</td>
<td>End pulley assy</td>
</tr>
<tr>
<td>D17</td>
<td>Belt tracking unit</td>
</tr>
<tr>
<td>D18</td>
<td>Belt 2</td>
</tr>
<tr>
<td>D19</td>
<td>Driven roller (Belt tracking unit)</td>
</tr>
<tr>
<td>D20</td>
<td>Bearing ball 1</td>
</tr>
<tr>
<td>D21</td>
<td>Bearing ball 2</td>
</tr>
<tr>
<td>D22</td>
<td>Slack chain detection</td>
</tr>
<tr>
<td>D23</td>
<td>Oilpump +conn. +varistor</td>
</tr>
<tr>
<td>D24</td>
<td>Tension wheel</td>
</tr>
<tr>
<td>D25</td>
<td>Antistatic brush connector 2</td>
</tr>
</tbody>
</table>

Section E: The last section, consists of multiple safety devices and controls to operate the SPO. The SPO has multiple safety devices integrated to protect the sorter in case of an incident. The first one is the missing pin detector. The diverts shoes have pin on the bottom which breaks when something is wrong, for example when the chain is breaks or when the carrier-mat is not fully closed after operations. The second safety device is the shift chain detector, which detects if the chain jumped a tooth at the entry section, because of a dirty chain. The third safety device is the slack chain detector, which detects if the chain tension is too low. The fourth safety device is the divert switch healthy, which give status feedback of every divert switch. During every switch moment, the divert
switch monitors the divert action (switch time and angle), sensor signal (checks if duration of signal is correct) and power supply (checks whether a connector is loose or the cable is broken). The last safety device is the safety wedge, which slides broken shoes to a safe position so they don’t harm the SPO.
Appendix L: Background information R&D process

Within a system many different item-numbers are present. Even between different SPO many different item-numbers are used, although the systems look-a-like. This appendix describes in what ways a SPO can differ from other SPO. First the end-of-life of the item-numbers is discussed. Second the physical differences between SPO is discussed.

When an old system returns to Vanderlande, an indication should be made about what components are EOL and what components are almost EOL. Figure 31 describes the life cycle of a component and thus when a component is EOL. The SPO is designed in the R&D phase and tested in the pilot and beta phase. During these two phases, the idea of the system is brought to the market and the service department starts preparing to offer the right services for the system. In the next phase, the active standard, the system is actively promoted and sold. During this phase, the R&D department is still trying to make improvements to the system by modifying certain parts. At one moment, the developments for the systems stop and this will be announced to the customers. In the next phase, full customer life-cycle services, the system is not sold anymore but the current operating systems are still being maintained, patched and modified if necessary. When the system comes in the support and maintenance only phases, no new spare parts can be ordered and the customer has only his own stock of spare parts left. In the last phase, dismantle phase, a customized life-cycle support will be created for each customer and plans for dismantle and a selling of a new product will be discussed.

According to a Product Engineer, the biggest modification that took place is the drive of the switches in the switch-frames. In the oldest version of the SPO, the drivers of this switches are pneumatic and in the newest version the drivers are electric. This change in design, changed the complete lay-out of the SPO. It is assumed that an SPO with pneumatic drivers cannot be updated to an SPO with electric drivers, because too much of the SPO should be changed, which is economically not beneficial. The SPO with pneumatic drivers are now in the full customer life-cycle services phase, while the SPO with electric drivers is in the active standard phase.

Moreover, the SPO with electric drivers got another modification which involves the side plates. First Vanderlande used only side plates made of steel, but now it is also possible to order plastic side...
plates. Depending on the wishes of the customer, new SPO’s will be equipped with steel or plastic side plates. Furthermore, other small modifications have also lead to the change of some item-numbers for components. So, there are a lot of different item-numbers of components that are almost the same. Figure 32 show a summary of the biggest differences between the SPO’s present in the market.

Figure 32: Physical elements in which a SPO can differ from another SPO.
Appendix M: Component type description.

The table below shows all component types that are identified for this research with a focus on failures.

<table>
<thead>
<tr>
<th>Section</th>
<th>Component type</th>
<th>Component-type description</th>
<th>Frequent failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A1</td>
<td>Bearing Block Flange 1</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>A11</td>
<td>Prox.switch 1</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>A12</td>
<td>Prox.switch 2</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>A13</td>
<td>SCU Hardware and Software</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>BE</td>
<td>Belt 3</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>PS</td>
<td>Prox.switch 3</td>
<td>No</td>
</tr>
<tr>
<td>B</td>
<td>B2</td>
<td>Divert pre-sort</td>
<td>Yes</td>
</tr>
<tr>
<td>C</td>
<td>C1</td>
<td>Subassy Carrier</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>C10</td>
<td>Divert sort</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>C11</td>
<td>Crossing</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>C12</td>
<td>Merge</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>C16</td>
<td>Divert Shoe</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>C17</td>
<td>Lock plate</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>C18</td>
<td>Washer wide</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>C21</td>
<td>Wheel with adapter</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td>Side plate</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>Special subassy side plate</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>DS</td>
<td>Divert switch</td>
<td>Yes</td>
</tr>
<tr>
<td>Code</td>
<td>Detail</td>
<td>Status</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>--------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>Guiding angle</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>Merge Block</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>PNE</td>
<td>Pneumatisch</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>TW</td>
<td>Tension wheel</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Wheel</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>WG</td>
<td>wheelguiding</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>BER</td>
<td>Bearing Roller</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>D12</td>
<td>Bearing Block Flange 3</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>D13</td>
<td>Drive pulley</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>D14</td>
<td>Take up pulley 1</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>DP</td>
<td>Drive part</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>MO</td>
<td>Motor</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>TB</td>
<td>timing belt</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>TBP</td>
<td>Timing belt pulley</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>BEA</td>
<td>Bearing</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BESA</td>
<td>Bearing Safety</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BR</td>
<td>Bracket</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>Cover</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>Electrical component</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>FA</td>
<td>Fastener</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
Appendix N: Method to determine correlation

According to the Research methodology for conducting a reliability analysis, as described in 6.4, the correlation between the component types need to be determined. In this appendix the method is discussed how the correlation is determined.

The formulas used to determine correlation between all component types are:

\[
\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \\
\bar{Y} = \frac{1}{n} \sum_{i=1}^{n} Y_i \\
\rho_{\text{cor}} = \frac{n \sum_{i=1}^{n} [(X_i - \bar{X})(Y_i - \bar{Y})]}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}}
\]

Here is \( n \) the number of used component types, \( X_i, Y_i \) are the number of failures at time \( i \). The correlation will check whether the failure of one component is related to the failure of another component. When the values are close to +1 or -1, this indicates that there is strong correlation (Puth et al., 1993). The number of occurrences in a period is taken as input instead of the number of failures, because one failure of a component can lead to multiple failures of another component. Otherwise the results will be misleading. The number of occurrences will be measured in time intervals of 20 days to make sure that any components that failed together, but are not replaced or found at the same time because of a mistake from the engineer or the operational employees, are still together. Because failures do not happen that often, grouping failures at a time interval of 20 days will not give misleading results.

Appendix O: Results correlation

The results of the correlation test are shown in Figure 33. In total, there are four combinations of components that have a possible correlation. The combination with the highest coefficient are PNE and DS with a coefficient of 0,65. Both components interact physical directly with each other but according to a Product Engineer, one is not directly involved in the breakdown of the other.

The second-highest correlation is C18 and C4, with a coefficient of 0,63. Component C18 is not a component that experience any wear but is only replaced when another component, for example C4, needs to be replaced due failure. The same reasoning can be used for the coefficient of 0,55 for the combination of C16 and C17. Component C17 is only replaced due to failure of another component because it needs to be removed to be able to replace component C16. The last potential correlation is DS and C16 with a coefficient of 0,59. This is because DS and C16 are interacting physical with each other and when DS breaks it could damage C16. However, C16 also breaks because of other issues and not only because of a failure of DS.
Figure 33: Correlation results
Appendix P: Reliability functions

This appendix shows all the reliability functions for all component types and the predicted trend lines. The y-axis indicate the reliability and the x-axis indicates the number of operation hours. How the reliabilities are determined is described in 6.4.4. Based on these reliabilities, different trend-lines are fitted, and the one with the highest $R^2$ is chosen. When the $R^2$ is still lower than 0.7, a Weibull fit is tested. When the $R^2$ is higher with the Weibull fit, the Weibull fit is chosen. Otherwise, the other trend-line with the highest $R^2$ is chosen. Notice that in the figures $y = R(k*m)$

\[
y = e^{-\left(\frac{x}{107077.9}\right)^{6.26653}} \\
R^2 = 0.7979
\]

\[
y = e^{-\left(\frac{x}{674572.4}\right)^{1.717718}} \\
R^2 = 0.8915
\]
**A12**

**Equation:**
\[ y = -0.0000064158x + 1.0000000000 \]

**R²:** 0.9013961685

**Graph:**
- Data points for A12
- Linear fit

**A13**

**Equation (Weibull):**
\[ y = e^{-(x/106723.8)^{0.929993}} \]

**R²:** 0.6999

**Graph:**
- Data points for A13
- Weibull fit

**B2**

**Equation:**
\[ y = -0.0000067152x + 1.0000000000 \]

**R²:** 0.9635341761

**Graph:**
- Data points for B2
- Linear fit
BE

\[ y = e^{-0.0000241026x} \]
\[ R^2 = 0.8984226730 \]

BEA

\[ y = -0.0000017676x + 1.0000000000 \]
\[ R^2 = 0.8051841747 \]

BERO

\[ y = -0.0000048135x + 1.0000000000 \]
\[ R^2 = 0.8562267269 \]
**BESA**

\[ y = e^{-0.0000523970x} \]

\[ R^2 = 0.7134387352 \]

**BR**

\[ y = e^{-(x/21508.06)^0.719009} \]

\[ R^2 = 0.8850 \]

**C1**

\[ y = e^{-(x/4946453764)^0.170803381} \]

\[ R^2 = 0.99841 \]
\[ y = -0.0000083678x + 1.0000000000 \]
\[ R^2 = 0.9296681181 \]

\[ y = e^{-0.0000100822x} + 1.0000000000 \]
\[ R^2 = 0.9714971639 \]

\[ y = e^{0.0000051587x} \]
\[ R^2 = 0.9389090472 \]
y = -0.0000067947x + 1.0000000000
R² = 0.9742424607

\[ y = e^{-(x/70235.54)^{4.89818}} \]
R² = 0.8184

\[ y = e^{-(x/176827.7)^{4.027526}} \]
R² = 0.9329
C4
\[ y = e^{-(x/225023,5)^{2,672335}} \]
\[ R^2 = 0,7169 \]

C5
\[ y = e^{-(x/3329516)^{0,362667}} \]
\[ R^2 = 0,921924 \]

CO
\[ y = -0,0000003632x + 1,0000000000 \]
\[ R^2 = 0,7171923733 \]
y = -0.0000084443x + 1.0000000000
\( R^2 = 0.9623005725 \)

y = e^{-0.0000249331x}
\( R^2 = 0.8705627023 \)

y = -0.000107410x + 1.0000000000
\( R^2 = 0.7610815218 \)
\[ y = -0.0000050281x + 1.0000000000 \quad R^2 = 0.9258345371 \]

\[ y = -0.0000122407x + 1.0000000000 \quad R^2 = 0.9353758010 \]

\[ y = -0.0000003525x + 1.0000000000 \quad R^2 = 0.8643065613 \]
FA

\[ y = e^{-(x/431967,7)^{2,204433}} \]

\[ R^2 = 0,7368 \]

MB

\[ y = -0,0000002616x + 1,0000000000 \]

\[ R^2 = 0,8212901338 \]

MO

\[ y = e^{0,0000289128x} \]

\[ R^2 = 0,9336589168 \]
PNE

\[ y = e^{-(x/353969.6)^2 \times 2.849148} \]
\[ R^2 = 0.9333 \]

PS

\[ y = e^{-(x/127402.4)^6 \times 6.240876} \]
\[ R^2 = 0.9005 \]

TB

\[ y = e^{-0.0000748955x} \]
\[ R^2 = 0.9714513088 \]
$y = -0.0000009266x + 1.0000000000$
$R^2 = 0.8130243936$

$y = -0.0000002180x + 1.0000000000$
$R^2 = 0.2784900285$

$y = e^{(\frac{-x}{186320.30})^{2.999748}}$
$R^2 = 0.53439$
$y = -0.0000000819x + 1.0000000000$

$R^2 = 0.9505707843$

$y = e^{-0.0000008906x}$

$R^2 = 0.7746317756$

$y = 1$

$R^2 = \#N/A$
$$y = -0.0000093750x + 1.0000000000$$
$$R^2 = 0.5639639640$$

$$y = -0.0000078947x + 1.0000000000$$
$$R^2 = 0.2046783626$$

$$y = e^{\frac{-x}{295489.7992}}^{5.830233035}$$
$$R^2 = 0.824075$$
Weibull

\[ y = e^{-(x/47054.6)^{8.246097}} \]

\[ R^2 = 0.6514 \]
Appendix Q: Values input parameters based on assumptions

This appendix describes what values are used for the input parameters that are determined by assumptions. Results are shown in Table 16.

Remark that because of confidentiality the values in the Value column are fictive.

Table 16: Input parameter determined by assumptions.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time spent on creating a purchase strategy</td>
<td>$T_{PS}$</td>
<td>16 hours</td>
<td>Project manager of the CEVA pilot</td>
</tr>
<tr>
<td>Time spent on negations with the customer</td>
<td>$T_{Neg}$</td>
<td>20 hours</td>
<td>Project manager of the CEVA pilot</td>
</tr>
<tr>
<td>Time spent on discussing the system</td>
<td>$T_{discuss}$</td>
<td>10 hours</td>
<td>project manager of the CEVA pilot</td>
</tr>
<tr>
<td>Time spent on searching for internal information of the system</td>
<td>$T_{searching}$</td>
<td>5 hours</td>
<td>project manager of the CEVA pilot</td>
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<tr>
<td>Time spent by a project manager on the complete project</td>
<td>$T_{PM}$</td>
<td>80 hours</td>
<td>Interviews with Service Project Managers, the CEVA pilot and the value given by CAP8 for a new project</td>
</tr>
<tr>
<td>Cost for storage for half a year per square meter</td>
<td>$sc$</td>
<td>100 Euros per square meter</td>
<td>on previous research of Lieshout &amp; Stralen (2017)</td>
</tr>
<tr>
<td>Percentage fee of extra cost for corrective maintenance</td>
<td>$fe$</td>
<td>1,1 %</td>
<td>Pricing department</td>
</tr>
<tr>
<td>The duration of replacing one component in the master-data</td>
<td>$ms$</td>
<td>1/12 hours</td>
<td>Master data department</td>
</tr>
</tbody>
</table>
Appendix R: Mean time to repair

For the value of $t_r$, one is assumed for this research. In Table 17 the results for the mean time to repair (MTTR) an 80-meter SPO are shown. How the MTTR are calculated is described in 6.5.

Remark that because of confidentiality the values for the MTTR are fictive.

Table 17: MTTR for each component type.

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<th>MTTR</th>
<th>Combination code</th>
<th>MTTR</th>
</tr>
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</tr>
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<td>D23</td>
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<td>DR</td>
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<td>110</td>
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<td>110</td>
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<td>FA</td>
<td>110</td>
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Appendix S: Values input parameters for test case

This appendix provides all values that are used for the base case.

Table 18: Values for the input parameter of the test case

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<th>Input parameter</th>
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<th>Unit</th>
<th>Input parameter</th>
<th>Value</th>
<th>Unit</th>
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<td>-</td>
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Table 19: Other input values for the base case

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<th>General state of component type</th>
<th>Number of spare-parts in old package</th>
<th>Number of spare-parts desired by new customer</th>
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Appendix T: Results dynamic programming solution component DS

This appendix shows the costs for replacement and down-time with dynamic programming for component DS with the input values as discussed in Appendix S. With these results the reconditioning decision can be made.

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</tr>
<tr>
<td>20</td>
<td>€</td>
<td>78,148</td>
<td>€</td>
<td>91,660</td>
<td>€</td>
<td>104,502</td>
<td>€</td>
<td>126,708</td>
<td>€</td>
<td>152,307</td>
<td>€</td>
</tr>
<tr>
<td>22</td>
<td>€</td>
<td>320,491</td>
<td>€</td>
<td>334,689</td>
<td>€</td>
<td>348,211</td>
<td>€</td>
<td>361,051</td>
<td>€</td>
<td>373,258</td>
<td>€</td>
</tr>
</tbody>
</table>

Figure 34: Results of the replacement and down-time costs for component DS
Appendix U: User manual of the tool

This appendix describes the developed LCC tool for reuse of systems. The tool can be used for:

- Providing insights in maintenance costs for a customer;
- Providing insights in the process costs to start a project;
- Support in the reconditioning decision.

In this appendix the following screenshots will be presented:

- The input sheet for the case dependent parameters;
- The result sheet.

Figure 35 presents a part of the input sheet. In this part only high-level information about the SPO, the reuse process, the new customer and some financial information is asked. The user should fill in all empty boxes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organization</td>
<td></td>
</tr>
<tr>
<td>- Length of operation</td>
<td>122 [yr]</td>
</tr>
<tr>
<td>- Number of components</td>
<td>42 [components]</td>
</tr>
<tr>
<td>Selling</td>
<td></td>
</tr>
<tr>
<td>- How found the customer (1 = Sales department, 0 = Service department)</td>
<td>1</td>
</tr>
<tr>
<td>- Time speed limiting by service department</td>
<td>50 [hr]</td>
</tr>
<tr>
<td>- Market value of the system</td>
<td>5000 [euro]</td>
</tr>
<tr>
<td>- The net present value of the future cashflow that are contractual committed for the system</td>
<td>0 [euro]</td>
</tr>
<tr>
<td>Information on customer</td>
<td></td>
</tr>
<tr>
<td>- Operating hours a day</td>
<td>12 [hr]</td>
</tr>
<tr>
<td>- Working days a year</td>
<td>260 [day]</td>
</tr>
<tr>
<td>- Average time of a shift</td>
<td>6 [hr]</td>
</tr>
<tr>
<td>- Average number of personnel each day</td>
<td>3.2 [people]</td>
</tr>
<tr>
<td>- Environmental condition factor (between 0.3 and 1.1)</td>
<td>1</td>
</tr>
<tr>
<td>Capacity</td>
<td></td>
</tr>
<tr>
<td>- Average system capacity</td>
<td>7100 [gph]</td>
</tr>
<tr>
<td>- Average system throughput</td>
<td>2657 [gph]</td>
</tr>
<tr>
<td>Storage and Transport</td>
<td></td>
</tr>
<tr>
<td>- Yearly percentage paid for storing the spare parts</td>
<td>0.02 [%]</td>
</tr>
<tr>
<td>- Binary indicator whether external warehouse is needed (1 = Yes, 0 = No)</td>
<td>1</td>
</tr>
<tr>
<td>- Number of trucks necessary to calculate for transport</td>
<td>3 [Trucks]</td>
</tr>
<tr>
<td>Financial information</td>
<td></td>
</tr>
<tr>
<td>- Nominal interest rate</td>
<td>0.08 [%]</td>
</tr>
</tbody>
</table>

Figure 35: Input sheet (1/4)

Figure 35 shows what specific decisions the customer must make on system level. These decisions effect the input for the component view.
Figure 36: Input sheet (2/4)

Figure 37 shows all identified component types. Vanderlande and the new customer must determine how many items of each component type is present in the system that will be delivered to the new customer and what the general state of each component type is. Vanderlande knows what the number of spare-parts was in the old package that they bought from the old customer for each component type. Together with the new client the desired number of spare-parts must be established. Note that the desired number must be same or more that the number of spare-parts in the old package.

<table>
<thead>
<tr>
<th>Component type</th>
<th>Number of items present in system</th>
<th>State of component type</th>
<th>Number of spare-parts in old package</th>
<th>Number of spare-parts desired by new customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>258</td>
<td>14</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>A2</td>
<td>227</td>
<td>14</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>A3</td>
<td>10</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>0</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>A6</td>
<td>0</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>3</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A8</td>
<td>0</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A9</td>
<td>3</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>0</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A11</td>
<td>2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A12</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A13</td>
<td>256</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A14</td>
<td>22</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A15</td>
<td>21</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>A16</td>
<td>8</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A17</td>
<td>72</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A18</td>
<td>40</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A19</td>
<td>236</td>
<td>14</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>A20</td>
<td>12</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A21</td>
<td>10</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A22</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>A23</td>
<td>1</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A24</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A25</td>
<td>6</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A26</td>
<td>2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A27</td>
<td>15</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A28</td>
<td>10</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A29</td>
<td>1</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A30</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A31</td>
<td>17</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A32</td>
<td>35</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A33</td>
<td>189</td>
<td>14</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>A34</td>
<td>0</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A35</td>
<td>1</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A36</td>
<td>27</td>
<td>14</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>A37</td>
<td>5</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A38</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>A39</td>
<td>1</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A40</td>
<td>15</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A41</td>
<td>4</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A42</td>
<td>1</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A43</td>
<td>1</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A44</td>
<td>1</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A45</td>
<td>1</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A46</td>
<td>1</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A47</td>
<td>1</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A48</td>
<td>1</td>
<td>14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Once all input values are filled in by the user, the tool should be saved. Next the user can run the R script which will output 4 columns in Excel. At last, Figure 38 shows where the results of the R scripts should be copied to. The boxes, are already linked with the output fill of the R script. So the boxes should only be refreshed.

Figure 38: Input sheet (4/4)

The lay-out of the results are shown in Figure 39. For each recondition option the LCC will standard be determined. The lowest option with the lowest LCC will turn green.
<table>
<thead>
<tr>
<th>Cost elements</th>
<th>Refurbish</th>
<th>As-Is</th>
<th>Remanufacture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project management cost</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Finding customer</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Buy-back</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Engineering</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Site work new customer</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Master data</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Research</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Site work old customer</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transport</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reconditioning</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Inspections</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Replacement &amp; down-time</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Spare-parts</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Operation</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Energy</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>€</td>
<td>€</td>
<td>€</td>
</tr>
</tbody>
</table>

Figure 39: Result sheet
Appendix V: Verification

In this appendix the model described in section 5.4.2 is verified by comparing the results of the computer program with the calculation by hand.

\[ V_n^i(x) = \begin{cases} 
\min \left\{ C_p + \sum_{y \in S} p_{k,y}^i \cdot V_{n-1}(y)/(1 + r)^{yrs}, \sum_{y \in S} p_{k,y}^0 \cdot V_{n-1}(y)/(1 + r)^{yrs} \right\} & x < L_i; \\
(C_u + \sum_{y \in S} p_{k,y}^i \cdot V_{n-1}(y)/(1 + r)^{yrs}, x = L_i. \\
C_{RE} = \sum_{i=1}^d \min(V_n^i(k), V_n^i(0) + C_{kC}) 
\end{cases} \]

For the example a component with 4 described states (0, 1, 2, L) will be used, with the following probabilities:

\[ p_{0,0}^0 = 0.09 \quad 0.1 \quad 0.9 \quad 0 \]
\[ p_{0,0}^1 = 0 \quad 0 \quad 0.09 \quad 0.9 \quad 0 \]
\[ p_{0,0}^2 = 0 \quad 0 \quad 0 \quad 0.09 \quad 0.9 \]
\[ p_{0,0}^3 = 0 \quad 0 \quad 0 \quad 0 \quad 0.09 \quad 0.9 \]

Also, preventive costs will be €100, corrective costs will be €500 and the reconditioning costs will be €50. Further the nominal interest rate will be 8%, the number of remaining periods is 3 and each period is 1,5 years.

For zero remaining periods: \( V_0^i(0), V_0^i(1) \) and \( V_0^i(2) \) the outcome is zero, and for \( V_0^i(L) \) the outcome is 500.

**For one remaining period:**
\[ V_1^i(0) = \min\{100 + 0.9 \cdot 0/(1 + 0.08)^{1.5} + 0.1 \cdot 500/(1 + 0.08)^{1.5}, 0.9 \cdot 0/(1 + 0.08)^{1.5} + 0.1 \cdot 500/(1 + 0.08)^{1.5}\} = \min\{144.55, 44.55\} = 44.55 \]
\[ V_1^i(1) = \min\{100 + 0.9 \cdot 0/(1 + 0.08)^{1.5} + 0.1 \cdot 500/(1 + 0.08)^{1.5}, 0.6 \cdot 0/(1 + 0.08)^{1.5} + 0.4 \cdot 500/(1 + 0.08)^{1.5}\} = \min\{144.55, 178.19\} = 144.55 \]
\[ V_1^i(2) = \min\{100 + 0.9 \cdot 0/(1 + 0.08)^{1.5} + 0.1 \cdot 500/(1 + 0.08)^{1.5}, 1 \cdot 500/(1 + 0.08)^{1.5}\} = \min\{144.55, 445.49\} = 144.55 \]
\[ V_1^i(L) = 500 + 0.9 \cdot 0/(1 + 0.08)^{1.5} + 0.1 \cdot 500/(1 + 0.08)^{1.5} = 544.55 \]

**For two remaining periods:**
\[ V_2^i(0) = \min\{100 + 0.9 \cdot 144.55/(1 + 0.08)^{1.5} + 0.1 \cdot 544.55/(1 + 0.08)^{1.5}, 0.9 \cdot 144.55/(1 + 0.08)^{1.5} + 0.1 \cdot 544.55/(1 + 0.08)^{1.5}\} = \min\{264.43, 164.43\} = 164.43 \]
\[ V_2^i(1) = \min\{100 + 0.9 \cdot 144.55/(1 + 0.08)^{1.5} + 0.1 \cdot 544.55/(1 + 0.08)^{1.5}, 0.6 \cdot 144.55/(1 + 0.08)^{3} + 0.4 \cdot 544.55/(1 + 0.08)^{1.5}\} = \min\{264.43, 271.35\} = 264.43 \]
\[ V_2^i(2) = \min\{100 + 0.9 \cdot 144.55/(1 + 0.08)^{1.5} + 0.1 \cdot 544.55/(1 + 0.08)^{1.5}, 1 \cdot 544.55/(1 + 0.08)^{1.5}\} = \min\{264.43, 485.18\} = 264.43 \]
\[ V_2^i(L) = 500 + 0.9 \cdot 144.55/(1 + 0.08)^{1.5} + 0.1 \cdot 544.55/(1 + 0.08)^{1.5} = 664.43 \]
For three remaining periods:

\[ V_3^i(0) = \min\{100 + 0.9 \cdot 264.43/(1 + 0.08)^{1.5} + 0.1 \cdot 664.43/(1 + 0.08)^{1.5}, 0.9 \cdot 264.43/(1 + 0.08)^{1.5} + 0.1 \cdot 664.43/(1 + 0.08)^{1.5}\} = \min\{371.24, 271.35\} = 271.35 \]

\[ V_2^i(1) = \min\{100 + 0.9 \cdot 264.43/(1 + 0.08)^{1.5} + 0.1 \cdot 664.43/(1 + 0.08)^{1.5}, 0.6 \cdot 264.43/(1 + 0.08)^{1.5} + 0.4 \cdot 664.43/(1 + 0.08)^{1.5}\} = \min\{371.24, 378.16\} = 371.24 \]

\[ V_2^i(2) = \min\{100 + 0.9 \cdot 264.43/(1 + 0.08)^{1.5} + 0.1 \cdot 664.43/(1 + 0.08)^{1.5}, 1 \cdot 664.43/(1 + 0.08)^{1.5}\} = \min\{371.24, 591.99\} = 371.24 \]

\[ V_2^i(L) = 500 + 0.9 \cdot 264.43/(1 + 0.08)^{1.5} + 0.1 \cdot 664.43/(1 + 0.08)^{1.5} = 771.24 \]

These results are exactly the same as the output of the computerized model, see Table 20.

Table 20: Output R example

<table>
<thead>
<tr>
<th>Remaining periods/ State</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>44.548</td>
<td>164.427</td>
<td>271.236</td>
<td>366.400</td>
<td>451.189</td>
<td>526.733</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>144.5486</td>
<td>264.427</td>
<td>371.236</td>
<td>466.400</td>
<td>551.189</td>
<td>626.733</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>144.5486</td>
<td>264.427</td>
<td>371.236</td>
<td>466.40</td>
<td>551.189</td>
<td>626.733</td>
</tr>
<tr>
<td>L</td>
<td>500</td>
<td>544.5486</td>
<td>664.427</td>
<td>771.236</td>
<td>866.400</td>
<td>951.189</td>
<td>1026.733</td>
</tr>
</tbody>
</table>

So, the code matches with the described model. The results are also plausible because if the remaining periods increases, the costs also increase, and if the state of the component comes closer to L, the results also appear to increase.

When certain parameters are changed all the results stay plausible. The parameters that are checked are the costs for corrective maintenance, length of the period, the probabilities per period. When the cost for corrective maintenance are decreased, the general output is lower for each state. Also, state 2 and 3 no longer have the same costs because preventive maintenance is no longer the optimal decision. Further when the periods are made shorter, the results per period increases, as expected. Last adjustment is the change in the number of states and the probabilities. In this case no strange results are encountered.
Appendix W: Calculation operation time before failure and remaining operation time before stop of measurement

This appendix describes in general what code is used to calculate the operation time for each component before it failed, and the remaining operation time before the measurement stopped. The data set for this calculation has the following information:

- The location of the failure;
- The date of replacement;
- Quantity of components replaced;
- What component type is replaced;
- The determined start date of that component type;
- The quantity of components of that component type in the system.

The idea of what times are calculated and how, is indicated in Figure 40. Component type A is considered and two of these components are present in the system, say A.1 and A.2. When component A.1 fails, a new A.1 component will be installed and the time for measuring the failure time is set to zero. When component A.1 fails again, it is replaced again and the time for the new A.1 will be set to zero. The time duration till the first failure is assigned to A.1.1, and the time duration from the first failure till the second failure is assigned to A.1.2. At time 10, the measurement stops, and the remaining operation time between the last A.1 and time 10 is calculated, this is indicated by A.1.3. The same steps are taken for A.2.

The model that is used to calculate these times, can be described by the following steps:

**Step 1:** Create a list of unique components. So, every component within a component type of a system at a location is identified.

**Step 2:** Create a matrix with every unique component and their start date.

**Step 3:** Calculate for each individual component failure the time difference between the date of replacement and the start date of the component, and change the start date of that component in the matrix described in step 2. The time to failures are stored in another matrix. When the number of failures of a component type is more than the number of component present, than the time to failure can be calculated with the adjusted start age of components that already have failed before.
**Step 4:** Calculate the time difference between all start dates (listed and adjusted in the matrix described in step 2) and the date that the measurement stopped.

**Step 5:** All time differences are in days. Based on the number of workdays in a week, and the average operation time a day, the time difference is calculated in hours.
Appendix X: Poster

A life cycle cost model for used systems of Vanderlende

L.S. (Lac) Aangenendt

Introduction

Vanderlende wants to decrease their environmental footprint by decreasing the material waste through reusing systems that are end of use. There is a demand for a life cycle cost (LCC) analysis from the customers and from Vanderlende. The customer wants to know the predicted maintenance and downtime costs. Vanderlende benefits from an LCC analysis by being able to make an assessment of the economic viability and market acceptance of the second-hand system, and choosing the best reprocessing strategy that results into the lowest LCC. Reprocessing is defined as the value-adding activity of a system. However, Vanderlende does not know what the LCC is for a second-hand system, and therefore the following research question is defined:

What is the LCC for a reused system?

To answer this question, a model is developed and tested.

Model development

To get the right input parameters for the model, the process for reuse is determined. Cost elements are determined based on the process description, and the input values are determined. How the values of the input parameters are found is shown in Figure 1.

Reprocessing strategy selection

The reprocessing strategy is defined by what components of the system are replaced. The objective is: Replace all components that decrease the total LCC because the reduction in maintenance and downtime costs for these components is greater than the reprocessing costs.

By using stochastic dynamic programming, the minimal expected cost for a component that operated k periods in a system with n periods to go before the system is end-of-life (EOL), can be calculated. See Figure 2 for representation of the situation.

Case study

A case study is conducted for a Postsorter of 14 years old and needs to operate 8 more years. The results are shown in Figure 3 for which the total cost are between one and two million. Downtime costs are around 76% of the total maintenance costs.

Conclusions and recommendations

Main conclusion

The LCC is dependent on the age of the system, the state of the component types, the environmental conditions, the size of the system and what reprocessing strategy is used. With the help of the developed model the LCC can be calculated for each individual case.

Main recommendation

Maintenance is the biggest cost driver, and it is very sensitive for a change in the reliability functions and the downtime cost. Vanderlende should increase the data availability and use another method of logging the failures so the actual times between failures can be determined. Also, Vanderlende should investigate the effect of environmental factors on the reliability of a system.