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Analysing improvement possibilities for use of dynamic base stock levels in spare parts inventory control

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Analysing improvement possibilities for use of dynamic base stock levels in spare parts inventory control

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Preface

This report is the result of my graduation project in completion of the master Operations Management and Logistics at Eindhoven University of Technology. I conducted my graduation project at the Customer Service department of Vanderlande Industries. The past 6 months, I have done a challenging project from which I learned a lot. I would like to thank several people for this opportunity and their support during the project.

From the university, I would like to thank Geert-Jan van Houtum for being my mentor and first supervisor. I learned a lot from the discussions we had about the project. Your critical view and interest in the project made these meetings enjoyable and motivating at the same time. Thanks as well for supporting me to keep my tight deadlines. I also want to thank my second supervisor Hao Peng for her useful feedback.

At Vanderlande Industries I want to thank Erlend Hessel for giving me the opportunity to conduct this project. You kept supporting me although the topic of my project gradually moved away from your department. I also want to thank Katja Kleinveld, for giving me the opportunity to redefine my project into the direction of spare parts inventory control. Thanks to both of you, that I could always interrupt your daily activities with questions. Also thanks to all my colleagues at Vanderlande Industries for the pleasant working environment and helping me to get all the data together.

Finishing this project also means the end of my life as a student. My student days would not have been as great as they were without my family and friends. I want to thank all of you for your interest and support during my studies. Special thanks go to my parents who always supported me, whatever choice I made. Also thanks to my sister; whether we lived together or not, you always were there for me. Finally I want to thank my friends for the good times we had.

Joke

Abstract

It is known that wear is a main driver for demand for spare parts. For items that wear out, an increasing demand rate is expected during the lifetime of the equipment. However, base stock levels for spare parts inventory point are usually kept at a constant level. This study analyzes the use of base stock levels that are adapted during the lifetime of a capital good. General insights are provided and a case study at Vanderlande Industries is conducted. It is found that the difference in demand during the lead time and the holding costs are the main drivers that determine whether it is attractive to adapt the base stock levels during the lifetime of a capital good.

Executive summary

Capital goods are products or systems which operate in the core process of their users. The availability of these systems is crucial because the operations of the users may stop due to failures of these systems and operational interruptions lead to significant losses (Öner et al. 2010). A trend found in practice is that capital goods get more and more complex and that users require a higher availability (Cohen et al. 2006). An increase in the technical complexity means that it gets more difficult for users to maintain their capital goods. The increased complexity has usually to do with increased automation resulting in a higher capacity loss when a failure occurs (Paz and Leigh, 1994). Guided by this increasing complexity and the increasing impact of a failure, more and more users of capital goods ask for after-sales service from the original equipment manufacturers (OEMs) of the capital goods (Öner et al., 2010). The OEM has more knowledge about its product, and, more important, OEMs have the possibility to collect data for many similar machines which enables them to improve the service chain by performing statistical analysis.

This research is executed within Vanderlande Industries (VI), an OEM of material handling systems. The trends described above are also visible at VI. Spare parts inventories are necessary because failure of a single component can cause a system breakdown leading to expensive downtime. Excessive spare parts stock should however be to prevent excessive inventory costs. This leads to a tradeoff.

It is found that forecasts for spare parts demand are improved by using dynamic parameters for the demand distributions. The term 'dynamic' means that the value assigned to certain parameters can change over time; the demand distribution does not have a fixed mean over time. Spare parts demand originates from wear. Considering items that occur multiple times in a system, it likely that the expected demand for this item is lower in a brand new system than in a system in which items started to wear out. Although it is known that the demand for spare parts increases during the lifetime of capital goods, it is common to keep the base stock levels of spare parts inventory constant. Based on these considerations, the following research question is defined: *In which situations is it useful to apply dynamic base stock levels at a VI system in order to decrease the total costs of ownership of a capital good?*

Model

The model that is used for the analysis is given in Figure 1. Demand for spare parts occurs at Location 1 and Location 2. The focus is on Location 1 which represents a single site, Location 2 represents all sites that generate a demand stream to Location 0. The Central Warehouse (CW) is represented by Location 0. The CW is delivered by a supplier which can be the VI factory or an external supplier. It is assumed that Location 2 has a fill rate of 100%. If demand occurs at Location 1, it is fulfilled from this stock point if possible. If a requested item is not available at Location 1, an emergency shipment will take place from Location 0, if the item is available there. If an item is not available at Location 0, it will be delivered from the supplier of Location 0. Obvious, different costs and different lead times are associated with the shipment from different locations.

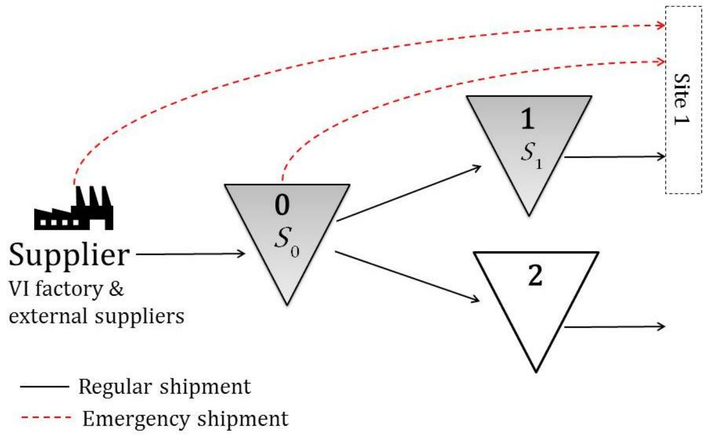


Figure 1 Model

Results

Based on the analysis, 3 main conclusions can be drawn. Two of these conclusions resulted from a case study at VI, one conclusion resulted from on a numerical experiment that is conducted to gain general insights.

A case study is performed to analyze the attractiveness of dynamic base stock levels within VI. The case study is performed for 5 items (Crossing, Divert Shoe, Divert Switch, Merge, Proximity Switch) of the Posisorter; a frequently used product in distribution and parcel and postal systems.

Assigning demand to supply chains

A result of the evaluation of the current situation at VI is that the performance of Location 0 is not optimal; the fill rate is less than 15% for 3 out of 5 items. It is found that an improvement can be made by assigning demand streams for spare part from different sources consciously. Demand for spare parts at VI originates from five sources:

- Failure due to wear
- Failure due to crash (wrong usage)
- Preventive maintenance during service visits
- Planned preventive maintenance
- Revisions

Preventive maintenance during service occurs when it is noticed that a part has worn out so far that it is likely to fail before the next service visit. The current assignment of demand streams is depicted in Figure 2. It is found that the fill rate of Location 0 can be improved, by only assigning unplanned demand streams to Location 0 like depicted in Figure 3. This increases the fill rate till at least 93% for the 5 items studied.

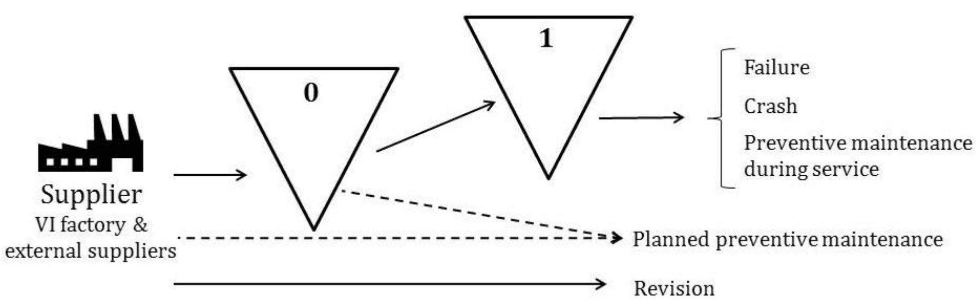


Figure 2 Current assignment of demand streams

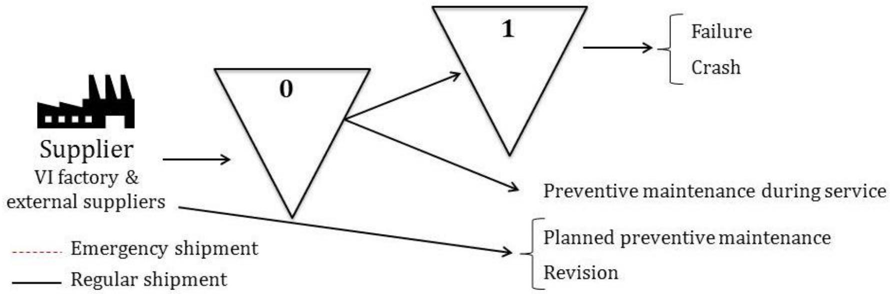


Figure 3 Improved assignment of demand streams

Dynamic base stock levels at Vanderlande

The introduction of dynamic base stock levels created minor costs savings for the 5 items studied. For 3 items there was no difference and for 2 items a cost reduction of approximately 7% was gained. A sensitivity analysis showed that the results are robust for changes in the costs, and sensitive to changes in de demand during the lead time. If the demand during the lead time decreased (increased), the attractiveness of dynamic base stock levels decreased (increased) as well. Although financial savings are minor, it is expected that dynamic base stock levels will create soft gains; an improved relation with the customer, a feedback loop on the current base stock levels and the possibility to use new information every time that the base stock levels are updated.

General findings

The numerical experiment showed that major financial gains (€ 1000 per item per year) can be gained when the holding costs are quite high (€ 50/week) and difference in demand is sufficient. Both the minimum demand rate and the relative increase in demand are shown to have an impact on the attractiveness of dynamic base stock levels. The absolute cost reduction is more for items with higher holding costs. The holding costs do therefore have an influence on the attractiveness of dynamic base stock levels as well.

Recommendations

Based on this study, some recommendations can be done for academics and for VI. For VI, it is recommended to take a strategic decision about the CW and to act accordingly. This study has shown that conscious decisions about the allocation of demand streams from different sources can bring improvements. Although dynamic base stock levels bring only minor financial gains, it is recommended to introduce this method because of the soft gains that will be made as well. Another recommendation to VI is to regard the value of information, this recommendation has two sides. Information should not be given away easily to customers on the one hand. On the other hand, data that can be gathered from the maintenance activities should be stored in a way that it can be used easily to improve the decisions that are made. This study is based on data and multiple assumptions had to be made because there was a lack age of data; if data can be obtained easily, it is much more attractive to do analysis and improve the processes.

For academics it is recommended to do deeper research to cutoff criteria to judge when dynamic base stock level are attractive and when not. It would also be interesting to develop a model that determines the moment when it is optimal to increase the base stock level. Another point that is not taken into account in this study, are the recent developments in condition monitoring. It becomes easier to monitor the condition of items remotely, it should be studied how these developments can help to make decisions in updating base stock levels.

Contents

List of variables

Input variables

$N = \{0,1,2\}$	set of locations considered in this model
L_n	replenishment lead time in time units for location n
EL^{CW}	lead time in time units for an emergency shipment from the central warehouse
EL^{sup}	lead time in time units for an emergency shipment from the supplier
C^{CW}	costs of an emergency shipment from the central warehouse
C^{sup}	costs of an emergency shipment from a(n) (external) supplier
h_n	inventory holding costs per time unit at location n per time unit
D_{max}	maximum logistic downtime in time units
T	set of periods considered in this model; $t \in \{1,2,3,...,\|T\|\}$
$m_{n,t}$	demand rate at location n in period t

Decision variables

S_n	base stock level at location n for $n \in \{0,1\}$

Output variables

$D(S_0, S_1)$	mean logistic downtime for orders at local warehouse 1
$C(S_0, S_1)$	total costs for the central warehouse and local warehouse 1

Other variables

m_n	demand per time unit at location n
β_n	fill rate at location n
θ_n	fraction of demand of location n that is directly satisfied by the central warehouse
γ_n	fraction of demand of location n that is directly satisfied by the (external) supplier
C^{hold}	total holding costs per time unit
C^{em}	total emergency costs per time unit
$C(S_{total})$	minimal costs that can be obtained under S_{total}
D	logistic downtime in time units
W_0	mean delay in time units for an arbitrary replenishment order at the central warehouse
LT_n	realized replenishment lead time for location n in time units; $LT_n = t_n + W_0$
$\overline{S}$	minimum inventory level of the central warehouse; $\overline{S} = \sum_{n=1}^{N} S_n$

μ_0	arrival rate of new items at central warehouse; $\mu_0 = {1}/{L_0}$
m'_0	demand rate at the central warehouse when the net inventory is not positive
B_n	backorders of location n
IL_n	Inventory level at location n
$\pi_{n,x}$	steady state probability for location n net inventory x
C_t^{hold}	total holding costs in period t
$\pi_{n,t,x}$	steady state probability for location n in period t for net inventory x
$\beta_{n,t}$	fill rate at location n in period t
LT_n	realized replenishment lead time for location n in period t
$m_{1,\min}$	minimum demand rate at location 1 in T
$m_{1,\max}$	maximum demand rate at location 1 in T

List of abbreviations

Abs	Absolute
ANOVA	Analysis of variance
Avg.	Average
BOM	Bill of material
CW	Central warehouse
DT	Downtime
FA	Amount of failures per year
LW	Local warehouse
MD	Maintenance delay per corrective maintenance action
METRIC	Multi echelon technique for repairable item control
OEM	Original equipment manufacturer
R&D	Research and development
RT	Repair time
SCMS	Supply chain management services
SKU	stock keeping unit
SPSS	Statistical software package
TC	Total costs
TCO	Total costs of ownership
VI	Vanderlande Industries

1. Introduction

Capital goods are products or systems which operate in the core process of their users. Examples of capital goods are computer networks, defense systems, medical systems and material handling systems. The availability of these systems is crucial because the operations of the users may stop due to failures of these systems and operational interruptions lead to significant losses (Öner et al. 2010). More and more users of capital goods therefore use the Total Costs of Ownership (TCO) concept to select the supplier of the capital good. The aim of the TCO concept is to determine the actual costs for the organization to use, maintain and dispose an asset instead of only the initial costs (Ellram and Sifert, 1998).

A trend found in practice is that capital goods get more complex and that users require a higher availability (Cohen et al. 2006). An increase in the technical complexity means that it gets more difficult for users to maintain their capital goods. The increased complexity has usually to do with increased automation resulting in a higher capacity loss when a failure occurs (Paz and Leigh, 1994). Lost capacity due to machine failures leads to significant costs in many manufacturing settings (Aka et al., 1997).

Guided by this increasing complexity and the increasing impact of a failure, more and more users of capital goods ask for after-sales service from the original equipment manufacturers (OEMs) of the capital goods (Öner et al., 2010). Besides only after-sales services, a growing amount of users requires a contract which specifies performance outcomes instead of the individual parts and repair actions (Kim et al., 2007). In the ultimate situation, users buy a function instead of a system (Cohen et al., 2006). Users are also demanding more services because they want to focus on their core competences (Baines et al., 2009). It can be concluded that OEMs are confronted with the task to maintain their equipment and guarantee a high availability.

However, delivering service, instead of only products, can create financial and strategic advantages for OEMs. Services do create a continuous and stable revenue stream and have higher profit margins (Baines et al., 2009). Strategic advantages are gained in two ways. First, services are less visible, which makes it hard to compare and providing service will enhance trust and loyalty. Second, by delivering after-sales, OEMs can gain a deep understanding of customers' technologies, processes and plans; knowledge that rivals cannot acquire easily and provides competitive advantage (Cohen et al., 2006; Oliva and Kallenberg, 2003). Finally, Cohen et al. (2006) state that providing services of a high quality are a proved way to increase the value of the company; studies have shown that there's a direct correlation between stock prices and the quality of firms' after-sales services. Due to these developments the service business becomes increasingly important for OEMs (Cohen et al., 2006).

In the end, these trends can result in a win-win situation. If an OEM has a contract that only identifies what is required and not how the requirements should be fulfilled, it is forced to make its service chain as efficient as possible. In this situation, the OEM has a stronger incentive to improve its spare parts inventory control, reduce administration overhead and make resource allocation decisions when compared to the situation where the OEM is paid per action (Kim et al., 2007). The OEM has many more opportunities to improve the service chain than a single user has. The OEM has more knowledge about its product and more important, OEMs have the possibility to collect data for many similar machines which enables them to improve the service chain by performing statistical analysis. Statistical analysis is a method to improve the decision making process for inventory control, maintenance management, and other service related processes. The OEMs do also have the opportunity to improve the service supply chain; for example by pooling inventory. OEMs can take a leadership role in improving maintenance and spare parts inventory decisions by using information about equipment history. Recent advances in sensor technologies enable the possibility to continuously monitor the health of operating components. If these sensor data is interpreted, a better understanding of the uncertainty and randomness of the physics of a failure can be acquired. This is possible because components usually show degradation behavior during their service life and these degradation processes are typically accompanied by specific physical phenomena which can be observed using sensor-driven conditional monitoring technology (Elwany and Gabraeel, 2008). The use of information technologies make the information flow easier, faster and cheaper leading to many improvements in supply chain management and inventory control (Tan, Güllü, & Erkip, 2007; Kennedy, Wayne Patterson, & Fredendal, 2002) These developments make remote condition monitoring possible and can lead to opportunities for OEMs in enhancing their service strategies. Making the service chain more efficient, will create advantages for the customer as well. When demand for spare parts can be predicted, downtime will be reduced. Other improvements will make the service chain more robust and reliable. All parties in the supply chain will gain from the advantages of a more reliable and cost efficient service chain.

This research is executed within Vanderlande Industries (VI), an OEM of material handling systems. Customers of VI use these material handling systems in their primary processes and require a high availability. The trends described above are also visible at VI. The turnover of customer services and consignment stock has grown in the last years and it is expected that this growth will continue. Improvements in the service supply chain are necessary, to realize planned growth. Chapter 2 gives a broader description of VI.

As discussed above, OEMs need optimized maintenance strategies and a well-coordinated support organization. This includes handling and storing spare parts; which will be studied during this research. Spare parts inventories are necessary because failure of a single component can cause a system breakdown leading to expensive downtime. Excessive spare parts stock should however be avoided because spare parts can be expensive. The trade-off between the risk of not keeping an item on stock and the costs of keeping an (extra) item on stock makes spare parts inventory management an integral component of the strategic service chain. In the remainder of this research, it will be assumed that the goal of the OEM is to optimize the service chain in order to decrease the TCO of its products.

In order to prevent expensive downtime, capital goods can have a dedicated spare parts warehouse located nearby the capital good. In these local warehouses, it is usual to keep inventory levels constant during the life time of equipment. It is however known that demand for spare parts originates from wear for most spare parts in the equipment. When speaking about parts with an increasing failure rate, it might therefore be valuable to adapt the base stock levels to the chance of failure. Base stock levels that can be adapted are dynamic base stock levels. Snyder et al. (2011) have shown that the traditional static Poisson distribution can be too restrictive to forecast intermittent demand in order to determine optimal inventory levels. This research will investigate whether it would be valuable to use dynamic base stock levels for VI and when it is valuable to use dynamic base stock levels in general.

The outline of the remainder of this report is given in Figure 4. After this introduction, Chapter 2 will give a description of Vanderlande Industries and their current service supply chain. In Chapter 3 a review of literature on spare parts inventory control and dynamic base stock levels will be given. Based on the current state of literature and the situation at VI, a problem is defined in Chapter 4. This problem will be solved using a mathematical model that will be discussed in Chapter 5. The method to solve this model, the implementation and the validation are also part of Chapter 5. The model and analysis procedure are used in the case study to access several options in which VI could improve its service chain. The case study is discussed in Chapter 6. Chapter 7 will provide insights in when it is valuable to use dynamic base stock levels. Finally Chapter 8 gives conclusions and recommendations.

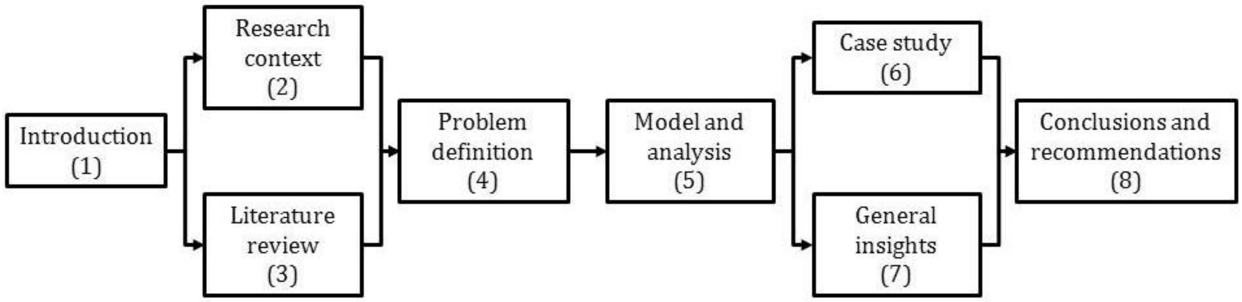


Figure 4 Outline report

2. Research context

A description of Vanderlande Industries is given in the first section. The second section discusses how the inventory for spare parts is controlled at VI. A description of all services delivered by VI is given in Appendix I.

2.1 Company description

Vanderlande Industries was founded in 1949 and its headquarters is located in Veghel, the Netherlands. VI provides automated material handling systems and services to their customers in the markets for baggage handling at airports, automated logistics processes in distribution centers and sorting solutions in parcel and postal facilities. The core value of VI is '*building reputation with customers*'. In line with this core value, the press release about the annual report of 2011 stated: '*We believe that only true partnership with customers can unlock the hidden improvement potential in logistics hubs. Our customers clearly appreciate the partnership approach that we have developed over the past decade. ... We are committed to continuing on this path*' (Vanderlande Industries, 2011). In the next sections the structure of VI and the Customer Services department will be discussed.

1.1.1 Structure

VI has 4 business units; Distribution, Baggage Handling, Parcel & Postal and Services (see Figure 5). The first 3 business units engineer and install systems for customer on project base. Their names refer to the type of customers where these business units deliver their project to.

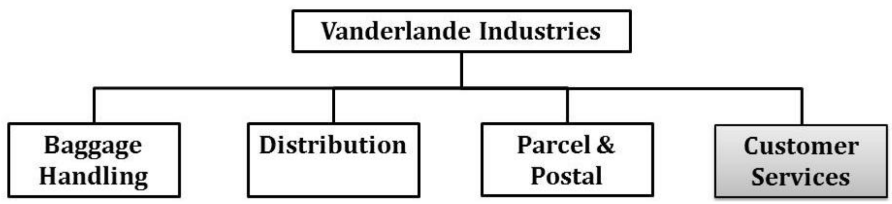


Figure 5 Organization Structure

- The goal of Baggage Handling is to provide fast, safe and robust transportation, storage and sorting from check-in to make-up for both, transfer and arrival baggage. The aim is to build long-term partnerships with airport operators to deliver lifetime operations support. VI is the world's leading supplier for baggage handling systems. The business unit baggage handling had an order intake of 48% of total VI order intake on average over the last 5 years, see also Figure 6 for the division of the turnover (Vanderlande Industries, 2011).
- The goal of the business unit Distribution Systems is to provide its customers with competitive automated solutions for goods receiving, storage, order picking, consolidation and shipping. Distribution systems are installed in a wide range of industries, for example food, fashion and pharmaceuticals. VI is among the top 5 suppliers of these solutions in Europe. The business unit distribution had an order intake of 16% of total VI order intake on average over the last 5 years (Vanderlande Industries, 2011).
- The goal of Parcel and Postal is to provide the optimal price-quality performance with robust, leading-edge technologies.

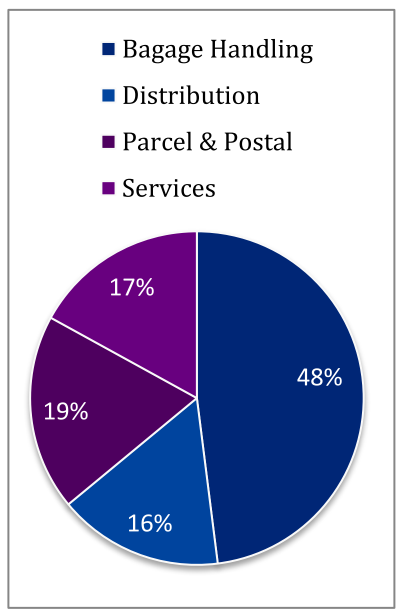


Figure 6 Division of turnover of VI, average over 2006-2011

Express parcel and postal systems range from local depots with a throughput of thousand items a day to an automated sorting hub handling well over 200,000 parcels per hour. The business unit express parcel & postal systems had an order intake of 19% of total VI order intake on average over the last 5 years (Vanderlande Industries, 2011).

- Customer Services, provides all services during the operational lifetime of the systems installed by the previous discussed business units. The goal of this business unit is to support the growing importance of service within the organization. The function of the departments in this business unit, will be discussed below. The business unit customer services had an order intake of 17% of total VI order intake on average over the last 5 years (Vanderlande Industries, 2011). This percentage is growing over the last years, this business unit was responsible for a turnover of € 111.5 million in the financial year 2011, which was 19 % of the total turnover.

VI is a global player. In order to maintain direct contact with their customer, the company operates locally through subsidiaries, called customer centers, handling all key business functions. A customer centre can be considered as a small, individual company, supported by the 4 business units in Veghel. Customer centers are located in the Netherlands, Belgium, Germany, France, Great Britain, Spain, Canada, PR China, South Africa and the USA.

1.1.2 Customer Services

Figure 7 shows the evolvement that VI made from an equipment supplier to a service provider. It can be seen that providing services is of growing importance for VI. Before 1995 VI was a pure equipment supplier and the only services delivered were providing spare parts on customer request and warranty management; delivering service was seen as necessary evil. With the foundation of the business unit customer services in 2005, VI recognized services as truly as an opportunity. VI is now able to deliver all services that are needed to maintain a VI system; they are a service one-stop-shop. Note that this means that VI is able to be a service provider. Only a few customers do buy all services at VI. These are either major customers who outsourced all services to VI or minor customers who trust VI to be the best supplier.

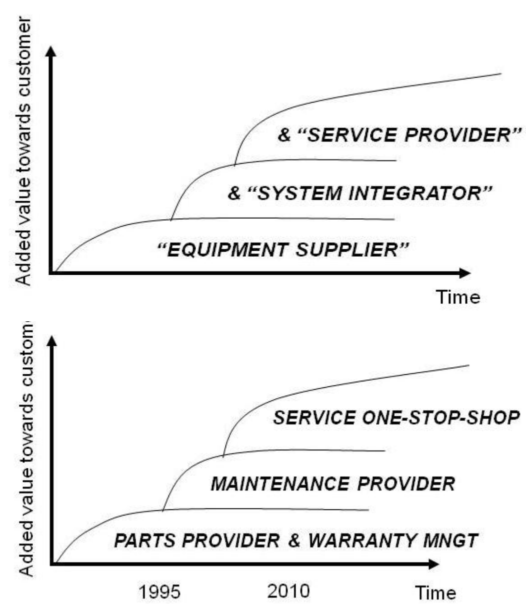


Figure 7 From Equipment supplier to service provider

The structure of the business unit is given in Figure 8. This research will be executed at the interface of the departments supply chain management services and service development.

Controls support supports serviceman who do have difficulties solving customers' problems on site. All customers centers or customers over the world can contact this department when they have a problem with repairing a machine; this department can be reached 24/7. Business support/development is split in 2 subdivisions; business support and development. Business support is supporting customer centers from the sales phase up to the site based maintenance phase for large projects. This subdivision is also taking care about the integration of information systems and responsible for the development of maintenance training. Service development is responsible for the developing and rolling-out projects to improve (site-based) maintenance and product management. This includes among other things projects in product maintenance, product documentation, sustainability and information systems. Supply Chain Management Services (SCMS) is responsible for purchasing spare parts and sending the spare parts to customers worldwide. Besides replenishment orders for spare parts, this department delivers initial spare parts packages to customers. This package must ensure that all critical components are at the site of a customer to make repair by replacement possible.

Most customers do buy a recommended spare parts package at VI after installation of their system. The next section explains how this advice is drawn. A trend regarding these packages is that customers are increasingly critical about the content of the recommended spare parts package. They want to know the effect of reducing or increasing the base stock levels of the items in the package. Service account managers are increasingly forcing SCMS to provide this information in order to justify the advice to customers.

Another trend is a growing amount of customers that demands offerings in which VI not only delivers the system but is also responsible for all maintenance activities including the provision of spare parts. In order to make competing offerings for these contracts VI needs to have insights in the effects of the base stock levels on the availability of a system. This catalyzes the force on SCMS to provide information about the effect of base stock levels on availability.

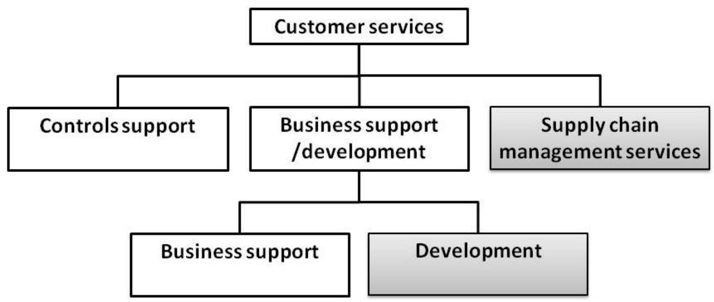


Figure 8 Structure of business unit 'Customer Services'

2.2 Inventory control for spare parts at VI

Spare parts inventory is controlled using a base stock policy. The first section discussed the supply chain for spare parts and the second section pays attention to the way in which base stock levels are determined.

2.2.1 Supply chain for spare parts

The department SCMS does handle all spare parts orders for customer center international and distribution, parcel and postal. The other customer centers chose whether they want to order spare parts via this department or directly at external suppliers. First it will be discussed how these orders at SCMS are handled in general. Next a distinction will be made between all possible sources of spare parts demand and how these are handled.

Overview

A spare parts order for a site can either be placed by the customer or by a VI employee who manages the stock. These orders are usually supplied from the Service Warehouse in Veghel. This warehouse will be called the central warehouse (CW) because it fulfills this function. The central warehouse is supplied by the manufacturing plant of VI and by external suppliers (see Figure 9). VI has a dedicated warehouse for spare parts; it is not shared with the warehouse for the VI plant and parts in this warehouse are only used to be delivered as spare part.

If an order consists of multiple items and there is no urgency, it is only shipped if all parts are available. If all spare parts from an order are available in the central warehouse in Veghel, the order lead time is 4 days at maximum and 2 days on average. If at least one part is missing, all items on the order will be backordered and the shipment will take place after all parts are received in Veghel. If this is the case, the lead time is significantly higher than 4 days. Spare parts do have a high lead time. This lead time does not cause significant problems because orders are usually to replenish a stock point or to build a stock point (just after installation of equipment). In case a customer needs the spare part immediately the lead time could be shortened because the customer is willing to pay extra; an emergency shipment takes place. VI has no contracts which obligate them to deliver spare parts within a certain time frame. There are contracts that do obligate VI to reach a certain availability, this is however always under the restriction that spare parts are available and the responsibility for the availability of spare parts is then assigned to the customer.

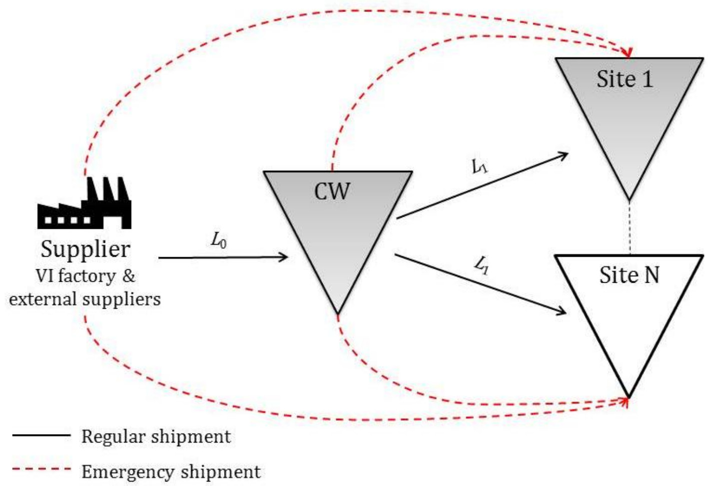


Figure 9 Spare parts supply chain

Usage of different supply chains

More specifically, demand for spare parts originates from five sources; failure due to wear, failure due to crash, preventive maintenance during service, planned preventive maintenance and revisions. Preventive maintenance during service occurs when it is noticed that a part has worn out so far that it is likely to fail before the next service visit. Figure 10 displays the supply chains used for these demand streams. The assignment of a spare parts demand to a certain supply chain is guided by the limitations of the stock point and the interaction between the service engineer and the service account manager. During a service visit, all preventive maintenance that can be executed by the spare parts on site is usually performed directly to prevent extra set-up costs. These maintenance actions will be referred to as preventive maintenance during service. If the spare parts that are necessary to execute the maintenance action are not available on site, the maintenance will be scheduled; planned preventive maintenance. All maintenance actions that require more spare parts than stored on site and are not a complete revision fall into this category. Whether these orders are delivered from the CW or the supplier depends on the way the maintenance action is offered to the customer. If it is offered as a maintenance action, the items are requested at the CW and if it is offered as a project, the items are requested at the supplier. Revisions are always offered as a project, the items are delivered from the supplier.

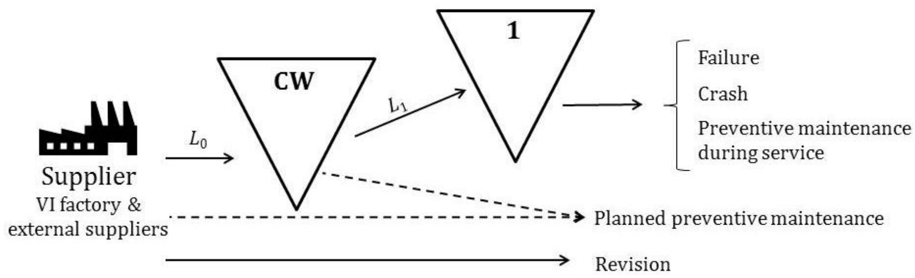


Figure 10 Current usage of supply chains

2.2.2 Determining base stock levels

VI has to decide upon the base stock levels of the central warehouse and advises about the base stock levels at the stock point at the customer. Whether VI advises or decides about the base stock level at the stock point at the customer and how this base stock level is maintained is dependent on the contract, see respectively Appendix I and II. The base stock level is presented to the customer as a recommended spare parts list. This list contains all items and the quantity that needs to be stocked. Usually, this list is not updated during the lifetime of an installed system, however sites with consignment stock and a site based maintenance team do update the base stock levels based on experience with their own system. First attention will be paid to the base stock levels at the central warehouse, then the advice for base stock levels at the sites will be discussed.

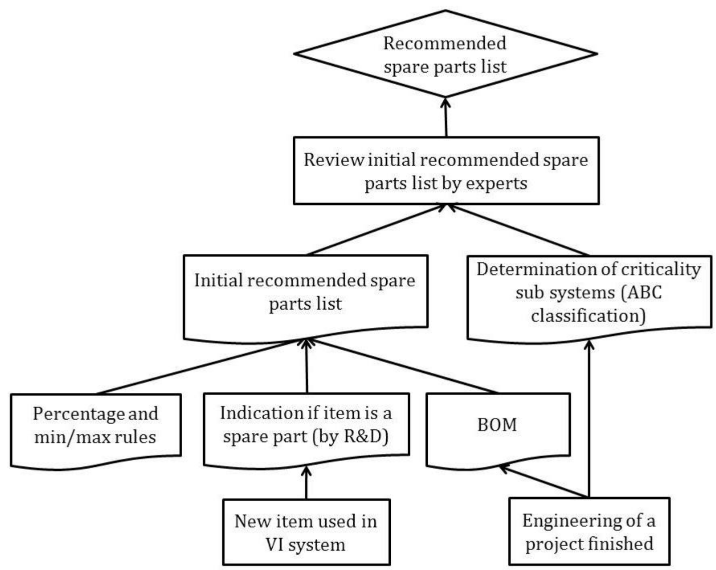


Figure 12 Creation initial spare parts list

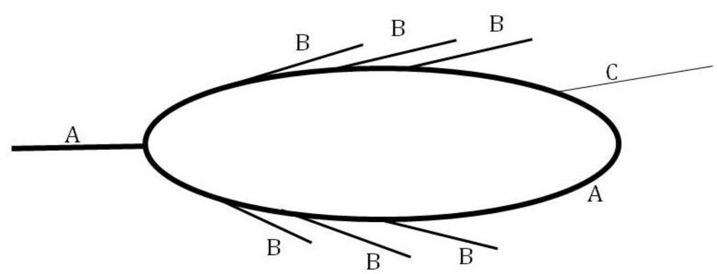


Figure 11 ABC classification; thickness of the line represents the intensity of use

The safety stock levels for items in the central warehouse in Veghel are determined as follows. Only items which were requested 3 times or more in the previous year and items with a lead time longer than 42 days are kept on stock. To determine the safety stock level, the average order quantity of customer orders at the CW is calculated and taken as the minimum. If there is a great variety in order quantities, this amount can be increased. For items from external suppliers the minimum order quantity is taken into account as well. Minimum order quantities do exist for part of the items. It is not quantified when the variety in order quantity is great and how the lead time is taken into account. Both are taken into account based on gut feeling. Base stock levels are updated twice per year based on these rules. This procedures is currently under review and will change.

The process of determining the

recommended spare parts list (including the base stock levels) is graphically displayed in Figure 11. SCMS creates a recommended spare parts list, based on information provided by the engineering department and the research and development (R&D) department. R&D indicated for all items whether it is a spare part. It has to be noted that this is a subjective process and that no fixed guidelines exist to decide whether an item is a spare part. Engineering indicated the *criticality* of all subsystems with 3 categories (ABC). The ABC category is linked to the location of an item in the system; all items at a specific location do have the same classification independent of their functionality. As can be seen in Figure 12, the main line, which is used by all packages/baggage is classified as A, a B-classification indicates a route which is used frequently, but in case of failure re-routing is possible whereas a C-classification indicates a route which is only used once in a while. Note that this classification is valid for all items in this part of the system; items used in the A part of the system, which failure does not affect the function of the system are classified as an A part. This procedure is under review as well.

Initially all items in a system that are indicated as spare part are placed on the recommended spare parts list. The base stock levels are determined using rules of thumb which are specific for several categories; all stock keeping units (SKUs) are classified into 37 categories based on their functionality (see Appendix III). These rules, together with the number of times that an item occurs in the system, are the input used to determine the base stock levels. The criticality categorization is not used, the ABC-classification is only notified in the recommended spare parts list. If an item is used several times in the system with different classifications, it appears one time on the recommended spare parts list with the highest classification. SCMS employees revise each list manually. Items are scrapped and base stock levels are revised based on expert opinion and the ABC classification.

The goal of SCMS is to set base stock levels as such that it is possible to perform both corrective and preventive maintenance actions during service from stock.

There is no feedback loop from customers or service engineers to SCMS about the base stock levels. Employees at the SCMS department do have the gut feeling that they are at the 'safe side' with the recommended spare parts list; that there are usually enough spares available. Service engineers do however notice that they don't understand all choices that are made regarding the spare parts that are kept on stock. They structurally miss some items and see that other items are almost never used.

3. Literature background

The goal of this chapter is twofold. On the one hand the goal is to provide background information about the constructs used in this research. On the other hand related studies will be discussed, so the place of this research can be determined.

In the introduction it is already explained that availability is important for capital goods. This construct will be defined and explained in detail in the first section. The second section discusses literature on spare parts inventory control.

3.1 Availability

The term availability is already used in the previous chapters. Availability is defined as 'the ability of an item to be in a state to perform a required function under given conditions at a given instant or time or over a given time interval, assuming that the required external resources are provided.' The system is not available after failure of a critical component and is available again after repair. The definition of availability can be expressed in the following formula according to van Houtum (2010):

$$Availability = 1 - \frac{Downtime}{Number\_of\_operational\_hours\_per\_year}$$

It can usually be assumed that planned maintenance is performed in the hours that the system should not be operating. The time required for these actions is not taken into account in the availability. Downtime can then be defined as follows:

$$Down\_time = FA \cdot (MD + RT)$$

in which FA denotes the number of failures per year, MD is the average maintenance delay per corrective maintenance action and RT is the repair time itself. The maintenance delay includes the time required to get everything required for the repair action (van Houtum, 2010). Based on this formula, there are two possibilities to increase system availability; increasing the reliability (decrease the amount of failures) or decreasing the downtime per failure. The reliability of a system is determined by decisions made in the design phase combined with the maintenance strategy. The speed of repair activities is determined by the availability of manpower, tools and spare parts (Paz and Leigh, 1994) and by the actual repair time. This review of availability is summarized graphically in Figure 13.

The design phase of capital goods falls outside the scope of this project. When SCMS has to advice upon spare parts inventory, the design of a system is already fixed at VI. The downtime per failure can be decreased by either decreasing the maintenance delay or the repair time. The speed of the actual repair can be increased by the repair-by-replacement concept; replacing a failed part by a ready-for-use one (Öner et al., 2010). The maintenance delay can be shortened by making sure that material, tools and repairmen are available. In order to decrease the downtime per failure, the material availability needs to be high. Spare parts inventories are necessary to keep the material availability as high as possible because these spare parts do have lead times (Aka et al., 1997). The availability of materials a for a VI system is determined by the spare parts advice and for customers without consignment stock, by whether this advice is followed. The availability of tools is usually not a problem if a repairman visits a site by car or if there is a maintenance team on site. Only if repairman has to visit a site by plane, he has limited possibilities to take tools with him. The availability of repairman is dependent from site to site. Some sites have an onsite maintenance team of VI, others have a general maintenance team with or without the option to call the VI helpdesk, and sites without repairman onsite do also exist. This project focusses on the availability of material.

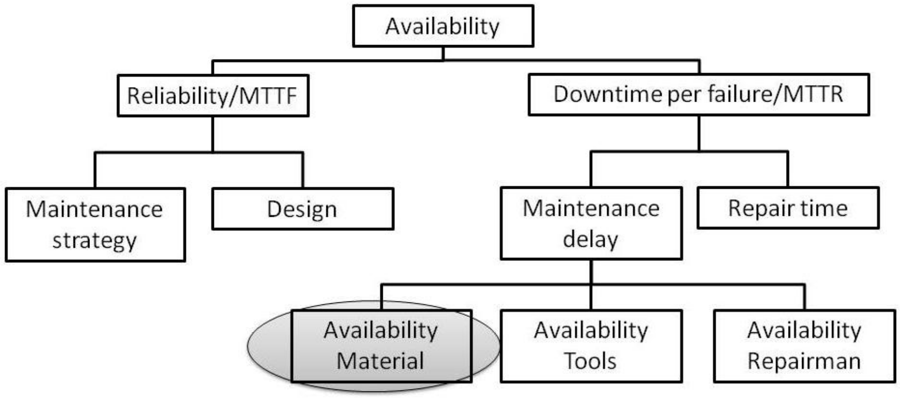


Figure 13 Availability

3.2 Spare parts inventory control

Almost all models for inventory control require a demand forecast and the best inventory model is useless if the demand estimates are garbage (Sherbrooke, 2004). The first section will therefore discuss the difficulties and possibilities to forecast demand for spare parts. The second section gives an short overview of optimization models for spare parts inventory that are available in literature.

3.2.1 Forecasting demand for spare parts

A distinction can be made between forecasting spare parts demand for a stock point for a single system, on site, or a CW.

Onsite spare parts inventories do have some unique aspects which cause extra difficulties when managing them. Three main difficulties are present in forecasting demand for spare parts; the demand of spare parts is often intermitted; random with a large proportion of zero values. Historical data of spare parts demand is usually limited and spare parts inventory level is largely a function of how equipment is maintained (Hua et al., 2007). Although it is found that many parts follow a Weibull failure process, the assumption of a Poisson demand process is less restrictive as it seems, because the number of identical parts in equipment is usually large in VI systems. If there are many similar parts in a machine, all having a Weibull failure distribution, the superposed demand process for spare parts will rapidly converge towards a Poisson process.

Beside these difficulties, need for spare parts is often influenced by maintenance policies (Kennedy et al., 2002). For planned (preventive) maintenance, the demand for spare parts is predictable and depends on maintenance schemes whereas the demand for unplanned, corrective maintenance is unpredictable. The demand process for spare parts differs for preventive and corrective maintenance, leading to the recommendation to follow a different approach for both types of spare parts in literature (Kennedy et al., 2002; Hopp and Spearman, 2008). It is usually possible to order spare parts for preventive maintenance in advance; the spare parts inventory does not have to be broken for preventive maintenance, this is what is called 'planned preventive maintenance' at VI, see Figure 10. An exception is, when the time between the moment at which the preventive maintenance is scheduled and the moment at which the preventive maintenance is executed is shorter than the lead time for spare parts. This is the case when preventive maintenance is executed during service at VI (see Figure 10). The maintenance is 'scheduled' at the moment that that a part has to be replaced (when the machine is opened) and the maintenance has to be executed before the machine closes again.

Sherbrooke (2004) stated that earlier demand prediction studies showed that the demand for spare parts, when looking at a specific system, for a short period tend to be a Poisson process with a constant mean and that the variance to mean ratio increases with an increasing observation period. It is stated that this implies that the demand process for most items is Poisson with non-stationary increments (where the mean may drift over time). Snyder et al. (2011) present a comparison of forecasting demand using a Poisson, Negative Binomial and a Shifted Hurdle Poisson distribution. For each model three methods for estimating the mean are implemented; a static mean, a damped dynamic mean (stationary autoregressive model for the mean) and an undamped dynamic mean (integrated moving average model for the mean). It is found that the traditional static Poisson distribution can be too restrictive for intermittent inventories. The results also show that all methods improve through the use of dynamic parameters. The unrestricted Negative Binomial distribution performs the best for the models with dynamic parameters. It can be concluded that for forecasting low volume intermittent demands one must look beyond the traditional Poisson format.

Besides these onsite inventories, VI also has to manage its CW. This CW has to deal with spare parts as well, however not all characteristics of spare parts demand that are discussed above are valid here. The demand for spare parts from a large number of sites comes together at the CW, making the demand stream less intermitted and has to deal with other variables like the size of the installed base. Because the CW does receive the demand streams from all locations, it is pre-eminently the location analyze these demand streams. It is possible to do statistical analysis on these demand streams in order to do improve the forecasts of demand at the inventory points on site.

3.2.2 Inventory control for spare parts

The goal of all models for spare parts inventory control is to advise upon optimal answers to the questions that are concerned in inventory control. Costs minimization and profit maximization are the most frequently used criteria in the optimization problem for inventory control in general. In spare parts inventory control, these are always used together with a service measure and service level in practice. Two types of service levels can be distinguished; type 1 service is the probability of no stock out during the lead time and type 2 service is the portion of demands met from stock (Nahmias, 2009). Type 2 service is also referred to as fill rate or β.

Many possible inventory models exist in literature. An overview of possible demand and delivery streams to take into account is given in Figure 14. The most basic spare parts inventory model is a single-echelon, single-item model. For this optimization problem the newsboy problem is used frequently in literature. The traditional newsboy problem determines the optimal service level based on the holding costs and penalty costs. Because penalty costs are usually hard to define, most applications in spare parts inventory modelling assume that the required service level is given. The minimum number of spares that need to be stocked to reach this service level is then calculated based on the demand distribution (Jardine & Tsang, 2006; Aronis et al., 2004; Louit et al., 2010).

An extension is the single-echelon multi-item inventory model for repairable items described by Sherbrooke (2004) and van Houtum and Hoen (2008) considers multiple items. It is a model that should be used for items that are 100% critical in order to assess the best mix of items to keep on stock. It assumes that all items in this group are equally important. Models in this category are especially useful when there are significant price diffences between items. The models use an aggregate performance measurement leading to an assessment of the contribution to the performance and the costs of keeping an extra item on stock. A more cost effective solution is found because a better performance of cheap items can compensate a lower performance of expensive items.

However, spare parts networks typically consist of local warehouses located nearby customers which are supplied from regional warehouses or from a central warehouse directly. The multi-echelon technique for recoverable item control (METRIC) developed by Sherbrooke (1986) is the basis for a large number of multi-echelon models. The objective of the METRIC model is to minimize the sum of backorders across all bases subject to a budget constraint. The corresponding METRIC evaluation approach is an approximation because the stochastic lead time at the local warehouses is replaced by its mean. It is also known that METRIC underestimates backorders. Graves (1985) developed the VARI-METRIC approximation and showed the this approximation gives more accurate results than the METRIC approximation. Both models METRIC and VARI-METRIC have been extended to multi-item optimization models by respectively Sherbrooke (1986) and Rustenburg et al. (2003). Muckstadt and Thomas (1980) extended the METRIC model with emergency shipments from both, the central warehouse and the external supplier. Axsäter et al. (2004) studied a model where customers demand occurs at the central and local warehouses and emergency shipments are possible from the supplier to the central warehouse. A two-echelon model with lateral transshipments and emergency shipments from both, central warehouse and supplier is studied by Alfredsson and Verrijdt (1999). If a local warehouse is not able to fulfill a demand, the possibility of lateral transshipments is tried first. If the item is available at none of the local warehouses a request for an emergency shipment from the CW is placed. If the items is also not available at the CW, it is delivered via an emergency shipment from the supplier who is considered to have infinite inventory. A disadvantage of their approximation method is that it is time-consuming. Özkan et al. (2011) studied a similar system without the possibility of lateral transshipment; the same model as studied by Muckstadt and Thomas (1980). Özkan et al. (2011) derived a fast approximate evaluation method and showed that their approximation outperforms the approximation of Muckstadt and Thomas (1980). Besides they showed that the performance measures of their system are roughly insensitive to the lead time distribution of the lead time from supplier to CW.

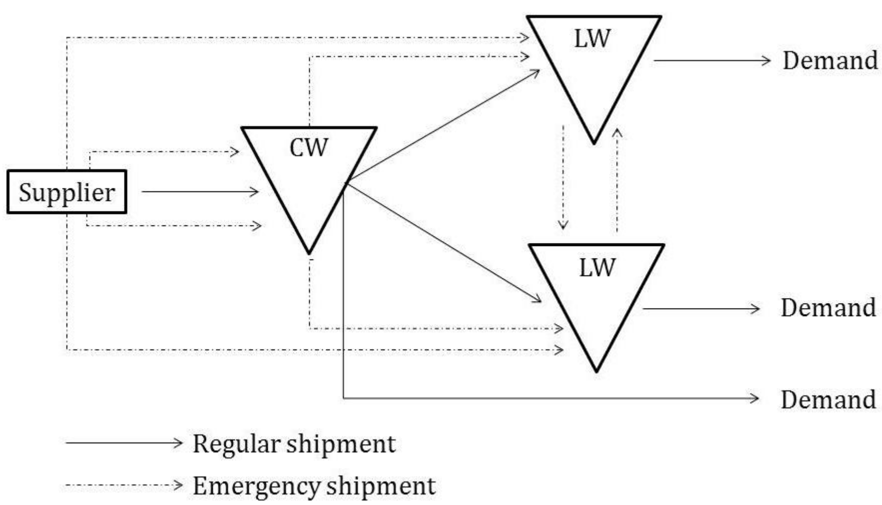


Figure 14 Possible demand and delivery streams to take into account

4. Research approach

Combining the literature discussed in Chapter 3 and the situation at VI, a research problem is defined in the first section of this chapter. The methodology used for answering the research question will be discussed in the second section. The scope of this research is given in the third section.

4.1 Research problem

In order to control spare parts inventories in an optimal way, forecasts for the demand are necessary. It is found that forecasts for spare parts demand are improved by using dynamic parameters for the demand distributions. With the term 'dynamic' is meant that the value assigned to certain parameters can change over time; the demand distribution does not have a fixed mean over time. Spare parts demand is originated by wear. Considering items that occur multiply times in a system, it likely that the expected demand for this item is lower in a brand new system then in a system in which items started to wear out.

Although it is shown that a better prediction is found using dynamic parameters in these models, most models in literature do use a Poisson process with constant parameters to model the demand for spare parts. Models with demand processes using dynamic, preset parameters are, to my knowledge, not applied in inventory control studies yet. This master thesis' can be placed in this gap in literature.

Base stock levels at VI are currently determined based on the rules described in section 2.2.2. These rules are developed in the past and not updated yet. The rules are based on expert opinion and not on historical data. The need for insights in the effects of base stock levels on availability is increasing by customers that become more critical and by the internal organization that has to offer competitive service contracts. It is also known that items in a VI system do wear out, so an increasing demand rate for these items during the lifetime of a system is expected. Based on these considerations, the problem is defined as follows:

> ***In which situations is it useful to apply dynamic base stock levels at a VI system in order to decrease the total costs of ownership of a capital good?***

4.2 Approach

In order to analyze whether dynamic base stock levels do create an advantage, an analysis of the costs and performance of an inventory control policy with and without dynamic base stock levels has to be compared. To analyze whether improvements are made with respect to the current situation, the costs and performance of the current situation have to be determined as well.

Three scenarios can be distinguished, see Table 1. Scenario I is the current inventory policy to determine base stock levels. These are constant and based on rules of thumb. Scenario II determines the performance of an inventory control policy with constant base stock levels that are determined by using historical data. Scenario III finally determines the performance of the controlling inventory by allowing for dynamic base stock levels. Scenario II is incorporated to make a fair comparison between constant and dynamic base stock levels.

Table 1 Scenarios inventory control of spare parts

Constant base stock levels	Scenario I *Current base stock levels*
	Scenario II *Constant base stock levels based on historical data*
Dynamic base stock levels	Scenario III *Dynamic base stock levels based on historical data*

The performance of three scenarios will be compared in a case study with some items used by VI. Besides the case study, an analysis will be performed to gain some general insights. In order to gain general insights, only scenario II and III will be compared because the rules of thumb used in scenario I are specific for VI. Based on the performance of the scenarios

To compare the performance of the three scenarios several steps has to be made (see Figure 15). First design choices about the scope and performance measures has to be made. Based on the scope and the performance measures, a model can be defined. It is important that this model is able to evaluate all three scenarios in order to prevent deviations in the performance caused by the calculation method. Based on this model an evaluation and an optimization procedure can be defined. It is self-evident that the performance of the base stock levels of all scenarios need to be evaluated. For scenario II and III, the optimal base stock levels have to be determined as well. To evaluate the scenarios, the input parameters of the model need to be defined using the available data. Knowing the input parameters, the results can be obtained. These have to be analyzed to draw conclusions.

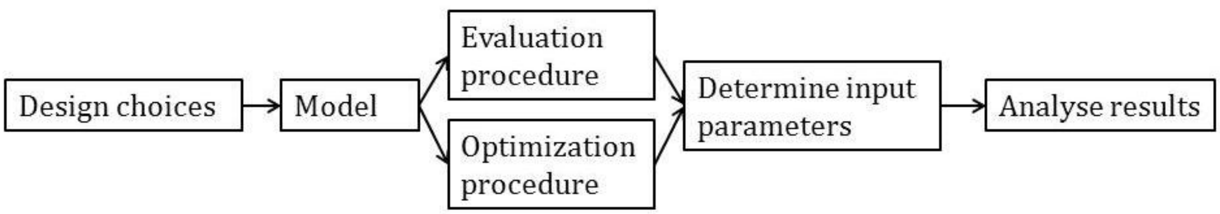


Figure 15 Research approach

4.3 Project scope

In this section only the scope of the model will be discussed. The scope of the case study is closely related with the availability of data. The consideration made in the selection of the product and items studied is therefore explained in Chapter 7.

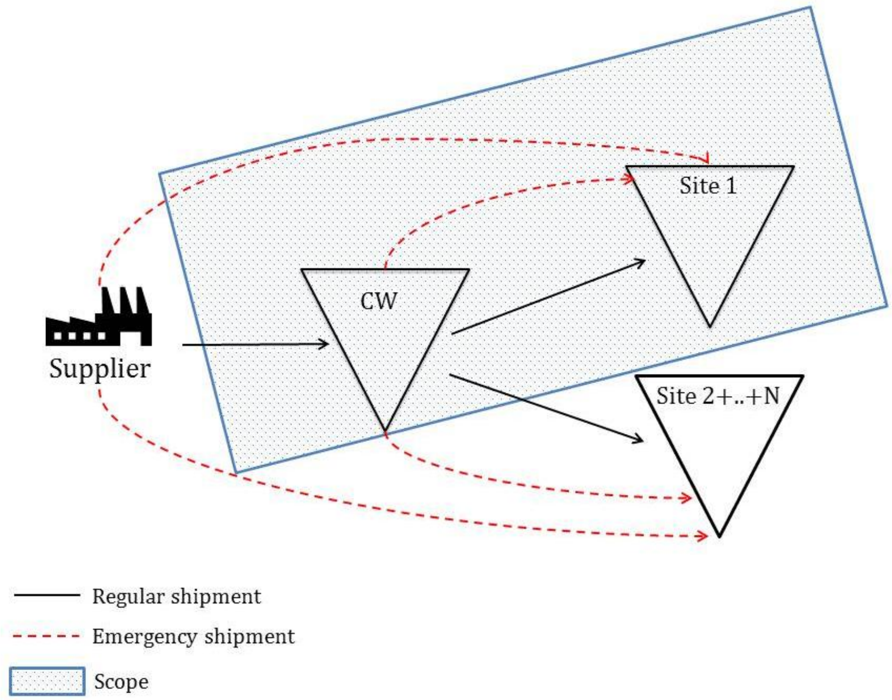


Figure 16 Scope

The scope of the model is graphically displayed in Figure 16. It can be seen that two locations fall inside the scope; one site and the central warehouse. The scope is determined based on the situation at VI. The need to have a good inventory policy is originates from customers that request VI to take care of the spare parts inventory management. All customers having a consignment stock contract, do have dedicated stock; VI is allowed to use the parts for a specific customer only. VI does have influence on the inventory policy at the other local sites, but lateral transshipments are contractually impossible. This led to the decision to take only one site into account. The optimal base stock level at a site is dependent on the lead time from the CW. The lead time from the central warehouse is dependent on the distance between the CW and a site and on the fill rate of the CW. The distance can be influenced by adding extra warehouses. This falls outside the scope because VI is interested in a way to make optimal use of the current warehouses. The fill rate of the CW can be influenced by adapting the base stock levels, and this does therefore fall into the scope. The CW does receive demand from all customers. These have to be taken into account in order to model the CW properly. The suppliers of the CW, which are either external organizations or the VI factory, fall outside the scope. The department Customer Services has a minor influence on these lead times, if at all. This makes the lead time for replenishment orders of the CW fixed. The possibility of emergency shipments from external suppliers to Site 1 fall inside the scope of this project. The arrow that depicts these emergency shipments is drawn from the supplier directly to the site. Note that it is still possible that the item is physically shipped via the CW. It is however not possible to use this item for another occurring demand; it is reserved for the customer having the emergency shipment. The possibility of emergency shipments from the CW to Site 1 is taken into account as well. Emergency shipments from both, CW and supplier to all other sites are not taken into account.

The only parameters that are considered as a variable are the base stock levels of the spare parts taken into account.

The model will use a single-item approach although Chapter 2 explained that a multi-item approach is better. The reasoning behind this decision is as follows. It is expected that the decision whether or not dynamic base stock levels are attractive, depends on item specific characteristics. A single item model will therefore be sufficient for this analysis. This does not implicate that inventory system with items for which dynamic base stock levels are attractive cannot be solved using a multi-item approach. After is it judged for which items dynamic base stock levels are attractive, it can be judged whether dynamic base stock levels are attractive for one of the critical components. If this is the case, a multi-item approach could be applied to determine the optimal base stock levels for every period.

It is stated that this study is performed with the perspective of total costs of ownership. Öner et al. (2007) stated that lifecycle costs for an engineer to order system can be split into acquisition costs, maintenance costs, operating costs and downtime costs. The VI systems are engineered to order, so it is assumed that these costs will cover all costs for VI systems. Only those parts of the TCO that are affected by the decision variables need to be taken into account. Acquisition and operating costs fall outside the scope of this study. Maintenance costs will be influenced via the spare parts inventory control policy and fall inside the scope of this study. However, only inventory holding costs and the costs of emergency shipments are influenced by the different inventory control policies and are the only costs taken into account. Downtime costs are influenced by the inventory control policy via the delay time that is caused by the (un)availability of spare parts. It is however hard to determine these cost. The costs of downtime will therefore be excluded from this research but the delay time caused by the (un)availability of spare parts falls inside the scope.

Note that although this thesis assumes consumable spare parts, the model can be easily adapted to repairable spare parts. The supplier will then be replaced by the repair facility, the lead time will be replaced by the repair time and the calculation of the holding costs will be simplified because the number of spare parts in the system is always equal.

5. Model and analysis procedure

The goal of this chapter is to show the models used to analyze the three scenarios. First the model for constant base stock levels will be discussed. If values are assigned to all variables, an evaluation is required. An approximate evaluation method based on the study of Özkan et al. (2011) is shown in the second section. The third section gives the optimization problem and the fourth section provides a procedure to approximate the solution. The fifth section gives adaptations that are required to use the model and procedures for a multi-period situation.

5.1 Model for constant base stock level

The focus of the model is on the local warehouse (LW) for spare parts at site 1 where a technical system is operating. This LW is replenished from the CW which is taken into account in this model as well. All other sites that create a demand stream to the central warehouse are modeled as LW2. The CW is denoted by index 0; n locations are modeled $n \in \{0,1,2\}$. The replenishment lead time for location n equals L_n.

The model assumes that it is impossible to repair failed items. Therefore new parts are required when a failure occurs. Failures lead to a demand of m_n units per period for LW n. If a demand occurs at LW 1, there are 3 possible relevant situations concerning the net inventory of the warehouses;

1. LW 1 can fulfill the demand from stock
2. LW 1 cannot fulfill the demand from stock, but a part is available at the CW
3. Both, LW 1 and the CW do not have the part on stock

If situation 1 occurs, the demand is satisfied immediately; it is assumed that local warehouse 1 is located on site and the mean delay time when an item is on stock here is neglected. In the second situation, the demand is satisfied by the CW via an emergency shipment leading to a mean delay time of EL^{CW} time units. The costs of emergency shipment from the CW equal C^{CW}. If the third situation occurs, it is assumed that the (external) supplier does always have a possibility to provide the spare part leading to a mean delay time of EL^{sup}, $EL^{sup} > EL^{CW}$ time units. The costs for this emergency shipment are equal to C^{sup}, $C^{sup} > C^{CW}$. As displayed in Figure 17, β_1 represents the fraction of the demand fullfilled from local stock, γ_1 is the fraction of the demand fulfilled from the CW and the fraction of the demand that is fulfilled by the suppliers is denoted by θ_1. Note that there are no backorders because of the emergency shipments from the central warehouse and (external) supplier.

It is assumed that LW2 has infinite inventory. This means that emergency shipments to Local Warehouse 2 do not occur; this location only generates a stream of replenishment orders to the CW.

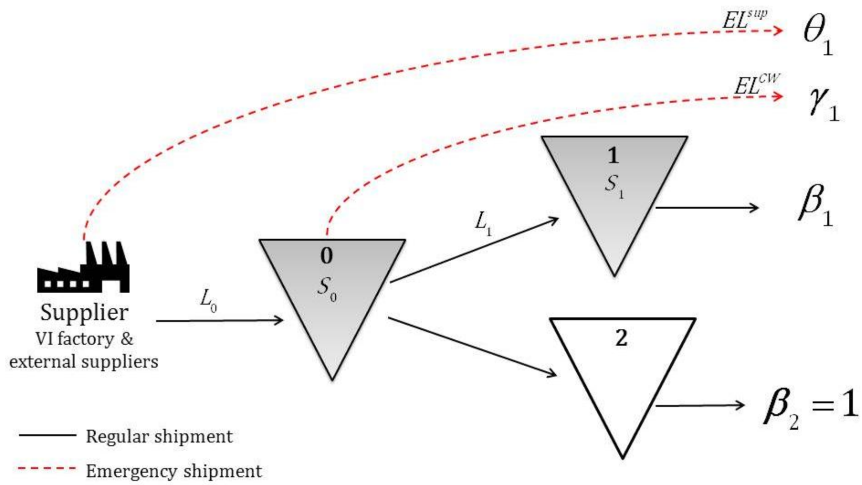


Figure 17 Possibilities to fulfill demand

The inventory at all warehouses, is controlled by a base stock policy with order up to level S_n; if the inventory drops below S_n parts are ordered to get the inventory level at S_n again. The holding costs for keeping an item on stock at location n equals h_n per time unit.

5.2 Evaluation procedure

The model described above is close to the model with a general number of local warehouses as studied in Özkan et al. (2011). Özkan et al. (2011) developed an approximate evaluation method to calculate β_n, θ_n and γ_n for all local warehouses n. In this study only the values for β_1, θ_1 and γ_1 are calculated which simplifies some calculations. The solution procedure is therefore slightly adapted for the application in this study. The adapted version of the algorithm is described in Appendix IV. Most of the approximation steps that are made for the use of this method are discussed when explaining the method. An important approximation is that all demand streams are independent of each other and independent of the actual inventory. This approximation is not violated because the demand stream at the central warehouse is largely influenced by location 2 which makes it almost independent of Location 1.

5.3 Optimization problem

The objective is to minimize the total costs subject to a performance measure. The construct downtime is discussed in chapter 3. Spare parts availability does influence the maintenance delay. The maintenance delay is however specified per failure. The yearly addition to the downtime will however be used in this study, logistic downtime is chosen as performance measure. The costs are assumed to consist of holding costs and emergency costs. Holding costs are calculated for all parts on hand at the central warehouse and local warehouse 1 (using the steady state parameters) and for the parts in the pipeline between the CW and local warehouse 1 $m_1 \cdot \beta_1 \cdot LT_1$. Emergency costs are calculated by multiplying the fraction of the demand delivered via an emergency channel by the corresponding emergency costs and the demand rate $m_1 \cdot (\theta_1 \cdot C^{CW} + \gamma_1 \cdot C^{\sup})$. These costs functions lead to the following objective function:

$$\min : C = \sum_{n=0}^{1} \sum_{x=1}^{S_n} h_n \cdot x \cdot \pi_{n,x} + h_0 \cdot m_1 \cdot \beta_1 \cdot LT_1 + m_1 \cdot (\gamma_1 \cdot C^{CW} + \theta_1 \cdot C^{sup})$$

The steady state parameters, β_n, θ_1 and γ_1 are obtained using the approximation analysis of Özkan et al. (2011). This minimization problem is constrained by a maximum logistic downtime that may be caused by the specific item. The logistic downtime can then be calculated by multiplying the demand rate with the expected logistic downtime per failure. The variable D is used to indicate the logistic downtime per time unit. The constraint is formulated as follows:

$$D \leq D_{\max}$$

where

$$D = m_1 \;\; \gamma_1 \cdot EL^{CW} + \theta_1 \cdot EL^{sup}$$

Note that this restriction for the logistic downtime is only concerning Location 1. To take the CW in a fair way into account, a restriction concerning the fill rate of the CW is necessary (otherwise all inventory will be placed at site 1).

$$\beta_0 \geq \beta_{0,\min}$$

5.4 Optimization procedure

Enumeration is used to optimize the base stock levels at the central warehouse and local warehouse 1. The optimization procedure systematically analyses all possible combinations of (S_0, S_1) via the variable $S_{total} = S_0 + S_1$., where one starts with $S_{total} = 0$. For every value of S_{total} the combination of (S_0, S_1) leading to the best solution is chosen as input for $\widehat{C}(S_{total})$. $\widehat{C}(S_{total})$ denotes the minimal costs that can be obtained under a total stock, S_{total}. The best solution is defined as the solution with the lowest costs out of all feasible options (all options with $D \leq D_{\max}$); if there is no feasible solution $\widehat{C}$ is set at infinite. Then S_{total} is raised with 1 unit leading to new combinations of (S_0, S_1). Again the best solution is chosen. This procedure is executed till the stop criterion is met. The stop criterion is defined using a lower bound on the inventory holding costs. It is known that the holding costs increase by keeping more items on stock. The behavior of the total cost function is unknown. If for S_{total} a value is reached at which the holding costs are higher than the most optimal feasible total costs of all solutions evaluated until that point, then it is sure that no options with lower cost can be found at the current or higher values of S_{total}.

For a stock point that is controlled by a base stock policy, the inventory at this stock point together with the pipeline stock is by definition equal to the base stock level. To find the number of items at a certain stock point, the pipeline stock has to be subtracted. The lower bound for the holding costs then becomes:

$$h_0 \cdot \left[S_0 - m_0 \cdot L_0 \right] + h_1 \cdot \left[S_1 - m_1 \cdot \;\; L_0 + L_1 \;\; \right]$$

This lower bound can be simplified by bounding3 the holding cots with the lowest holding costs; $h = \min(h_0, h_1)$ leading to:

$$h(S_0 + S_1) - h_0 \cdot m_0 \cdot L_0 - h_1 \cdot m_1 \cdot (L_0 + L_1)$$

At the end, all feasible solutions are analyzed and the feasible option with the lowest costs is chosen.

5.4.1 Adaptions for dynamic base stock levels

When working with dynamic base stock levels, a finite horizon T is considered. T is split in periods, $t \in \;\; 1,2,3...|T|$ (see Figure 18). The base stock levels of the LWs can be updated each period. It is assumed that the duration of these periods is long enough to make the assumption of steady state behavior justified.

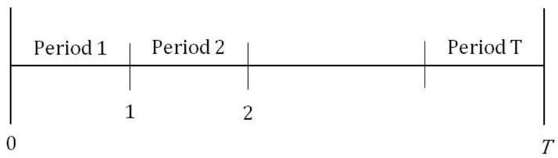


Figure 18 Split in periods graphically displayed

If a base stock level is increased, this implies that the current stock level is too low and an order is placed to increase the current inventory level up to the new base stock level. If the base stock level is decreased, the net inventory comes to this new level by attrition; no inventory is scrapped.

Dynamic base stock levels are evaluated and optimized for each period using the procedure described above. Because the base stock levels are dynamic, all related variables also get dynamic and thus an extra indict t . The optimization model for each period for the scenario with dynamic base stock levels becomes:

$$\forall t \in T : \min : C = \sum_{n=0}^{1} \sum_{x=1}^{S_{n,t}} h_n \cdot x \cdot \pi_{n,t,x} + h_0 \cdot m_{1,t} \cdot \beta_{1,t} \cdot LT_1 + m_{1,t} \cdot (\gamma_{1,t} \cdot C^{CW} + \theta_{1,t} \cdot C^{sup})$$

Subject to: $$\forall t \in T : D_t \leq D_{t,\max}$$

$$\forall t \in T : \beta_0 \geq \beta_{0,\min}$$

where

$$D_t = m_{1,t} \ \ \theta_{1,t} \cdot EL^{CW} + \gamma_{1,t} \cdot EL^{sup}$$

While the method of evaluation and optimization does not change concerning the content, retyping this procedure with the extra indices is regarded needless.

5.5 Implementation of the model and optimization procedure

The evaluation and optimization procedure as described above are programmed in the software tool MATLAB. During this programming one approximation is made. The code and the way the program is built up can be found in Appendix V. The validation of the program is also discussed in this Appendix. For the validation of the program, a distinction is be made between subprograms that do calculate something and subprograms that have the function to select the best possibility from a subset of possible solutions. Subprograms that calculate something are validated by doing the calculation by hand. Subprograms that have to select the best option are validated by checking all options, choosing the best one by hand and comparing this with the output of the program. The programs were found to be valid.

6. General insights

A numerical experiment is conducted to gain general insights. Using the experimental results, two questions will be answered:

1. Under which conditions is it potentially attractive to apply dynamic base stock levels at a local stock point?
2. What is the order of magnitude of savings that can be gained by the application of dynamic base stock levels at the local warehouse compared to constant base stock levels.

Note that these questions focus on the local stock point. Dynamic base stock levels will not be attractive for the CW because it is assumed that the product studied is in the mature phase of its lifetime; the installed-base and its distribution of the age of these systems are assumed to be constant.

To judge the attractiveness of dynamic base stock levels, a time frame should be kept in mind. A horizon of 12 years will be considered. It is assumed that the demand rate is the only parameter that changes during these years. The change in demand rate will be represented by a minimum and a maximum demand rate during the time frame studied, respectively $m_{1,\min}$ and $m_{1,\max}$.

The questions will be answered in the 2 sections below. The test bed to answer Question 1 will have a broad scope. The test bed to answer Question 2 will than focus on the situations for which dynamic base stock levels are potentially attractive.

6.1 Potential attractiveness of dynamic base stock levels

The first section will discuss some background information and the reasoning that is used behind the setup of the test bed and to explain the results. The second section gives the test bed used for this numerical experiment, and the third section discusses the results. The fourth section provides a conclusion.

6.1.1 Background

It can be argued that a dynamic base stock level is only potentially attractive when different base stock levels are optimal at different points in time. Based on the optimal base stock levels alone, it cannot be decided if dynamic base stock levels are attractive. For example, for a cheap screw of which the optimal base stock level only slightly changes, it will not be cost effective to apply dynamic base stock levels.

The only variable that changes over time, is the demand rate. The change in demand rate is expected to have an effect on the potential attractiveness of dynamic base stock levels; a larger difference in demand rate will increase the potential attractiveness of dynamic base stock levels. The base stock levels are however not only determined by the demand rate. All other input variables are likely to influence the potential attractiveness of dynamic base stock levels as well. The goal of this section is to find out how these variables interact and what the effects are on the potential attractiveness of dynamic base stock levels. The direction in which the variables are expected to influence the potential attractiveness of dynamic base stock levels is discussed below.

Two reasons to keep stock can be identified for the optimization problem drawn in section 5.3:

1. To satisfy the constraint of the maximum logistic downtime.
2. From a costs perspective; if the expected holding costs are less than the expected emergency costs.

When at least one of these reasons is true, it is expected that it is efficient to keep stock in general. The reason to keep stock is expected to influence what variables determine the potential attractiveness of dynamic base stock levels. Some variables are expected to have influence in both situations, others only in one situation. The lead time of a replenishment order is expected to influence the potential attractiveness of base stock levels in both situations. A long lead time will increase the effect of a change in the demand rate and thus the likeliness that dynamic base stock levels are potential attractive.

If the reason to keep stock is to satisfy the logistic downtime constraint, it is expected that the input variables concerning the lead time of emergency shipments will have an effect on the potential attractiveness of dynamic base stock levels. A shorter lead time for emergency shipments makes the contribution of an emergency shipment to the yearly logistic downtime smaller.

If stock is kept from a cost perspective, it is expected that input variables concerning the costs do influence the potential attractiveness of dynamic base stock levels. Lower holding costs and higher costs for emergency shipments will lead to higher base stock levels then high holding costs and low emergency costs. It is however unclear how these variables do influence the potential attractiveness of dynamic base stock levels.

Besides, it is expected that, if these reasons to keep stock do not hold for the maximum demand rate, there will be no advantages to keep stock and dynamic base stock levels will be unattractive.

6.1.2 Method

As mentioned above, dynamic base stock levels are only potentially attractive if different base stock levels are optimal at different points in time. To test whether the optimal base stock level differs over time, the optimal base stock level is calculated using the minimum demand rate as well as using the maximum demand rate.

This section will identify in which situations the optimal base stock levels do and do not change over time and the influence of the different input parameters on this change. A diverse set of input variables will be used to identify these situations.

In order to answer this question, only the minimum and the maximum demand rate have to be known. Whether or not two different base stock levels are optimal with demand rate $m_{1,\min}$ and $m_{1,\max}$ is not dependent on the demand pattern in-between. Different possibilities of demand patterns are given in Figure 19.

For all combinations of input parameters, the optimal base stock levels are calculated for certain combinations of $m_{1,\min}$ and $m_{1,\max}$. Dynamic base stock levels are judged to be potentially attractive if the optimal base stock level under $m_{1,\min}$ is different from the optimal base stock level under $m_{1,\max}$.

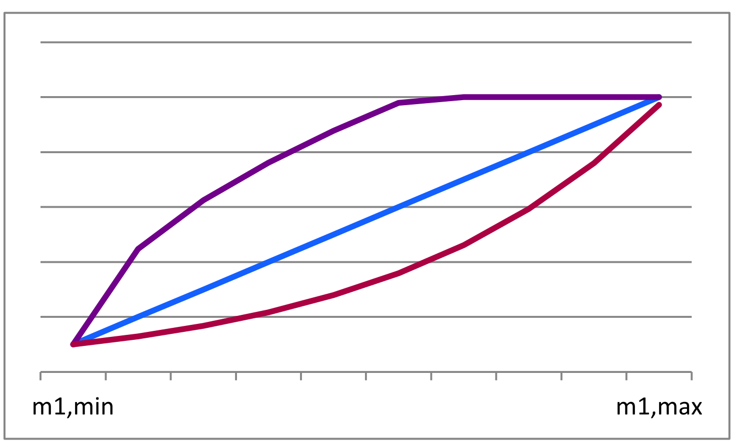


Figure 19 Path between $m_{1,\min}$ and $m_{1,\max}$.

6.1.3 Test bed

Ten input variables determine the optimal base stock level at a certain point in time in the model discussed in Chapter 5. These are the inventory holding costs, the regular lead time and the demand rate at both locations, the lead time and the costs for emergency shipments from the supplier and the CW to Location 1, the maximum logistic downtime at Location 1, and the minimum fill rate at the CW.

In case the optimal base stock levels are different in both situations, it can be concluded that dynamic base stock levels are attractive.

In order to analyze the effect of all input variables on the attractiveness of dynamic base stock levels, a full factorial analysis should be executed. As mentioned earlier, there are 10 input variables and performing a full factorial analysis with 2 values for each variable will lead to 2048 combinations. It will therefore be argued below which values will be kept constant in this experiment. Next the complete test bed will be discussed.

Variables that are kept constant

The focus of this numerical experiment is on Location 1. The CW falls within the scope of the model. Some of the input variables do therefore affect the CW and do not have a major influence on the base stock levels at Location 1. These will be kept constant during this experiment to limit the amount of combinations in the factorial design.

The assumption that the product studied is in the mature phase of its lifetime implies that the demand rate at the central warehouse is not changed during the lifetime of equipment at Location 1. To keep the total demand $m = m_1 + m_2$ constant, m_2 will be decreased if m_1 increases and vice versa. The value of m_2 can decrease in real life when an older system gets a revision or is scrapped and a new system is installed (elsewhere). The value of m_0 does not directly influence the base stock levels at location 1, because a minimum fill rate for the CW is enforced. The only restriction to this value is that $m_2 >> m_1$ to keep the results of the approximation of Özkan et al. (2011) reliable. The value of m_2 can however not be too large because the computation time increases when the demand rate increases. For this analysis, $m_0 = 10$ items per week is set; so, $m_2 = 10 - m_1$ items per week.

The lead time for orders from the supplier to the CW has a minor influence on the local base stock levels. The same reasoning is valid; the effect of this lead time will be balanced by the constraint of the fill rate of the CW in this study.

The lead time from the CW to Location 1 does influence the base stock levels. The optimal base stock levels are among others determined by the demand during the lead time. The demand rate is kept variable leading to different values for the demand during the lead time. It can be argued that it is equal for the analysis whether this change is caused by a change in demand rate or by a change in lead time. An overview of the parameters that are kept constant is given in Table 2.

Table 2 Values assigned to variables that are kept constant

Variable	Unit	Value
Demand rate location 2 (m_2)	Items/week	$10 - m_1$
Lead time to location 0 (L_0)	Weeks	7
Lead time to location 1 (L_1)	Weeks	1

To limit the amount of input variables, it is assumed that holding costs at the site of the customer are equal to the holding cost in the CW. This is a reasonable assumption from the perspective of consignment stock (the inventory at both locations will then be owned by one party).

Variables that change during the experiment

All variables that will be changed during the experiment will be mentioned in this section. The minimum demand rate of the system at location 1 will get three values ($m_{1,\min}$ =0.01; 0.08; and 0.3 items per week). The maximum demand rate will also get three values that are dependent on $m_{1,\min}$. The effect of a relative and an absolute change in the demand can be analyzed by using this approach. The values for $m_{1,\max}$ are: $m_{1\min} \cdot 1.1$, $m_{1\min} \cdot 2$ and $m_{1\min} + 0.1$ items per week. The holding costs are dependent on the price of an item. The value of items has a broad range, a broad range of holding costs is therefore considered; $h = 0.5$ and $h = 50$ €/week are considered. This corresponds to respectively € 26 and € 2600 per year. The costs of an emergency shipment from the CW are mainly costs for transportation. Transportation costs can have a wide range; it depends on the transportation mode and the distance. The values used for this analysis are $C^{CW} = 100$ and $C^{CW} = 1200$ euro per shipment. The lead time of emergency shipments for the CW will be set at two values $EL^{CW} = 1$ day and $EL^{CW} = 0.5$ week per shipment. The costs of an emergency shipment from the supplier will also get two values. These values do have a wider range than the cost of an emergency shipment from the CW. Apart from the transportation costs, it is reasonable that a high fee is requested if an item is urgently ordered at an external supplier because this party has to interrupt its regular production scheme. Two values will be used as input for the emergency costs ($C^{sup} =$ € 300; € 3000 per shipment). For the lead time of emergency shipments from the supplier two values will be used as input as well; $EL^{sup} = 2$ days and $EL^{sup} = 1$ week per shipment. The lead time for an emergency shipment from a supplier is limited by the production time of an item. It is assumed that the time needed to produce and ship an item from the supplier is longer than an emergency shipment from the CW. The maximum allowed downtime per year is set at two values; $D_{max} = 20$ minutes per year and $D_{max} = 18.3$ days per year. The difference between these values is large and the first value is more realistic than the second value assigned to this variable. The high acceptable downtime is used to lose the delay time constraint. Such a value could occur in practice if the failure of an item does not lead to stoppage of the whole system. The minimum fill rate for the CW is set at two values; a quite low fill rate of 0.3 and a fill rate of 0.92. An overview of the parameters that are kept constant is given in Table 3. The only combination that will not be analyzed is $C^{sup} = 300$ and $C^{CW} = 1200$ because this is an unrealistic combination.

Table 3 Values assigned to variables that change in numerical experiment

Variable	Unit	Values
Maximum logistic down time (D_{max})		20 min/year; 18.3 days/year
Lead time of an emergency shipment from the supplier (EL^{sup})	Weeks	(2/7);1
Lead time of an emergency shipment from the CW (EL^{CW})	weeks	(1/7);0.5
Minimum demand rate at location 1 ($m_{1,\min}$)	Items/week	0.01;0.08,0.3
Maximum demand rate at location 1 ($m_{1,\max}$)	Items/week	$m_{1\min} \cdot 1.1$; $m_{1\min} \cdot 2$; $m_{1\min} + 0.1$
Costs of an emergency shipment from the supplier (C^{sup})	Euro/item	300;3000
Costs of an emergency shipment from the CW (C^{CW})	Euro/item	100;1200
Holding costs ($h = h_0 = h_1$)	Euro/(week$\cdot$ item)	0.5;50
Minimum fill rate CW ($\beta_{0,min}$)	-	0.3;0.92

6.1.4 Results

The results of this numerical experiment are shown in Appendix VI. A summary of the results is provided in Table 4. The effect of all variables that are changed in this analysis will be discussed per variable below.

Table 4 Results potential attractiveness dynamic base stock levels

Parameter	Value	# instances	Difference in base stock level	
			# instances	%
D_{max}	20 min/year	432	198	23%
	18.3 days/year	432	188	22%
EL^{sup}	0.29 weeks	432	202	23%
	1 weeks	432	184	21%
EL^{CW}	0.14 weeks	432	191	22%
	0.5 weeks	432	195	23%
$m_{1,\min}$	0.01 items/week	288	128	15%
	0.08 items/week	288	130	15%
	0.3 items/week	288	128	15%
$m_{1,\max}$	$m_{1\min} \cdot 1.1$	288	22	3%
	$m_{1\min} \cdot 2$	288	194	22%
	$m_{1\min} + 0.1$	288	170	20%
C^{sup}	€ 300 /item	288	108	13%
	€ 3000 /item	576	278	32%
C^{CW}	€ 100 /item	576	248	29%
	€ 1200 /item	288	138	16%
h	€ 0.5 item/week	432	207	24%
	€ 50 item/week	432	179	21%
$\beta_{0,min}$	0.3	432	167	19%
	0.92	432	219	25%
All		864	386	45%

Maximum logistic down time

The maximum logistic downtime does not influence the potential attractiveness of dynamic base stock levels.

Lead time of emergency shipments

The lead time of emergency shipments from both CW and supplier does not influence the potential attractiveness of dynamic base stock levels.

Demand rate

The maximum demand rate clearly has an effect on the attractiveness of dynamic base stock levels based on Table 4. Table 5 gives closer insights in the effect of the minimum and maximum demand rate.

Table 5 Effect demand rate; # instances where dynamic base stock levels are potentially attractive (for each combination 96 instances were studied)

	$m_{1\min} \cdot 1.1$	$m_{1\min} \cdot 2$	$m_{1\min} + 0.1$	factor of $m_{1\min} + 0.1$
$m_{1,\min} = 0.01$ items/week	0 (0%)	38 (40%)	90 (94%)	11.0
$m_{1,\min} = 0.08$ items/week	0 (0%)	61 (64%)	69 (72%)	2.3
$m_{1,\min} = 0.3$ items/week	22 (23%)	95 (99%)	11 (11%)	1.0

The numbers in the left part of Table 5 indicate the amount of instances were dynamic base stock levels are potentially attractive. The right part gives the factor that makes $m_{1,\min} \cdot factor = m_{1,\min} + 0.1$. It can be seen that an increase in the factor with which $m_{1,\min}$ is multiplied leads to an increasing potential attractiveness of dynamic base stock levels. Another result that follows from this overview is that an increase in $m_{1,\min}$ leads to an increase in attractiveness of dynamic base stock levels.

Costs

Based on the results of Table 4, it can be judged that costs do have an effect on the potential attractiveness of dynamic base stock levels. Deeper analysis showed that this result is dependent on the value of D_{max} as well. Table 6 gives an overview of this relation.

Table 6 Effect costs and maximum downtime; # instances where dynamic base stock levels are potentially attractive

	C^{sup}		C^{CW}		h	
	€ 300	€ 3000	€ 100	€ 1200	€ 0.5	€ 50
# instances	288	576	576	288	432	432
D_{max}=20 min / year	66 (23%)	132 (23%)	131 (23%)	67 (23%)	99 (23%)	99 (23%)
D_{max}=18 days / year	42 (15%)	146 (25%)	117 (20%)	71 (25%)	108 (25%)	80 (19%)

It can be seen that in the cost do not influence the results when D_{max}=20 min / year. If D_{max}=18 days / year stock is kept from a costs perspective. A decrease in the holding costs or an increase in the costs of an emergency shipment leads to a higher base stock level in general. These circumstances do make it more attractive to change the base stock level over time.

Minimum fill rate CW

The results in Table 4 show that dynamic base stock levels are potentially less attractive when $\beta_{0,min} = 0.3$. This can be explained as follows. The reliability of timely delivery of the CW is quite bad with $\beta_{0,min} = 0.3$. The application of dynamic base stock levels requires that it is possible to keep less items on stock while still meeting all requirements. A less reliable supply from the CW, increases the risk of keeping less items on stock locally. This hinders the application of dynamic base stock levels.

6.2 Savings by the application of dynamic base stock levels

This section has a similar structure as the previous section. The method is discussed first. Then the test bed is explained, followed by the results. Finally a conclusion is provided.

6.2.1 Method

The savings that are made are determined by comparing the costs of the scenario with dynamic base stock levels and the costs of the scenario with constant base stock levels. For the case with constant base stock levels, the downtime restriction should be met for all periods so the highest demand rate is used as input for the analysis.

Figure 20 shows how the demand rate is assumed to change over time. As mentioned in the introduction, a time horizon of 12 years is taken into account in this analysis. At time point 0, the demand rate equals $m_{1,\min}$ and at time point 12 the demand rate is $m_{1,\max}$. The time frame is split in periods of 2 years. It is assumed that the demand increases linear over time (purple line). This increase in demand rate is approximated by the blue blocks. For each block of 2 years, the optimal base stock level is calculated by the average demand of this time frame.

In case the demand would exponentially increase, the savings would be higher when compared to linear growth. The base stock level of the period with the highest demand will then deviate more during a longer period of time.

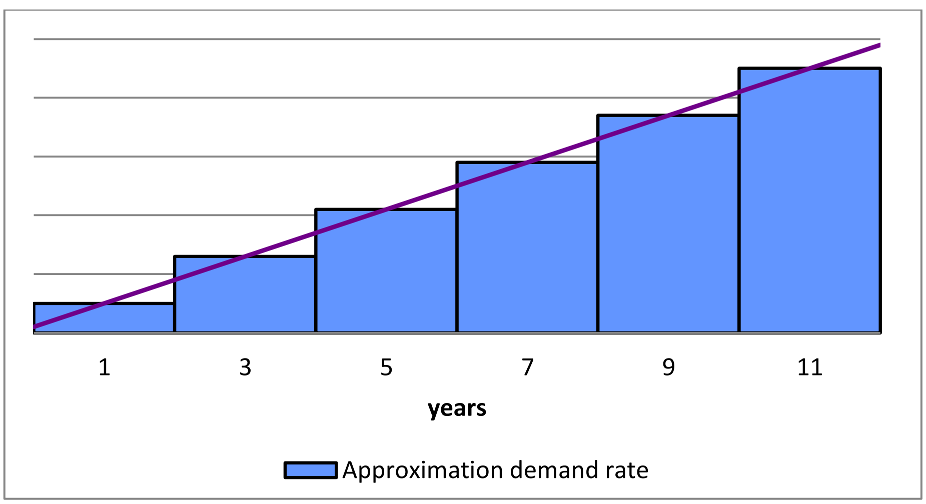


Figure 20 Approximating the demand rate

6.2.2 Test bed

The goal of this test bed is to answer the question regarding the magnitude of savings that can be gained by applying dynamic base stock levels. Section 6.1 showed that the potential applicability of dynamic base stock levels is mainly dependent on the change in demand rate. This analysis is more extensive because it takes the intermediate periods into account as well. It is chosen to vary only a limited amount of parameters, based on the results of the previous section.

Based on the analysis in the previous section, $m_{1,\min}$ and $m_{1,\max}$ do have an effect on the potential effectiveness of dynamic base stock levels. All three values for $m_{1,\min}$ are used as input and linked to one value of $m_{1,\max}$. The difference between potentially attractiveness of dynamic base stock and real attractiveness of dynamic base stock levels is determined by the cost difference. The costs for emergency shipments and the holding costs are therefore taken into account. The value of D_{max} influences the relation of the costs and the potential attractiveness of dynamic base stock levels and is taken into account as well. The minimum fill rate is fixed at 0.92 because this is assumed to be the most realistic assumption. The lead time for emergency shipments from the CW is also taken into account. The lead time of an emergency shipment from the supplier is fixed at 2 days. An overview of the values assigned to the parameters is given in Table 7.

Table 7 Test bed analysis of saving of the application of dynamic base stock levels

Variable	Unit	Values
Maximum logistic down time (D_{max})		20 min/year; 18.3 days/year
Lead time of an emergency shipment from the supplier (EL^{sup})	Weeks	2/7
Lead time of an emergency shipment from the CW (EL^{CW})	Weeks	1/7;0.5
Minimum demand rate at location 1 ($m_{1,\min}$)	Items/week	0.01;0.08;0.3
Maximum demand rate at location 1 ($m_{1,\max}$)	Items/week	$m_{1\min}+0.1$ for $m_{1,\min}=0.01$ and $m_{1\min}\cdot 2$ for $m_{1,\min}=0.08;0.3$
Costs of an emergency shipment from the supplier (C^{sup})	Euro/week	300;3000
Costs of an emergency shipment from the CW (C^{CW})	Euro/item	10;1200
Holding costs ($h=h_0=h_1$)	Euro/week	1;200;1000
Minimum fill rate CW ($\beta_{0,min}$)	-	0.92
Demand rate location 2 (m_2)	Items/week	$10-m_1$
Lead time to location 0 (L_0)	Weeks	7
Lead time to location 1 (L_1)	Weeks	1

6.2.3 Results

The results of this numerical experiment are shown in Appendix VII. A summary of all results is provided in Table 8. The effect of all variables that are changed in this analysis will be discussed per variable below. The focus of this discussion will be on the change of costs. The absolute change in the base stock level can sometimes help to provide an explanation of the results and is therefore explained as well. The difference in optimal S is the difference between the optimal base stock level under $m_{1,\min}$ and the optimal base stock level under $m_{1,\max}$. The potential savings are higher when a greater change is necessary to keep the base stock level optimal. After discussing all parameters, an explanation will be provided for the differences in optimal base stock level under the given parameter.

Table 8 Results attractiveness dynamic base stock levels, all instances

		# instances	% change Avg. TC (€/year)	Abs. change Avg. TC (€/year)	Sum of difference in optimal S (items)
D_{max}	20 min/year	36	-13%	- € 654.70	43
	18.3 days/year	36	-17%	- € 338.23	33
EL^{CW}	0.14 weeks	36	-13%	- € 390.57	34
	0.5 weeks	36	-16%	- € 602.36	72
$m_{1,\min};m_{1,\max}$	0.01;0.11 items/week	24	-20%	- € 501.68	31
	0.08;0.16 items/week	24	-5%	- € 151.97	12
	0.3;0.6 items/week	24	-18%	- € 835.75	33
C^{sup}	€ 300 /item	24	-13%	- € 436.11	22
	€ 3000 /item	48	-15%	- € 526.64	54
C^{CW}	€ 100 /item	48	-17%	- € 530.98	49
	€ 1200 /item	24	-11%	- € 427.44	27
h	€ 0.5 item/week	36	-13%	- € 12.55	42
	€ 50 item/week	36	-16%	- € 980.38	34
all		72	-15%	- € 496.47	608

Maximum logistic down time

The previous section stated that the maximum logistic downtime did not have an effect on the potential attractiveness of dynamic base stock levels. The results in Table 8 show a difference in savings for the two values of maximum logistic downtime. A contradiction is found between the highest savings when comparing the change in terms of percentage and the absolute change. Under a maximum downtime restriction of 18.3 days per year, less stock is needed to fulfill this restriction and stock is kept from a costs perspective in several instances. This makes the solution more cost efficient (2.8 times cheaper) leading to this contradiction in change.

The difference in terms of absolute savings can be explained in the absolute change that is required to keep the base stock levels optimal.

Lead time of emergency shipments

A longer lead time for emergency shipments seems to make dynamic base stock levels slightly more attractive. This can be explained by the absolute change in base stock level that is required to keep the base stock level optimal.

Demand rate

The minimum and maximum demand rate influence the savings that can be made by introducing dynamic base stock levels. The relation between the savings and the sum of the difference in optimal base stock level is visible.

Costs of an emergency shipment

The effect of the costs of an emergency shipment seem to influence the attractiveness of dynamic base stock levels. The difference savings can be explained by the difference in the optimal base stock level that is necessary to keep the base stock levels optimal.

A contrasting result is found for the effect of the cost of an emergency shipment from the CW and an emergency shipment from the supplier. The results are split for the maximum logistic downtime in Table 9. With a maximum logistic downtime of 20 minutes per year, only minor differences in the costs are found. The tight restriction allows only a small amount of emergency shipments which limits the influence of the costs of an emergency shipment. In the cases where the maximum logistic downtime is 18 days per year, an assessment is made between the holding costs and the emergency costs.

Table 9 Relation maximum logistic downtime and costs of an emergency shipment on the average yearly savings

		$D_{max} = 20 \min / \; year$	$D_{max} = 18.3 days \; / \; year$
C^{sup}	300	- € 656.02	- € 216.21
	3000	- € 654.04	- € 399.24
C^{CW}	100	- € 655.46	- € 421.60
	1200	- € 653.17	- € 201.71

Holding costs

The holding costs have the greatest impact on the absolute savings. Savings in the holding costs are the only potential savings that can be made if different base stock levels are optimal over time. Below it is explained that this is true independent of the motivation to keep stock.

If the motivation to keep stock comes from the delay time restriction this is straightforward. Let period A be the period with lower demand rate and period B the period with a higher demand rate. Let the optimal base stock level be 3 in period B and 2 in period A. The savings that are gained are then the holding costs for one item during period A.

If the motivation to keep stock came from a costs perspective, it is less straightforward that the only savings are the holding costs. Let again period A be the period with lower demand rate and period B the period with a higher demand rate. The optimal base stock level are again 3 in period B and 2 in period A. Based on the consideration between holding costs and inventory costs, it is determined that it is optimal to use a base stock level of 2 items in period A. This means that moving to 3 items on stock for period A, implies an increase in holding costs that is greater than the decrease in emergency costs. The only savings are the holding costs while the emergency costs will never decrease by keeping less inventory. It is already argued that the maximum demand rate is used in the situation of constant base stock levels and a lower demand rate will never lead to an optimal solution with more inventory in the same optimization model. The emergency costs do however influence the result because a lower base stock level will increase the emergency costs which will have a counteracting effect on the decrease in holding costs. The holding costs therefore determine the potential savings.

Differences in optimal base stock level

Based on the discussion above, it can be stated that the absolute change in base stock level has a relation with the savings that can be made. The effect on the saving could be explained by this value for all parameters except the holding costs. The reason that the holding costs are stronger in determining the savings is explained above.

The changes in the sum of the difference between optimal values for the base stock level can be explained for the demand rate. The proportion between the sum of the difference in optimal base stock level corresponds to the results of Table 5. Table 10 is similar to Table 5, expect that the sum of difference in optimal base stock level is given here. A similar conclusion as for Table 5 is valid here. An increase in both, $m_{1,\min}$ and the factor with which $m_{1,\min}$ is multiplied do have a positive relation with the sum of the difference in optimal base stock level.

Table 10 Effect demand rate on the sum of the difference in optimal base stock level (for each combination 96 instances were studied)

	$m_{1\min} \cdot 1.1$	$m_{1\min} \cdot 2$	$m_{1\min} + 0.1$	factor of $m_{1\min} + 0.1$
$m_{1,\min} = 0.01$ items/week	0	38	133	11.0
$m_{1,\min} = 0.08$ items/week	0	61	69	2.3
$m_{1,\min} = 0.3$ items/week	22	152	11	1.0

For the other parameters, no logic could be discovered behind the instances where the attractiveness of dynamic base stock levels was influenced by a change in the parameter and the instances where the attractiveness of dynamic base stock levels was not influenced by a change in the parameter. It is found that it depends on how close to optimal the base stock level for the minimum demand is. Base stock levels are by definition integers and therefore an approximation of the optimal value. How close this approximation is to optimal, influences whether the same approximation is optimal for a higher demand and if the base stock level does change or not.

6.3 Conclusion

It can be concluded that only a few of the ten input variables that determine the optimal base stock level have a major effect on the attractiveness of dynamic base stock levels. These are the inventory holding costs and the difference in demand rate during the replenishment lead time. For the other parameters it depends on the combination of the slack of the optimal solution and the increase in demand, whether or not the optimal base stock level is changed due to this increase in demand; if the slack is able to absorb the difference in demand the base stock level will not be changed. A greater difference in demand rate will increase the chance that this cannot be absorbed by the slack. The savings that will be made by the application of dynamic base stock levels are made because less stock has to be kept. The gains that can be made are therefore mainly dependent on the inventory holding costs.

There are two possibilities to reach significant saving by the application of dynamic base stock levels; the change in demand rate has to be great so that the decrease in inventory holding costs has a noticeable effect independent of the holding costs per item, or the holding costs have to be high so that a base stock level that is decreased by one item does have a noticeable effect.

7. Case study

This chapter discusses the case study at Vanderlande Industries. Recall that the 3 scenarios will be evaluated using real data of VI. The scenarios are displayed in Table 1.

Figure 21 displays the steps that were necessary to evaluate the different scenarios. This chapter is organized in these steps. The first step is data collection, in order to determine the values of the input variables for the second step. Usually a demarcation of a product, items and customers to perform a case study on is made beforehand. As discussed before, not much data is available within VI. This will therefore be the most important selection criterion to do the demarcation. This intertwined the data collection and the demarcation which are discussed together in the first section. The second section discusses how the input parameters are determined based on the data.

With these values of the input parameters, the current policy is evaluated in the third step. This is discussed in the third section. The fourth section discusses the last step in Figure 21; the optimization and evaluation of scenario II and III which are possibilities for improvement. A sensitivity analysis is executed and the last section will give a conclusion.

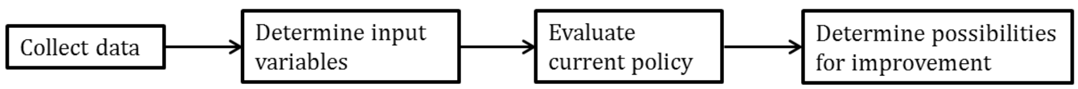


Figure 21 Steps to perform a case study

7.1 Data collection

Field data is required to execute the analysis described in the previous section. The required information consists of the lead time, holding costs, cost of an emergency shipment and demand data for both, site and CW. Although the model focusses on a single customer, it is impossible to derive a demand distribution for spare parts based on a single system. The demand pattern of multiple customers of a certain product is required. In addition, demand data has to be time dependent in order to analyze the difference between dynamic and constant base stock levels. It is known at VI that wear is influenced more by running hours then by real hours, which creates the requirement to get data about the running hours as well.

The methods to collect these different types of data are discussed in the following sections.

7.1.1 Data collection to determine the demand rate for spare parts

The richest amount of data is available for customers having a contract for consignment stock and an on-site maintenance team. The combination of these services is delivered at a limited number of locations. Other sites for which a rich amount of data exists are sites with consignment stock combined with a contract that specifies that VI executes all maintenance activities. This combination occurs at a limited amount of sites. The products installed at all sites are different which makes it not possible to obtain a representative sample in order to derive the average demand rates. However, financial data is available for all spare parts shipped. A distinction can be made between spare parts that are resale items (items that are available on the market) and VI-items (items that are not available on the market). All systems sold by VI contain these VI-items. Because VI-items need to be bought at VI, it is possible to derive the demand rate for these items using the financial data. An important limitation is that only 35% of all spare parts are VI-items. This doesn't have to be a problem, if it does not affect too much critical spare parts. The case-study focuses therefore on such a product for which not many critical items are resale items.

In the first section below the selection of the product is discussed. To derive the demand pattern for a certain product, the demand pattern of this product at several customers is compared. The selection of items and customers is intertwined and is discussed together in the second section. The selection of the items and customers made it possible to filter all demand occurrences from the financial data. These data points do include a time stamp which is linked to the date at which the site went operational. Also other site specific information like the system configuration is necessary to derive the demand pattern. The way in which this data is collected is discussed in the third section.

Selection of a product

The case-study was performed for one VI product due to limited time. The requirements for the selection of this product were based on the data availability which was necessary to evaluate and optimize all scenarios (see Appendix VIII). Looking at the data, only the Posisorter could be used for this study. Lifetime sheets are developed within VI and provide information about the critical spare parts that wear out. Except the motor all items on the lifetime sheet of an Posisorter are VI-items. This minimizes the disruption of the fact that only 65% of all spare parts are resale items for which the demand rate cannot be obtained.

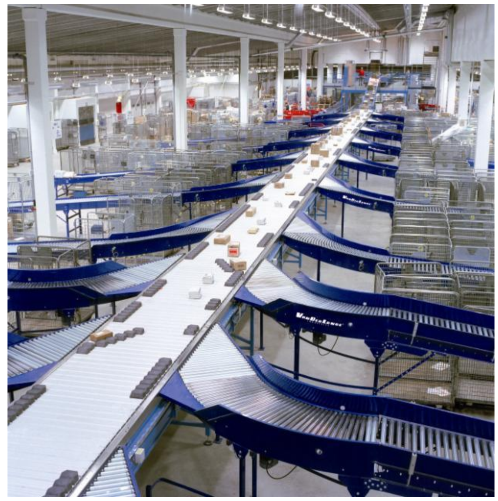


Figure 22 Posisorter

The Posisorter is a frequently used product in distribution and parcel and postal systems. The Posisorter is generally the heart of a system of a customer. All packages are put on the Posisorter and the function of the Posisorter is to slide the packages into the right exit. A picture of the Posisorter is given in Figure 22. Appendix IX describes how the Posisorter performs its function technically.

Selection of customers and items

The goal of this data selection is to get a dataset with the spare parts usage of the critical spare parts of an Posisorter. To get a good view on the spare part usage of Posisorters it was required that the information came from a representative subset of the Posisorters in the field. It was not possible to use the Posisorters of a single customer (with several Posisorters) because it was given that customer specific variables like cleanness, capacity (packages/hour), running hours, etc. do have an effect on the demand pattern for spare parts. It was therefore chosen to focus on a diverse set of customers.

It may be that not all critical spare parts are on the lifetime sheet. Recalling the definition of critical in this project; failure leads to (partial) stoppage of the Posisorter. If a spare part does not wear out, but failure leads to stoppage of the Posisorter the spare part does not occur on the life time sheet, but it is critical according to the definition of this study. Therefore all VI-spare parts on the spare parts list were kept in the analysis for so far. This selection is made at point 1 in the overview in Figure 23. This step is explained in more detail in Appendix X.

Knowing the spare parts and the corresponding item numbers, the sales history of these spare parts was found by linking the data to the database with spare parts sales. How this is done exactly is discussed in detail in step 2 in Appendix X.

Knowing the sales of all VI-spare parts, a selection of customers and spare parts to take into account had to be made. It was not possible to take all customers into account because site-specific information like the running hours and system configuration had to be collected and a limited time was available. Spare parts are left outside the analysis for several reasons; only VI-items are taken into account, demand had to be occurred at the customers studied and it had to be critical items. This selection had to be a representative sample of all Posisorter customers and the items had to be critical. It is known at VI that spare parts ordered at SCMS are used for planned preventive maintenance as well. These had to be deleted because goal of this data selection is to find the demand rate for items in the local spare parts inventory. It is assumed that orders with a high order quantity were meant for planned preventive maintenance, revisions or big crashes these were also deleted from the dataset. The details of this selection can be found in Appendix X.

The items that were left in the selection are the crossing, divert shoe, divert switch, merge and proximity switch. More information about the function of these items can be found in Appendix IX.

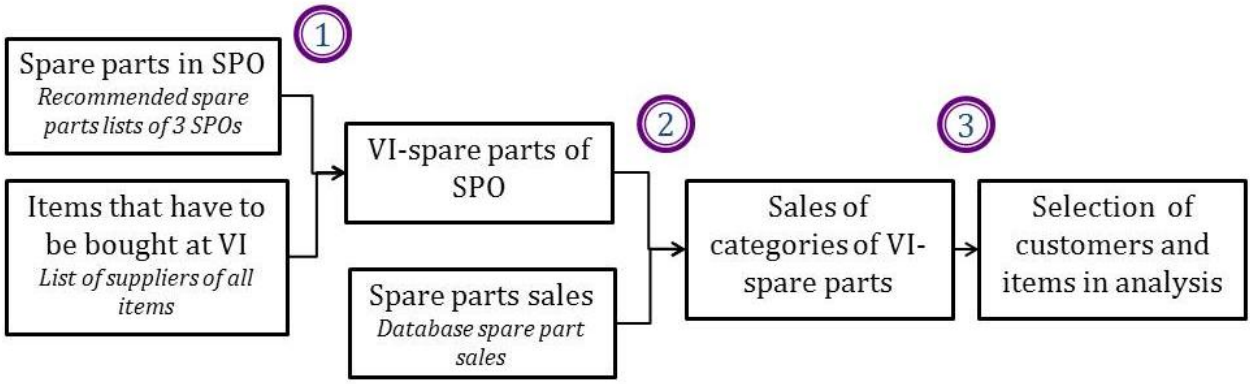


Figure 23 Data selection

Transforming the data

The result of the selection steps discussed in the previous section is a list of all demand occurrences of the selected customers for the selected items. Data was available for the period between April 1st 2003 and August 8th 2010. In order to analyze the possibility of dynamic base stock levels, it had to be known how many running hours a system had made at the time that the demand occurred. This information was derived from the date that the system went operational and the yearly running hours. The date that the system went operational was first looked up in the sales reference database and (when available) checked at the service account manager. Otherwise the date was estimated by the service account manager. The yearly amount of running hours was estimated by the service account manager as well. It is known that this is an approximation, it is however believed that the service account manager is the person able to make the best guess about the yearly running hours.

The average demand related to the amount of running hours is estimated over a period as long as possible by combining the demand occurrences of several customers. The fact that several sites with different ages are used in the dataset, incurred that the quantity of items in the dataset studied changed over time. This can be explained using Figure 24. The horizontal lines indicate the lifetime of the Posisorter at a customer. The lifetime of the Posisorter is much longer than 7 years so three possibilities are possible:

- The system of the customer went into operation before 01-04-2003 and closed before 13-08-2010 (customer A in Figure 24)
- The system of the customer went into operation before 01-04-2003 and was still operating at 13-08-2010 (customer B in Figure 24)
- The system of the customer went into operation after 01-04-2003 and was still operating at 13-08-2010 (customer C in Figure 24)

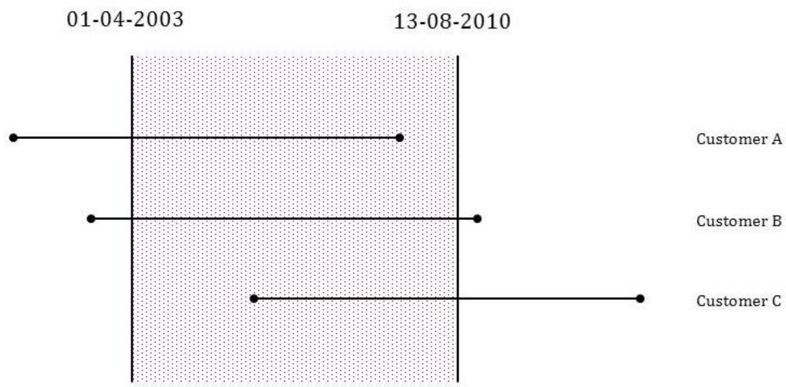


Figure 24 Amount of customers in the dataset differs at different time sections

Appendix XI provides an overview of the lifetime of the sites in the dataset. If a site went into operation before April 1st 2003 it is also indicated how many running hours were made before the data collection started. All Posisorters are customer specific and all customers use the Posisorter differently. Therefore the amount of occurrences of a specific item and the running hours at a specific age were different for all Posisorters. This means that the amount of items are studied after a specific amount of running hours differs. To determine the chance on a demand occurrence, it had to be known how many items were studied at a specific moment (amount of running hours). The picture in Figure 24 has to be transformed to the picture in Figure 25.

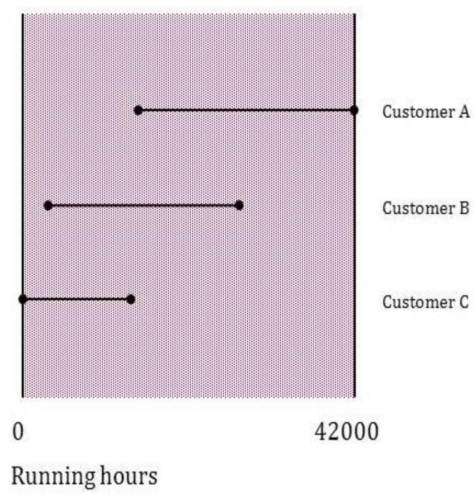


Figure 25 Amount of customers studied to running hours

The procedure that is used for this transformation will be described by an example. Consider customer A, B and C as the total selection of customers in the dataset and the crossing as the item studied (see Figure 26). Customer A had 20,000 running hours at the 1st of April 2003, a failure resulting in a demand occurrence of three crossings at 25,000 and is broken down after 40,000 running hours. Customer B had 5,000 running hours at the 1st of April 2003, 35,000 running hours at the 13th of August 2010 and no failures in between. Customer C went into operation at the 15th of May 2005, had a failure resulting in a demand occurrence of 1 crossing after 10,000 running hours and had run for 20,000 hours by the 13th of August 2010. For the failure of customer A at 25,000 running hours, 25+5=30 crossings were in the dataset resulting in a probability for a demand occurrence of 3/30. For the failure of customer C at 10,000 running hours, 5+10=15 crossings were in the dataset resulting in a probability for a demand occurrence of 1/15.

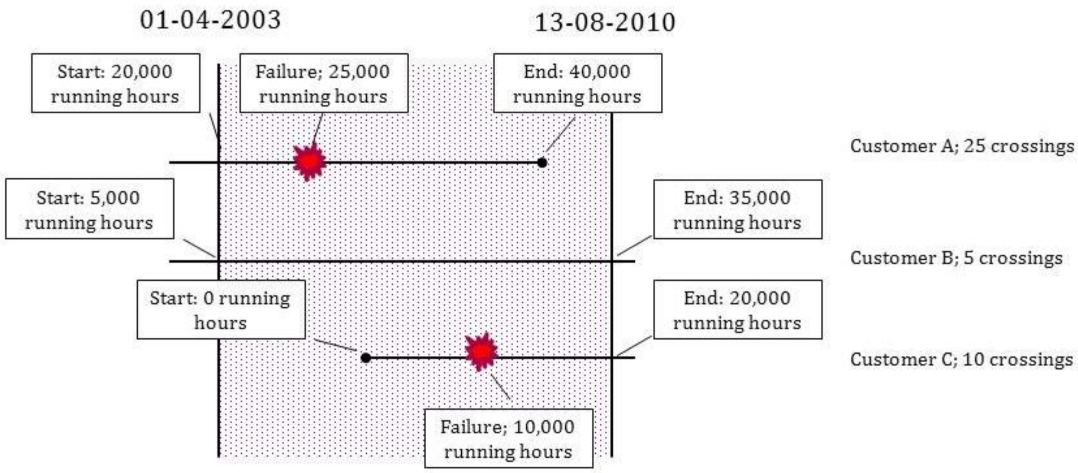


Figure 26 Determining the chance of failure

Note that using this method makes sure that it is taken into account that the intensity of use of a system can vary from customer to customer. From the amount of running hours and the dates, it can be derived that customer B uses its Posisorter less hours per year than customer A and C.

The quantity of an item in the Posisorter(s) of a certain customer is determined using the technical drawings of the project. This turned out to be the most reliable way to determine the quantities in the system.

Assumptions made in data collection

Several assumptions were made during the data collection process:

- As soon as an item breaks down, it is replaced using a spare part. After using a spare part, an order is placed to get the inventory level at the desired level again.
  Note: it is known that this assumption might not be fully justified. This assumption is however necessary because the financial data is the only data available.
- Orders that were placed before the system went live are not taken into account. It is assumed that these items were either missing when installing the machine or broke down during the test phase of the system.
- If an order occurred with an order quantity larger or equal than the total quantity of the item in the system, it is assumed to be a (partial) revision. After a (partial) revision the running hours for this part are set at zero.

7.1.2 Collecting data to determine other input variables

Besides the information about the demand rates for the items studied, other input variables had to be determined. These variables are listed below as well as the way these variables are determined:

- Demand rate at location 2
  - Was obtained from the financial data. The method is described in section 6.2.3.
- Base stock level at the central warehouse
  - The historical base stock levels as used at VI in 2009 were used because these were the most recent for which both, the historic base stock levels and the total demand rate were known.
- Base stock level at the location studied
  - Was obtained by applying the min-max rules (given in Appendix III) to a fictitious system that is assumed to be at Location 1. This fictitious system will be defined below.

- Lead time to the central warehouse
    - The agreed lead time from a supplier to Veghel is given. Several items are put together in one category and different lead times are agreed for the different items. The lead time of the item that occurred most frequent is chosen. When there were large differences between the lead times of the items in one category, the most extreme values were used as input for the sensitivity analysis which will be discussed in section 6.5.
- Lead time from the central warehouse to the customer
    - If an item is available in Veghel, it takes 2 days to reach the customer on average.
- Yearly holding costs at central warehouse
    - The yearly holding costs are assumed to be 17.5% of the cost price. Several versions of the same item are put together in one category and different versions have different costs. The costs of the item that occurred most frequent is chosen. When there were large differences between the prices of the items in one category, the most extreme values were used as input for the sensitivity analysis which will be discussed in section 6.5.
- Holding costs at customer
    - The yearly holding costs are assumed to be 17.5% of the sales to customer value. This are costs calculated to customers having consignment stock. Several items are put together in one category and different items have different costs. The costs of the item that occurred most frequent is chosen. When there were large differences between the prices of the items in one category, the most extreme values were used as input for the sensitivity analysis which will be discussed in section 6.5
- Costs of an emergency shipment from the central warehouse
    - No additional costs are counted for an emergency shipment because no additional costs are calculated at VI.
- Costs of an emergency shipment from the supplier
    - Most suppliers do not calculate extra costs for an emergency shipment and VI does not calculate an extra fee for emergency shipments. The costs from an emergency shipment from the supplier are therefore assumed to be 0. The effect of this choice will be analyzed in the sensitivity analysis.
- Duration of an emergency shipment from the CW
    - It is assumed that the customer is located in the Netherlands, Belgium, Germany, France, Great-Brittan, etc. Delivery can than take place within 1 day.
- Duration of an emergency shipment from the supplier
    - It is assumed that a supplier delivers in 1/3 of the regular delivery lead time in case of an emergency shipment

7.2 Determine the input parameters

As discussed before, all Posisorters are customer specific and all customers use an Posisorter in their own way. This creates the need to define an average Posisorter. The average Posisorter and its determination is discussed the first section. Data gathered via the method described above was used to determine the average demand in the lead time. How this is done is described in the second section. The demand rate from all customers not at the location studied, but creating a demand stream to the CW, was determined in the way described in section 6.3.

7.2.1 An average Posisorter

Based on the information of the Posisorters at the customers studied, an average Posisorter is defined. This Posisorter has a length of 135 m, 16 points with exits on 2 sides and 7 points with a single exit. The average customer runs its system on average 3333 hours per year which is equal to approximately 64 hours per week or 9 hours per day. The standard deviations that go along with these averages are quite high. The analysis will therefore also be performed for an extreme large, an extreme small system and the amount of running hours will also be varied. The effect of these changes will be discussed in the sensitivity analysis in section 6.5

7.2.2 Demand rate per item

Knowing all demand occurrences at a certain amount of running hours for the items studied gave the opportunity to analyze this data. The data provided demand rates at very specific time point. To be able to see a pattern in the data, the data need to be grouped. The demand was grouped per 1000, 3000, 5000 and 7000 running hours. A consideration had to be made between seeing too many and too less details. It is chosen to use the grouped demand per 5000 running hours because it showed results without giving too many details. These data were plotted in graphs, like the demand rate for the crossing is given in Figure 27. The graphs for the other items can be found in Appendix XII. The demand rate is expressed in a change that a single item fails in a time interval of 5000 running hours. It has to be noted that demand occurrences found in the intervals later than 35,000 running hours are less reliable; they are based on a smaller subset of the total population which gives coincidence a greater impact (more extreme).

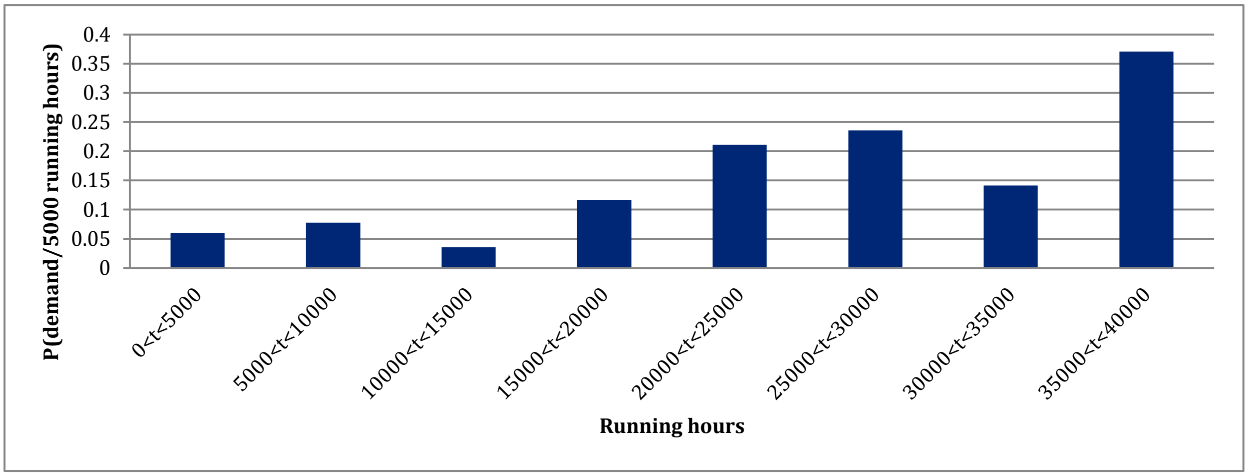


Figure 27 Demand rate for the crossing

These graphs were discussed with experts within VI to see whether the information from the data corresponded with practice. According to these discussions an extra test was performed to check whether the order quantity of the demand occurrences in different intervals were different. This was tested using a analysis of variance (ANOVA) in SPSS, no significant changes were found. This rejected the option that customers did order a large quantity of crossings in the interval 25000<t<30000 causing that they only needed a small quantity in the interval 30000<t<35000 (which could have explained the dip in the graph in Figure 27). Another unexpected result is the decreasing demand for the merge. However the merge is an item that does usually not fail due to wear during operation but it does fail at crashes. The demand rate is therefore assumed to be constant because crashes are assumed to occur random. It seemed to be impossible to explain all data, together with the experts it was decided which part of the data was realistic and should be used to determine the demand rate and how to overrule the data that seemed to be unrealistic. This is shown in Table 11.

Table 11 Combining data and expert opinion

Crossing	Use all data
Divert shoe	Use data till 30,000 running hours, after this point the demand rate becomes constant
Divert switch	Delete data point 30,000<t<35,000
Merge	Use data till 25,000 running hours and force a constant demand rate
Proximity switch	Use all data but force a constant demand rate

For the selection of the data left after the discussion with the experts a regression analysis was done in order to fit an empirical distribution for the demand rate. The average amount of running hours in an interval is used as input for the regression analysis. The bar at 0<t<5000 with an expectation of 0.06 failures per 5000 hours has been used as input for the regression analysis at the point with t=2500 and x=0.06. Besides using the regular data points x as input for the linear regression, the data is also transformed in four ways; x^2, $\sqrt{x}$, e^x and $\ln(x)$. The best fit is chosen resulting in the following empirical distributions:

$$P(failure/5000runninghours)_{cros\sin g} = (0.18 + 9.622 * 10^{-6} * t)^2$$

$$P(failure/5000runninghours)_{divertshoe} = \begin{cases} (0.096 + 1.839 * 10^{-6} * t)^2 & t \leq 30000 \\ 0.02148 & t > 30000 \end{cases}$$

$$P(failure/5000runninghours)_{divertswitch} = (0.114 + 1.157 * 10^{-6} * t)$$

$$P(failure/5000runninghours)_{merge} = 0.0011$$

$$P(failure/5000runninghours)_{proximityswitch} = 0.0057$$

Note that regression analysis is only executed for the crossing, divert shoe and divert switch because these are the only items that are expected to have an increasing demand rate. For the part of the data that is used to fit a graph, quite good fits are obtained (crossing: R=.845, α=.08, divert shoe: R=.863, α=.027, divert switch: R=.655, α=.110). In Figure 28 it can be seen how this empirical distribution fits the real data for the crossing. The graphs and the result of the regression analysis can be found for all items can be found in Appendix XIII.

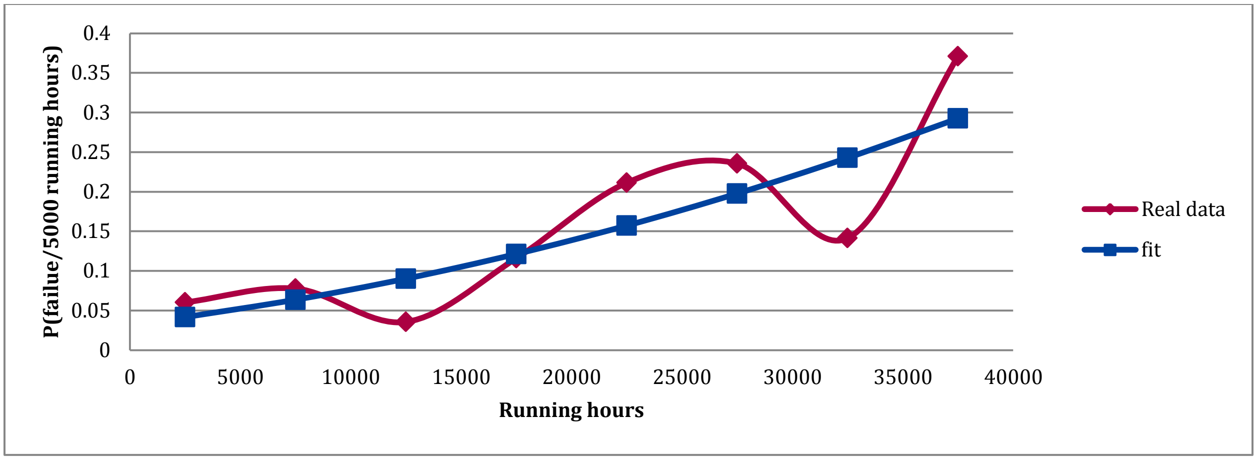


Figure 28 Fit of the empirical distribution to the real data

The result of the regression analysis is an expected amount of failures per 5,000 running hours. This has to be transformed to an expected demand during the lead time. The total lifetime of an Posisorter is assumed to be 45,000 running hours and this lifetime is divided in 9 periods. It is chosen to stick to the 5,000 running hours for convenience, with the usage profile discussed, this corresponds to 1.5 year. If it seems that major increases in the base stock levels are required with this interval, smaller intervals will be used as input for the analysis. The expected demand per time unit is determined per period in the following way:

1. Calculate expected number of failures per 5,000 running hours using the regression formula: A
2. Determine the expected number of failures per item per hour: $B = A/5{,}000$
3. Determine the expected number of failures per item per day: $C = B \cdot T$ (T represents time per day, recall that the Posisorter studied runs 9.1575 hours per day).
4. Determine the expected number of failures per site per day, were an item occurs Q times at an average site. $E = C \cdot Q$

7.2.3 Demand rate for all locations not studied

The demand rate is obtained from the financial data as mentioned above. All demand occurrences for the items in the selection are filtered. These are sorted per year to get the yearly demand. The yearly demand for all items is growing, so it is of importance to use a demand rate and a base stock level of the same year. The most recent year of which both were available was 2009. This demand rate is assumed to be constant during the lifetime of the Posisorter at site 1. It is known that this level changes, but it is assumed that the base stock level at the CW is adapted in such a way that the performance of the CW does not change over time.

7.3 Evaluation current inventory control policy

Before optimizing the base stock levels, the current situation is evaluated first. The results serve as a base for comparison and the average values of for fill rate of the CW, β_0 and the delay, D are used to determine the minimum fill rate for the CW, $\beta_{0,\min}$ and the maximum delay, D_{max}.

The current inventory policy is evaluated using the method described in section 5.2. The input parameters for this evaluation can be found in Table 12. The model assumes that all parts are requested one by one. This assumption is violated for the divert shoe, the other items usually fail (either due to wear or due to a crash) alone, so it is reasonable to assume that they are requested one by one. The most frequently occurred order quantity for the divert shoe was 10, therefore some parameters for the divert shoe are divided by 10.

Table 12 Input parameters for the evaluation of the current inventory policy

	L_0 (days)	L_1 (days)	EL^{CWH} (days)	EL^{sup} (days)	m_1 (items/day)	m_2 (items/day)	Quantity in system
Crossing	35	2	1	11.67	.00506	0.92	16
Divert shoe	28	2	1	9.33	.0059	55.4 (5.54)	1064 (106)
Divert switch	63	2	1	21	.0117	2.55	39
Merge	28	2	1	9.33	.0008	0.92	39
Proximity switch	28	2	1	9.33	.0002	0.04	23

	h_0 (€/day)	h_1 (€/day)	C^{CWH} (€/shipment)	C^{sup} (€/shipment)	S_0	S_1
Crossing			0	0	22	2
Divert shoe			0	0	1000 (100)	1 (10)
Divert switch			0	0	147	2
Merge			0	0	35	4
Proximity switch			0	0	5	1

The average results of the evaluation are given in Table 13, the complete results are given in Appendix XIV. The values for the betas, the logistic downtime and the costs are the average values for the items with an increasing demand during the lifetime. The logistic downtime during the lifetime of an Posisorter increase in a similar way as the demand rate for these items increases. This behavior is as expected because an increase in demand causes an increase in the chance that an item cannot be fulfilled from stock directly which increases the expected logistic downtime on its turn. This is graphically displayed for the crossing in Figure 29.

Table 13 Results evaluation current situation

	Avg. β_0	Avg. β_1	Logistic downtime (minutes/year)	Avg. holding costs customer (€/year)	Avg. costs (€/year)
Crossing	2.40%	99.73%	49		
Divert shoe	0.00%	96.08%	246		
Divert switch	13.07%	99.72%	118		
Merge	94.99%	100.00%	0		
Proximity switch	99.33%	99.95%	0		

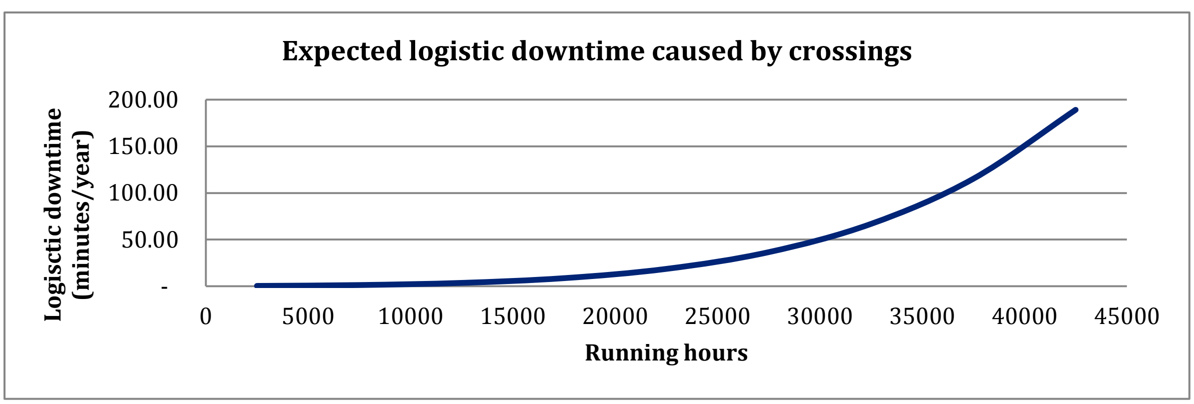


Figure 29 Average delay when a crossing is required to running hours

Although the logistic downtime increases during the lifetime of an Posisorter, the average logistic down time is still low and acceptable. This is also true for the value of β_1. A remarkable result of this analysis is however the performance of the central warehouse which is quite low on average. This is not so much a remarkable result from the point of view that is was not known within VI, but it is remarkable because it shows that this warehouse does not fulfill its function properly. Note that fill rate is worsen by the approximation that items are requested one by one.

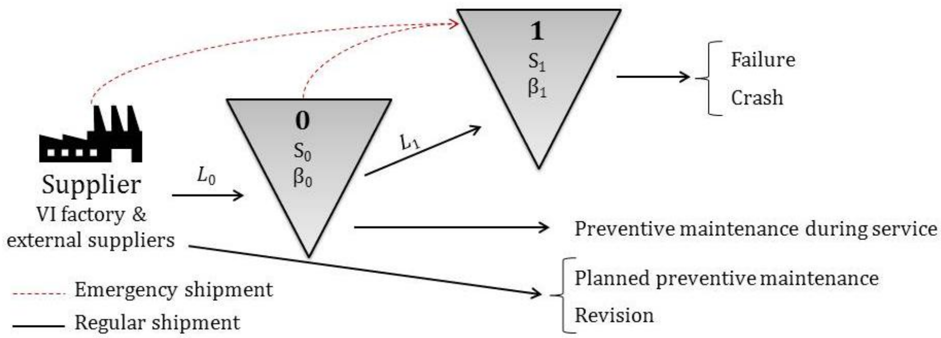


Figure 30 Improved usage of supply chains

Although the results are worsen, there is still room for improvement. A possibility to improve the performance of the CW, is by increasing the base stock levels. However it is found that the reason for this variable and quite bad performance can be found in the way VI uses its supply chains. As discussed in section 2.2 VI distinguishes spare parts demands originating from different sources. Figure 30 gives a distinction which led to an improvement. It is clear that a spare part is needed immediately in case of a failure either due to wear or due to a crash; these demand streams need to be fulfilled from the spare parts inventory on site. However, for preventive maintenance during service it is not necessary to get the part out of stock point on site, there is a possibility to refill this stock point before the end of the service visit. These service visits have a duration of multiple days, creating possibilities to ship the item from the CW. Planned preventive maintenance is usually scheduled according to the availability of engineers, material and tools. This creates possibilities to relieve the CW from orders with high order quantities which are creating a great pressure on the warehouse. For this change, no new supply chains are required. By taking the source of a spare parts demand into account and assigning it to an existing supply chain consciously the performance of the CW can be improved.

Table 14 Change in the demand rate for the CW

	m_2 current (items/day)	m_2 improved (items/day)	Percentage reduction
Crossing	0.92	0.44	-52%
Divert shoe	55.4	4	-93%
Divert switch	2.55	1.50	-41%
Merge	0.92	0.53	-42%
Proximity switch	0.04	0.04	0%

The demand rate at the CW for this situation is estimated by assuming that preventive maintenance is planned if the order quantity is greater than the maximum quantity that is stored on site. This leads to a significant decrease in the demand for the CW (see Table 14). The demand for Location 1 is not changed as planned preventive maintenance was already removed from the demand data (see section 6.1.1). The demand stream for preventive maintenance during service should also be removed from the demand stream at site 1. Unfortunately there is a lack of data to make this distinction. The usage of the supply chain that is analyzed is depicted in Figure 31.

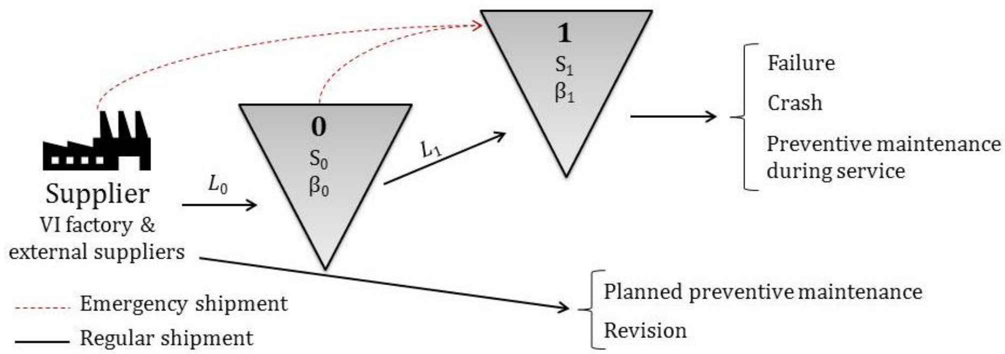


Figure 31 Usage of supply chains that is analyzed

The evaluation is performed again with a new, lower demand rate from location 2. The results are given in Table 15. It can be seen that the performance of the CW is significantly improved. This leads to improvements at the site of the customer. Figures 32 en 33 show the logistic downtime and the holding costs for the customer. It can be seen that the improvement for the logistic downtime is made at a minor increase in costs. However, these improvements come at high total costs. This increase in total costs is caused by an increase in holding costs at the CW, the inventory levels are possibly too high for the lower demand obtained by the new situation. Costs for emergency shipments are zero, so the increase in the performance of the CW is not rewarded from a costs perspective.

Table 15 Results evaluation improved supply chain

	Avg. β_0	Avg. β_1	Logistic downtime (minutes/year)	Avg. holding costs customer (€/year)	Avg. costs (€/year)
Crossing	92.61%	99.99%	1		
Divert shoe	100.00%	99.32%	5		
Divert switch	100.00%	99.98%	0		
Merge	100.00%	100.00%	0		
Proximity switch	99.33%	99.95%	0		
Total			6		

The results of the evaluation of the improved supply chain are judged to be more natural; the goal of a warehouse is to be able to deliver parts directly most of the times.

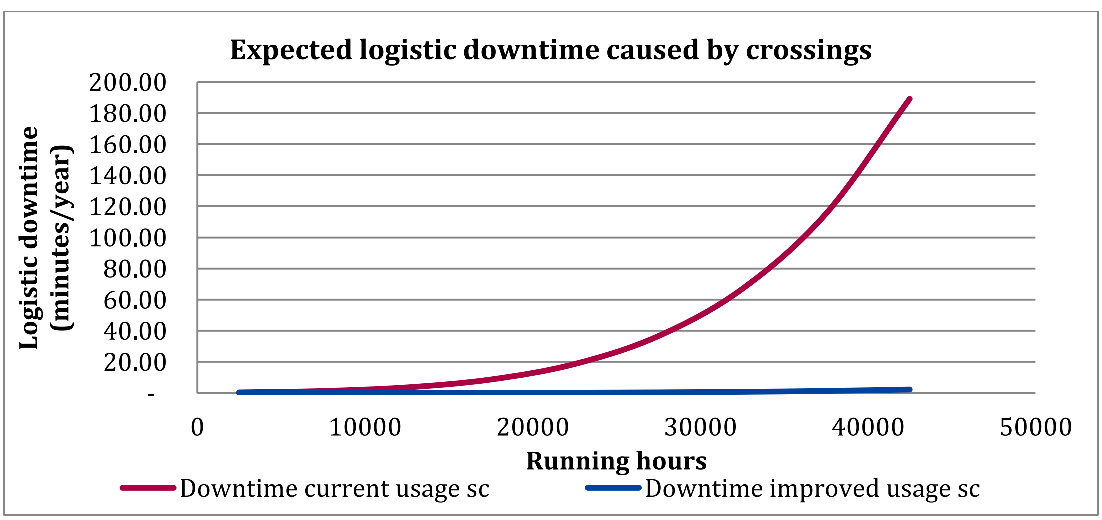


Figure 32 Effect improvement supply chain on logistic downtime of the crossing

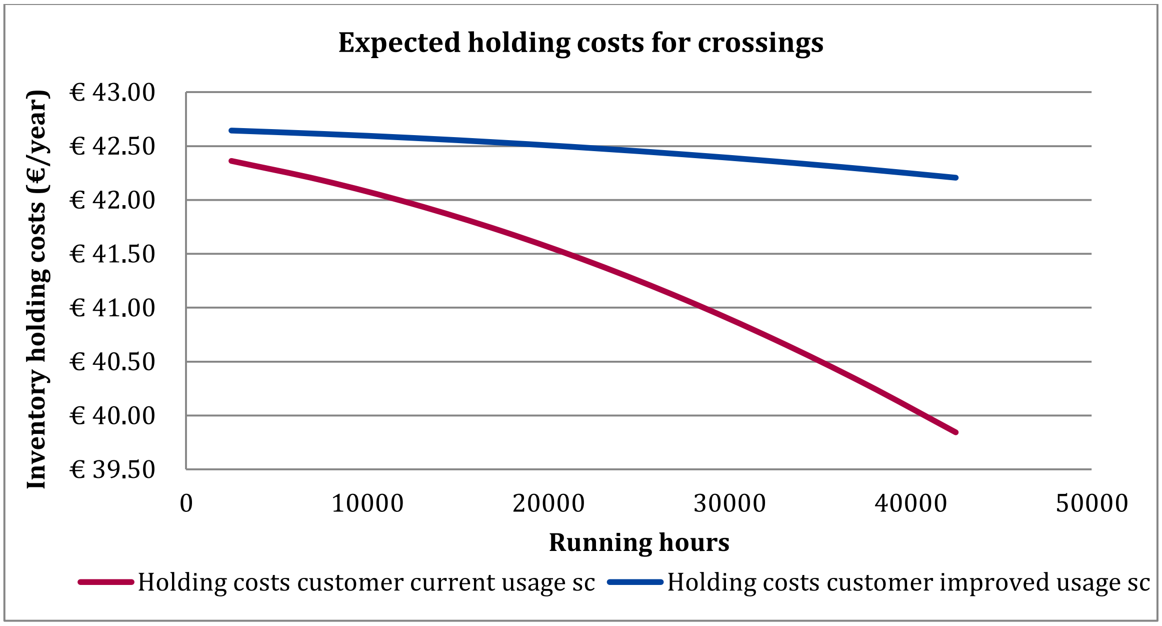


Figure 33 Effect improvement supply chain on the inventory holding costs for the crossing

7.4 Optimization inventory control policy

This section will explore possible improvements for the spare parts inventory control. The first subsection will hold for the constant base stock levels. The improvement option that is explored is the determination of these base stock levels using the demand distribution which is determined based on historical data. The second paragraph will assess whether dynamic base stock which are determined using the demand distribution leads to an improvement.

7.4.1 Using constant base stock levels

In optimizing the base stock levels, an equal performance of the CW and the logistic downtime of all items is required. The optimization part is executed one time per item with the maximum demand rate as input parameter. The maximum demand rate is chosen in order to be sure that the restriction $D \leq D_{\max}$ is met for all periods. See Table 16 for the input parameters that changed or are added with respect to the input parameters in Table 12.

Table 16 Input parameter optimization constant base stock levels

	m_2 (items/day)	$\beta_{0,min}$	D_{max} (minutes/year)
Crossing	0.44	.9839	3.13
Divert shoe	4	.9839	3.13
Divert switch	1.50	.9839	3.13
Merge	0.53	.9839	3.13
Proximity switch	0.04	.9839	3.13

The result of the optimization were optimal values for the base stock levels for both CW and site 1, these are given in Table 17. The evaluation that is performed for the current base stock levels, is executed using these base stock levels. The average results are given in Table 18, the complete results can be found in Appendix XV.

Comparing these results with the results displayed in Table 15 a cost increase for the crossing and a decrease in costs for the other items are observed. The costs for the crossing are increased because the performance of the CW in the previous situation was insufficient and as expected a decrease in costs for the other items.

Table 17 Output optimization

	S_0 old	S_0 new	S_1 old	S_1 new
Crossing	22	26	2	2
Divert shoe	1000 (100)	20 (200)	1 (10)	2 (20)
Divert switch	147	118	2	2
Merge	35	25	4	1
Proximity switch	5	5	1	1

Table 18 Results evaluation optimization constant base stock levels

	Avg. β_0	Avg. β_1	Logistic downtime (minutes/year)	Avg. holding costs customer (€/year)	Avg. costs (€/year)
Crossing	99.00%	99.97%	0.2	€ 42.48	€ 109.81
Divert shoe	98.83%	100.00%	0	€ 180.48	€ 430.21
Divert switch	98.67%	99.98%	0.8	€ 192.48	€ 865.58
Merge	98.84%	100.00%	0.3	€ 9.69	€ 39.43
Proximity switch	99.33%	99.90%	0	€ 148.23	€ 321.01
Total			1.3	€ 573.29	€ 1756.59

7.4.2 Using dynamic base stock levels

In this section, only 3 items are discussed. These are the crossing, the divert shoe and the divert switch. The demand rate of the remaining items was constant, so dynamic base stock levels will not have an advantage.

The base stock levels are optimized using the same procedure as for constant base stock levels, however this optimization is executed for each period like discussed in section 5.4. As a result of the optimization procedure, the base stock levels for the crossing and the divert shoe are decreased in the first three periods. The base stock level of the divert switch is kept constant. Because the optimal solution for the divert switch is not changed when compared with the previous optimization, these results are not given again. The average results for the crossing and the divert switch are given in Table 19. The complete results can be found in Appendix XVI.

Table 19 Results evaluation optimization dynamic base stock levels

	Avg. β_0	Avg. β_1	Delay (minutes/year)	Avg. yearly holding costs customer	Avg. Yearly costs
Crossing	98.92%	99.86%	0.80		(-6.5%)
Divert shoe	98.94%	99.84%	0.89		(-7%)
Total holding costs for 5 items studied					(-2%)

For both crossing and divert switch a costs decrease is gained. The reduction in costs looks small from first sight, but it has to be taken into account that the average value of these spare parts related to the complete spare parts package is only 1 to 2 %.

For the other two items a slight decrease in costs is obtained by the application of dynamic base stock levels. This is as expected.

7.5 Sensitivity analysis

Most parameters of the analysis above were estimated. A sensitivity analysis is therefore important. The goal of a sensitivity analysis is to analyze the effect of changing a certain parameter on the results. The goal of this case study is to analyze whether advantages can be gained by using dynamic base stock levels when compared to constant base stock levels. With respect to this goal, the results do not change if the answer to the question whether dynamic base stock levels are an improvement is not changed. Because it is known that dynamic base stock levels only have the potential to create an improvement for the items crossing, divert shoe and divert switch, these are the only items taken into account.

This sensitivity analysis does not indicate how much a parameter can change before influencing the results. However for parameters that were estimated, it was tested how the results are influenced by taking the most extreme values instead of the average values. The previous chapter on general insights, showed that the demand rate and the costs do have a major influence on the attractiveness of dynamic base stock levels. The first section will discuss the effect of changing the demand during the lead time, the second section discusses the influence of the costs.

7.5.1 Change in demand during lead time

Recall that the procedure to calculate the daily demand is explained in section 6.2.2. The demand during the lead time is influenced by several parameters.

- The quantity of an item in the system
- The lead time
- The daily running hours
- The parameters of the regression analysis (see section 7.2.2 for the regression analysis)

The effect of the first three parameters is tested in this analysis. The parameters of the regression analysis are not changed. This expectation is the best possible fit for the available data so no extreme points can be tested. The effect of change in the demand during the lead time will become clear by the variations of the other variables, the result will also be valid for changes in the parameter of the regression analysis.

Two extreme cases are tested, case I had an extreme low demand during the lead time and case II had an extreme high demand during the lead time. The input parameters and the results of this analysis can be found in Appendix XVII. The results of the analysis did not change for the divert switch; the base stock level is kept constant during the life time of the equipment for both cases. The results for the crossing and the divert shoe did change. In case I, base stock levels were kept constant for both items. A decrease in the demand rate makes the absolute increase in the demand during the lead time smaller which seems to influence the attractiveness of dynamic base stock levels here. For case II, the results were not changed when compared to the average system. In case II, the base stock levels were updated during the life time. It was observed that base stock levels were updated at other periods in case II than in the average situation.

7.5.2 Changes in costs

Two types of costs are incorporated, emergency costs and holding costs. The minimum emergency costs are 0; in the current analysis. The maximum emergency costs are determined by the transportation costs and dependent on the location of a customer. Transportation costs of €1000,- taken as a value for emergency costs, to analyze whether emergency costs do influence the results. The base stock levels for the crossing and the divert switch did not change by adding these costs. The base stock level for the divert shoe did increase over the whole lifetime. However dynamic base stock levels are still applied.

For the crossing and the divert switch multiple versions with different costs are used in the analysis. The minimum and maximum value of these versions are used as input to test the sensitivity to the holding costs. The results are given in Appendix XVII. No changes in the optimal policy are found.

7.6 Conclusion

The performance of the average system in the three scenarios can be shown in a graph with the logistic downtime on the horizontal axis and the costs on the vertical axis. This means that shifting downwards and to the left represents an improvement.

Figure 34 gives the graph for the divert shoe. It can be seen that scenario II represents an improvement with respect to scenario I; the average costs are lower and the average logistic downtime is shorter. For the comparison of scenario II and scenario III no conclusions can be drawn so far. Scenario III has a better performance when only looking at the optimization problem that is formulated; it provides a cheaper solution within the feasible area. However, this costs improvement comes with a longer delay. To investigate whether scenario III performs really better than scenario II an extra analysis is done; the optimization problem for scenario III is run again with the logistic downtime of scenario II as restriction for the maximum logistic downtime for each period. As a result the same solution is found as for scenario II, with these more strict requirements no advantages seemed to be gained from the application of dynamic base stock levels. This is likely to be caused by bounding the feasible area for each period exactly at the point where the solution for scenario II is found. This is explained for a general example in Appendix XVIII.

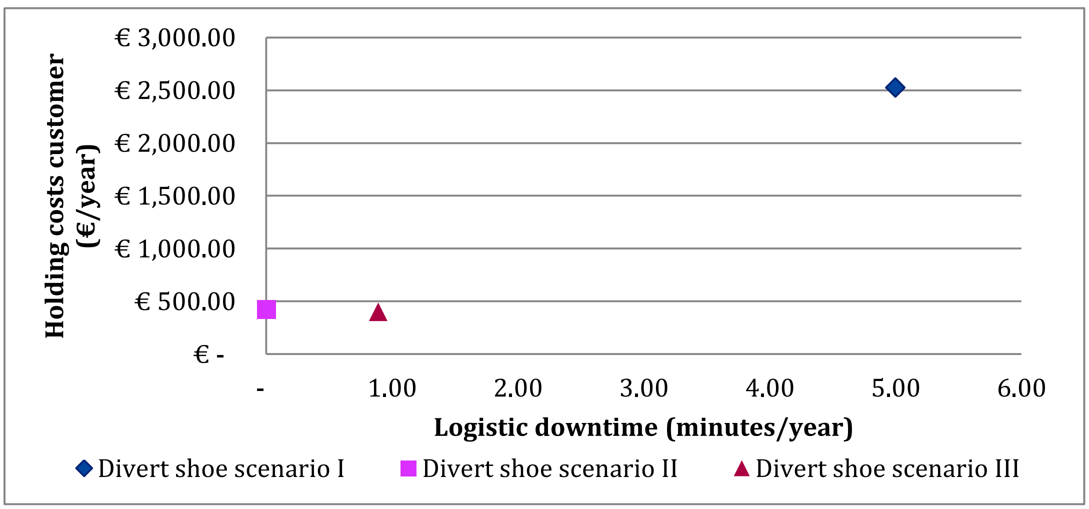


Figure 34 Comparison scenario I, II and III of the divert shoe

This analysis is executed for all items. The graphs can be found in Appendix XIX. An overview of the results can also be found in Table 20.

Table 20 Overview results case study

	Scenario I: Current situation				Scenario II: Constant base stock level		Scenario III: Dynamic base stock level	
	Current usage sc		New usage sc					
	Log DT (min/year)	Costs (€/year)	Log DT (min/year)	Costs (€/year)	Log DT (min/year)	Costs (€/year)	Log DT (min/year)	Costs (€/year)
Crossing	49.00	€ 42.08	1.00	€ 84.59	0.20	€ 109.81	0.80	€ 102.70
Divert shoe	246.00	€ 88.08	5.00	€ 2,525.44	-	€ 420.76	0.89	€ 399.69
Divert switch	118.00	€ 214.65	-	€ 1,737.31	0.80	€ 865.58	-	-
Merge	-	€ 46.53	-	€ 78.52	0.30	€ 39.43	-	-
Proximity switch	-	€ 321.01	-	€ 321.01	-	€ 321.01	-	-

For the crossing, the lowest costs are obtained under scenario I, with the new usage of the supply chain. This is however an unfeasible solution according to the requirements set for scenario II and III. The solution in scenario III gives a feasible result with lower costs then scenario II. However the mean logistic downtime is slightly increased like for the divert switch. For the divert shoe, the result of scenario II is an improvement with respect to scenario I. Scenario III does not provide an improved result. For the merge, scenario II does provide a feasible solution at lower costs. However, improvement in costs comes with a slightly higher delay.

The sensitivity analysis showed that these results are not robust to the demand during the lead time. In the case where the demand during the lead time was decreased, it seemed that the opportunity of dynamic base stock levels did not create an advantage. The results are robust to the costs perspective. This indicates that the reason to keep stock here, is to meet the logistic downtime restriction.

Based on this analysis it can be stated that dynamic base stock levels can create an advantage when applied to the crossing (cost decrease of 6.5%) and the divert shoe (cost decrease of 7%). Only 5 items are studied and the results of the sensitivity analysis show that these results are not robust. It is therefore difficult to pronounce upon general guidelines on these results.

It seems that the change in demand rate of the items that are selected is too small to lead to a noticeable effect with the low holding costs of these items. Based on conversations with (service) engineers, a motor and an invertor are candidates for which it is likely that dynamic base stock levels are attractive based on the insights that are gained in Chapter 6.

8. Conclusion and recommendations

Based on the preformed research conclusions are drawn, those are discussed in the first section of this chapter. The second section gives recommendations both for academics and for Vanderlande Industries.

8.1 Conclusion

The goal of this study was to identify in which situations it is attractive to use dynamic base stock levels in order to decrease the total costs of ownership of a VI system. Three main conclusions can be drawn from this study.

General findings

Whether dynamic base stock levels are attractive or not from a costs perspective depends on two variables; the change in the demand rate and the inventory holding costs. A change in demand rate is required because there has to be a reason to adapt the base stock level. A high minimum demand rate and a great factor with which the demand rate grows have both a positive effect on the attractiveness of dynamic base stock levels. If the demand rate changes over time, there are two possibilities to reach significant saving by the application of dynamic base stock levels; the change in demand rate has to be great so that the decrease in inventory holding costs has an noticeable effect independent of the holding costs per item, or the holding costs have to be high so that a base stock level that is decreased by one item does have a noticeable effect.

Assigning demand to supply chains at VI

Concerning the current situation at VI it is found that significant improvements are possible by assigning demand for spare parts consciously to different supply chains that are already used. The pressure on the CW can be relieved by directing planned spare parts demand to the suppliers of the CW. This has significant effect on the performance of the CW. The fill rate is less than 15% for 3 out of 5 items in the current situation. Assigning the demand streams consciously improves the performance to a minimum fill rate of 93% for the 5 items studied.

Dynamic base stock levels at VI

Leaving from the improved situation at the CW, it is found that dynamic base stock levels can create minor financial advantages for the crossing and the divert shoe. The results are found sensitive for a decrease in the demand during the lead time. This means that it is not justified to pronounce on these results. The results give the indication that it is not possible to make significant financial savings by the application of dynamic base stock levels for these items.

To say something about gains for other items, the general findings are compared with the situation at VI. For some like a motor or an invertor, it could be beneficial to decrease the base stock level during part of the lifetime.

The magnitude of the increase in demand rate for an item is not only dependent on item specific characteristics. The number of occurrences of an item in the system and the intensity of use of a system (daily running hours) do have a major influence in the magnitude of change in demand rate. It is therefore expected that dynamic base stock levels have the greatest potential for large sites that are used intensive.

Even if the financial gains are not that large, it might be attractive to apply dynamic base stock levels. Periodical visits to discuss the adaptions to the spare parts inventory will have positive effects on customer relationships. The introduction of dynamic base stock level will create other positive effects. By periodically meeting a customer to discuss the spare parts inventory, a feedback loop from customers to SCMS will be established. Using this feedback loop, a learning process could be started. Forecasts for spare parts demand can be improved by this learning process. New forecasts can also initiate an adaption in base stock levels. Other information streams can lead to new forecasts for spare parts demand as well. This information is only used for the formulation of the base stock levels of new customers in the current situation. Current customers can also make use of improved forecasts when dynamic base stock levels are applied. Leaving the perspective of TCO, it is likely that more spare parts can be sold in sum when the acquisition is spread over time.

In sum, the results of the case study indicated that only minor financial gains can be made by applying dynamic base stock levels to the items studied. A greater effect is expected for large sites and for items that are more expensive. Besides the financial gains, some major soft gains can be made by the application of dynamic base stock levels of which a learning process is the most important.

8.2 Recommendations

The recommendations are split in recommendations for academics and recommendations for Vanderlande Industries. Both will be discussed in the following sections.

Recommendations for academics

Different recommendations for academics can be done based on this research.

First, no hard cut-off point for the change in demand rate is found to judge on the applicability of dynamic base stock levels. Further research is necessary to determine whether it is possible to determine such a cut-off criterion and if so, what the criterion is. It expected that the change in demand rate that is necessary to force an increase in the demand rate, does have a relation with the slack of the solution for the minimum demand rate. This relationship can be studied as well.

Then, in this study it is assumed that the base stock level can only be updated at some predetermined moments. The average demand is calculated for each period between two possible updating moments. The optimal base stock level is calculated based on this average demand. If the optimal base stock levels increase from one period to another, dynamic base stock levels are judged to be attractive. It would be interesting to develop a model that indicates the latest moment at which the base stock level should be increased to keep the situation optimal. This is also interesting if the position of this model is taken into account. Concern a multi-item situation where the latest moment to increase the base stock level is determined for each individual item. It would be possible to determine the optimal moments to increase base stock levels by making the considering between holding costs and transport costs.

Finally, condition monitoring is mentioned in the introduction as one of the possibilities that can help OEMs in improving their service chain. This possibility fell outside the scope of this research. If it would be possible to get an early sign of failure and the time between this sign and the failure is long enough to deliver the spare part, a great reduction in spare parts inventory can be obtained. The forecast to increase the stock level is no longer based on historical data itself but on the real condition of an item as well. This is especially useful in situations with a great variety in the demand data.

Recommendations for Vanderlande Industries

In this research a case study is performed to analyze opportunities for VI in the application of dynamic base stock levels. Based on these findings, recommendations can be done to VI, these recommendations will be discussed in this section. First, recommendations concerning spare parts inventory control will be given. Second, while working within VI, information is gained about their way of working. Based on this information some general recommendations will be given.

Spare parts inventory control

The recommendations concerning spare parts inventory control will be given below, they can be split in recommendation for the CW and the stock points on site. Recalling that this study is done from the TCO perspective, it is recommended to improve the performance of the CW before improving the stock points on site. A fill rate of 0.3 at the CW does lead to higher optimal base stock levels on site as shown in the analysis in chapter 6. Part of the uncertainty of spare parts demand can be pooled in the CW leading to advantages for the stock point on site. So it is recommended to improve the performance of the CW first and then pay attention to the stock points on site.

Central warehouse

Based on the results of this research, it is recommended to VI to make a strategic decision about the function of its CW. The moment that VI gets complete responsibility to guarantee an agreed availability cannot be far away, with the growing amount of customers requesting for complete service contracts. It is recommended to deal proactively with this change.

It is recommended to use the CW only for replenishment orders and not for spare parts orders that are used for planned preventive maintenance or initial spare parts packages. The rough analysis of this effect that is done shows already major improvement possibilities. The high lead time of some items does cause that this approach is not applicable for all items, so decisions have to be made.

The performance of the CW can also be increased by using two inventory levels that provide a guideline; an order up to level (base stock) and a minimum level (in inventory drops below this minimum only requests for emergency shipments will be delivered). This increase in performance of the CW will come at higher inventory costs, because the average inventory will increase. A possible way to earn (part of) this money back is by requesting an extra fee when customers place an emergency shipment. A requirement for introducing a fee is that VI must be able to deliver the emergency shipments on time, so this should be researched before it could be implemented.

Although not all recommendations can be applied to all items, the main problem is that the possible strategic function of the CW is not always clear within VI. This leads to the main recommendation; to take strategic decisions about the function of the CW and optimize the warehouse accordingly. The strategic function that is recommended is to be able to deliver replenishment order directly in a great fraction of the time and to be able to deliver emergency shipments almost always directly. No strict recommendation will be done for the fill rate at the CW, but it would be recommended to keep them in the order of magnitude of 90% to 100%. This will lead to a more reliable stock point, which is expected to have a positive effect on the turnover.

Stock point on site

Different recommendations for the stock point on site can be done based on this research. The sensitivity analysis unfortunately showed that there is no single answer per item. Besides the item specific characteristics, the intensity of use of the system and the quantity of items in a system, influence the decision whether dynamic base stock levels should be used or not. The reduction in holding costs of the items studied will not have a major influence. However, these items only account for 1 to 2% of the total value of the spare parts package. For these items a costs reduction of 6 to 7% is gained. If this could be reached for the whole package, the reduction will be noticeable. To be get more insight in the opportunities of dynamic base stock levels, it is therefore recommended to do the analysis for more expensive items that wear out, for an average or a large system. Note that the price of an item will not influence whether dynamic base stock levels are attractive or not; the sensitivity analysis showed that the result (whether to apply dynamic base stock level or not) is robust for the costs for the VI items. The price of an item does however influence the costs saving that can be reached. These cost reductions are especially interesting for

VI for customers with a service contract. Luckily these are mainly major customers with large sites. It is recommended analyze whether dynamic base stock levels are attractive or not for expensive items that wear out at major sites because these have the greatest potential.

Second, the spare parts at VI are kept to limit logistic downtime. The boundary for this restriction is now set at the average logistic downtime reached with the current base stock levels. It might be good to gain more insight in acceptable logistic downtimes. Note that these could be different for different items.

Third, as for the CW, an improvement could also be made by using the stock point consciously. The inventory at the stock point on site is currently used for both, corrective and preventive maintenance during service. As for the central warehouse, it could however be argued that the goal of spare parts inventory is to reduce the effects of a failure, so to perform corrective maintenance. An extra difficulty arises here because it is not known in advance what preventive maintenance actions will be necessary during service, this is determined when the machine is opened. However taking into account that these maintenance visits usually takes some days, there is a possibility to refill the stock point on site before the end of the maintenance visit if the lead time from the CW is not too long. This creates an extra need to improve the performance of the CW. It is recommended to start to keep track on the source of a spare parts demand in order to be able to analyze the improvement possibility of this distinction.

A final recommendation to improve the inventory policy for the stock point on site is to introduce a feedback loop. Employees at SCMS do create many recommended spare parts lists and they make considerations by drawing this list every time. After the recommended spare parts package is sold, they never get to know whether they made the right decisions in their considerations. Many customers do have contacts for periodical maintenance checks and assistance for corrective maintenance. These are performed by VI engineers who are using the spare parts stock to execute these maintenance actions. These engineers do have information that is can be used to give the feedback on the advice that employees of SCMS provide.

General

First, VI should explore the possibilities that condition monitoring can bring to them. Stadhouders (2011) identified a possibility to use operational data for condition monitoring at VI. The application of CM in inventory control can lead to further improvements of local stock. As discussed in the recommendations for academics this is especially true the situation with a great variety in the demand data which is the case at VI. A possible way to explore opportunities of CM for VI is discussed in Appendix XX.

Second, the value of information should be better regarded at VI. This means storing gathered data in a well arranged way on the one hand, and not giving information away easily on the other hand. Storing valuable data is important to improve the processes; if data can be assessed easily, it is attractive to do analysis to improve the processes. Information is given away easily in the recommended spare parts lists for example. If the item description in the list includes all information that customers need to order the item themselves, the way to abuse this information is paved. This is also valid for information about items of assemblies. If the complete assembly is defined as the level of replacement unit, it is not necessary to give customers the item numbers and prices of the parts of this assembly. It is recommended to take conscious decisions about the information that is given to a customer.

Finally, it is recommended to introduce some standardization in service packages delivered. All service contracts are customized at the moment. This means that there are as many different service packages for customers and that this amount increases with the growth of the number of customers. This leads in the first place to unnecessary complexities because no one has a complete overview about what service is sold to which customers. Secondly, doing an analysis or optimizing processes is very complicated without standardization.

Bibliography

Aka, M., Gilbert, S. M., & Ritchken, P. (1997). Joint inventory/replacement policies for parallel machines. *IIE Transactions, 29*, 441-449.

Alfredsson, P., & Verrijdt, J. (1999). Modeling emergency supply flexibility in a two echelon inventory system. *Management Science*, 1416-1431.

Aronis, K.-P., Magou, I., Dekker, R., & Tagaras, G. (2004). Inventory control of spare parts using a Bayesian approach: A case study. *European Journa of Operations Research, 154*(3), 730-739.

Axsäter, S., Kleijn, M., & Kok, T. de (2004). Stock rationing in a continious review two-echelon inventory model. *Annals of Operations Research*, 177-194.

Cohen, M. A., Agrawal, N., & Agrawal, V. (2006). Winning in the Aftermarket. *Havard Business Review*.

Ellram, L. M., & Sifert, S. P. (1998). Total cost of ownership: A key concept in strategic cost management decisions. *Journal of Business Logistics, 19*(1), 55-84.

Graves, S. C. (1985). A Multi-Echelon Inventory Model for a Repairable Item with One-for-One Replenishment. *Management Science, 31*, 1247-1256.

Hopp, W. J., & Spearman, M. L. (2008). *Factory Physics.* Mc Graw Hill.

Houtum, G. J. van(2010). *Maintenance of Capital Goods.* Eindhoven: TU/e.

Houtum, G. J. van, & Hoen, K. (2008). *Single-Location, Multi-Item Inventory Model for Spare Parts.* Eindhoven: Eindhoven University of Technology.

Hua, Z. S., Zhang, B., Yang, J., & Tan, D. S. (2007). A new approah of forecasting intermittent demand for spare parts inventrories in the process industries. *Journal of the Operations Research Society, 58*, 52-61.

Jardine, A. K., & Tsang, A. H. (2006). *Maintenance, Replacement, and Reliability.* Boca Raton: CRC Press.

Kennedy, W. J., Wayne Patterson, J., & Fredendal, L. D. (2002). An overview of recent literature on spare parts inventories. *International journal of production economics, 76*, 201-215.

Kim, J.-S., Shin, K.-C., & Yu, H.-K. (1996). Optimal Algorithm to determine the spare inventory level for a repairable-item inventory system. *Computers Operations Research, 23*(3), 289-297.

Louit, D., Pascual, R., & Jardine, A. (2010). Optimization models for critical spare parts inventories - a reliability approach. *Journal of Operations Research*, 1-13.

Muckstadt, J., & Thomas, L. (1980). Are multi-echelon inventory methods worth implementing in systems with low-demand-rate-items? *Management Science, 26*, 483-494.

Nahmias, S. (2009). *Production and operations analysis.* New York: McGraw-Hill.

Oliva, R., & Kallenberg, R. (2003). Managing the transition from products to services. *International Journal of Service, 14*(2), 160-172.

Öner, K. B., Kiesmüller, G. P., & Houtum, G. J. van (2010). Optimization of component reliability in the design phase of capital goods. *European Journal of Operational Research, 205*, 615-624.

Öner, K., Franssen, R., Kiesmüller, G., & Houtum, G.J. van (2007). Life Cycle Cost Measurement of Complex Systems Manufactured by an Engineer-to-Order Company. *Flexible Automation and Integigent Manufacturing*, (pp. 589-596). Philadelphia. Retrieved from http://alexandria.tue.nl/repository/books/627209.pdf

Özkan, E., Houtum, G. J. van, & Serin, Y. (2011). A New Approximate Evaluation Method for Two-Echelon Inventory Systems with Emergency Shipments. doi:Working papaer series 363

Paz, N. M., & Leigh, W. (1994). Maintenance Scheduling: Issues, Results and Research Needs. *International Journal of Operations & Production Management*, Vol. 14, No. 8, pp. 47-69.

Rustenburg, W., Houtum, G.J. van, & Zijm, W. (2003). Exact and approximate analysis of multi-echelon, multi-identure spare parts systems with commonality. In J. Shanthikumar, D. Yao, & W. Zijm, *Stochastic modeling and optimization of manufacturing systems and supply chains* (pp. 143-176). Dordrecht: Kluwer Academic.

Sherbrooke, C. C. (1986). METRIC: A Multi-Echelon Technique for Recoverable Item Control. *Operations Research, 16*, 122-141.

Sherbrooke, C. C. (2004). *Optimal inventory modeling of systems, multi-echelon techniques, second edition.* Dordrecht: Kluwer Academic Publishers.

Snyder, R. D., Ord, J. K., & Beaumont, A. (2011). Forecasting the intermittent demand for slow-moving inventories: A modelling approach. *International Journal of Forecasting*.

Stadhouders, H. (2011). *A Framework of implementing Condition Based Maintenance based on Operational Data.* Graduation report, Eindhoven.

Tan, T., Güllü, R., & Erkip, N. (2007). Modelling imperfect advance demand information and analysis of optimal inventory policies. *European journal of operational research, 177*, 897-923.

Vanderlande Industries. (2011). *Annual Report 2011.* Veldhoven: Verhagen Grafische Media.

Vanderlande Industries. (2011, 6 30). *www.vanderlande.com*. Retrieved 6 30, 2011, from http://intranet/News/corporate/Pages/Vanderlande%20Industries%20sees%20improving%20markets.aspx

Appendix I: Services provided by VI

VI is offering a range of services to its customers. The service packages offered are mainly customer specific. The services offered range from giving the customer the possibility to call the VI helpdesk 8 hours a day to an on-site maintenance team taking care about the system and spare parts inventory with a guaranteed uptime. The services offered can be split in a rough way to technical support and spare parts services (see Figure 35). All combinations of all possibilities of both occur.

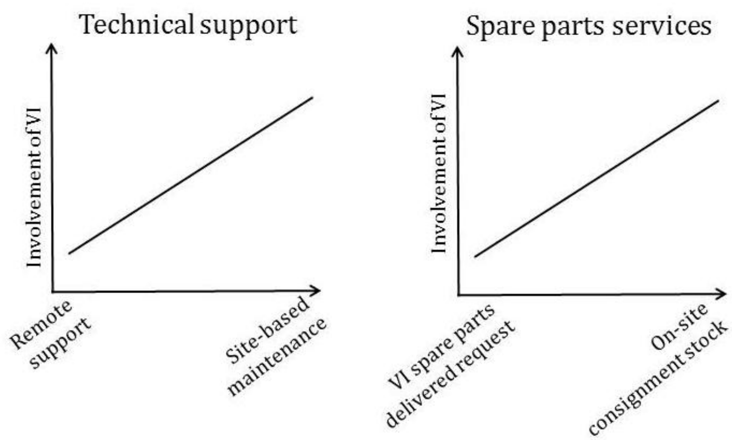


Figure 35 Services provide by VI

Most customers only have a contract for technical support (left side of Figure 35). These customers own, and manage the spare parts themselves. In its limited way, the contract for technical support includes a helpdesk supporting a customer's maintenance team with repairing the system. Technical support can also include preventive and/or corrective maintenance. A contract for preventive maintenance includes an agreed amount of visits by an engineer to inspect the state of the system. The result of this inspection is an advise to perform preventive maintenance; repair or replace some parts of the system to prevent failure in the future. If a customer wants these activities to be executed, he has to request VI and pay seperately. In the most broad contract, site-based maintenance, there is a VI site based maintenance team taking care about all maintenance activities. In this case, the customer does pay in the contract for the man hours of the service engineers and only the spare parts need to be paid if maintencance is performed.

As depicted on the right in Figure 35, VI offers also services concerning spare parts. The narrowest service offered is the delivery of spare parts on customer request; there is no contract and customers are not obligated to buy spare parts at VI. In case customers do have a contract for consignment, VI owns the spare parts for the customers, called consignment stock. The stock can be held on site or off site. If stock is held off site, inventory can be shared among several customers, or kept on stock for a specific customer. At this moment there are no customers who have consignment stock shared with other customers, some do share stock among several locations/systems within their own organization. When a customer has off site consignment stock this is usually stored at a local warehouse close to the customer. Whether the inventory is located on site or off site and whether it is shared or not, is decided by the customer.

The yearly costs of having unshared consignment stock is 17,5% of the actual sales to customer value. If the inventory is kept off site, the customer has to pay additional storing costs. For inventory that is shared with other customers, the yearly costs are 13,5% of the actual sales to customer value excluding storage costs. In both situations these costs only include the inventory holding costs. If an item is used and reordered, the customer has to pay the same price as customers without having consignment stock for this item. The transportation costs for both the initial inventory and the refill deliveries are excluded as well.

Contracts for consignment stock have a duration of 5 years. At the end of the contract, the customer has the possibility to extend the contract for another 5 years or to take over the spare parts inventory at the current value discounted with a depreciation of 10% per year. After having consignment stock for 10 years, the customer owns the inventory.

If the stock is stored off site, VI will manage the spare parts inventory for their customer. If the spare parts are located on site and there is no on site maintenance team, the spare parts are usually controlled by the customer. If a customer has the highest level of service in both pictures of Figure 35, site-based maintenance and on-site consignment stock, the inventory of spare parts is usually controlled by a VI employee working on the customers site. Currently 19 customers do have consignment stock of which 3 have site-based maintenance as well.

There are customers with whom VI has an agreement to deliver a certain availability with a bonus/penalty arrangement. However these contracts are under the condition that spare parts are available.

For customers where VI has a contract for technical support and consignment stock, the consignment stock at location is usually used for corrective and preventive maintenance during service. After a spare part is used for preventive or corrective maintenance, a new spare part is ordered.

Appendix II: Differences in Inventory controlled by customer and by VI

There are several types of spare parts services offered. In this section these will be split in three categories which will be discussed in greater detail. A distinction will be made between customers without a contract for supply chain services, customers with consignment stock that is controlled by themselves and customers having consignment stock controlled by VI.

Items with defects, will be replaced on costs of VI for all customers with consignment stock.

Customers without a contract for spare part services

After the installation of the system, a customer usually buys the items on the recommended spare parts list (after an agreement is made about the items on this list). The customers without a contract for spare parts services, manage the spare parts inventory themselves. This means that a customer orders spare parts if he thinks that this is necessary. Of course the customer has the choice where to order spare parts which lead to a range of possibilities that occur; some customers do buy all their spare parts at VI, some order only VI equipment at VI and all options in between are possible as well. A graphical representation of this process is depicted in Figure 36.

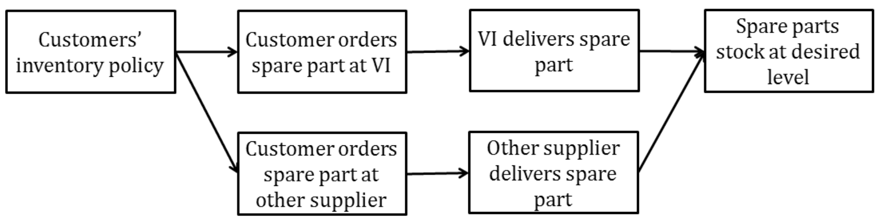


Figure 36 Spare parts delivery for customers without contract for spare parts services

Consignment stock controlled by customer

Having a consignment stock agreement, means that VI owns the spare parts inventory and that it is kept at the base stock level as indicated in the recommended spare parts list. This is controlled by the customer, if a customer has an agreement for onsite consignment stock without a VI site based maintenance team. The customer usually indicates when a new spare part is used by placing a replenishment order, to keep the inventory at the base stock level. VI counts the stock at the customer twice per year. It is assumed that missing items have been used, so the customer does have to pay them and they are re-ordered (see Figure 37).

The base stock levels as indicated in the recommended spare parts package are updated periodically based on experience.

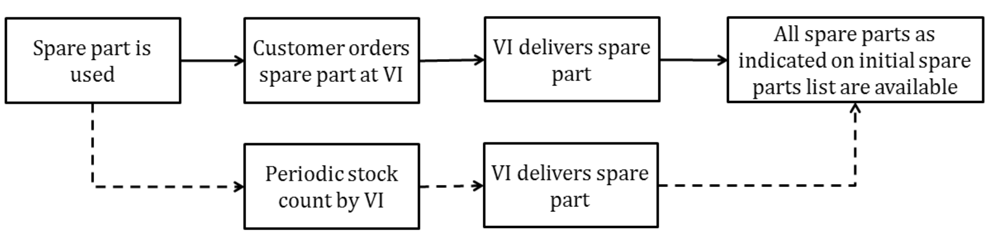


Figure 37 spare parts delivery for customers with consignment stock controlled by themselves

Consignment stock controlled by VI

VI controls the consignment stock for customers who have a contract which includes both, on consignment stock and a VI site based maintenance team, and for customers having offsite consignment stock. The only difference with the situation above is that here a VI person is managing the stock. This is also done according to the base stock levels given in the recommended spare parts list. These base stock levels are also updated periodical based on experience. Like in the previous situation there is a the periodic stock count and it is assumed that all missing items are used by the customer.

It has to be noted that a VI person manages the spare parts for the customer. This does not mean that all items are bought at VI in Veghel. If an item is also produced somewhere else with a lower lead time at an acceptable price, it can be ordered at another supplier directly instead of ordering at the CW in Veghel. See Figure 38.

Figure 38 Spare parts delivery for customers with consignment stock controlled by VI

Appendix III: Rules of thumb for setting base stock levels

Appendix IV: Evaluating the constant base stock level

The evaluation method starts with calculating the fill rates β_0 and β_1 using an iterative algorithm after which θ_1 and γ_1 are approximated. This iterative procedure is necessary because β_1 and W_0 are dependent on each other. The dependence will be explained first. Next, the adapted version of the method is described.

Dependence β_1 on W_0 and vice versa

The replenishment lead time for local warehouse L_1 is delayed because the central warehouse may not always have a positive net inventory. W_0 is defined as the mean delay for an arbitrary replenishment order at the central warehouse and LT_1 as the average realized replenishment lead time for local warehouse 1. Then,

$$LT_1 = t_1 + W_0 \tag{1}$$

The realized replenishment lead time LT_1 is used to calculate β_1 which makes β_1 dependent on W_0; an increase in W_0 leads to a decrease in β_1. W_0 is on its turn affected by the fill rate β_1; a higher fill rate at the local warehouse means less emergency shipments from the supplier, causing a higher demand at the central warehouse leading to a slightly higher W_0. The interdependence of β_1 and W_0 is illustrated in Figure 39.

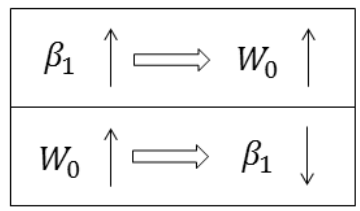


Figure 39 Dependence β_1 on W_0 and vice versa

Calculating β_1

An algorithm is proposed in order to calculate β_1. This algorithm is given first. Then step two and step three are explained in more detail.

Algorithm

The algorithm provides an approximation for the fill rate β_1 and the mean delay W_0:

Step 1: $W_0 := 0$

Step 2: Compute β_1 given W_0

Step 3: Compute W_0 given β_1

Step 4: Repeat *step 2* and *step 3* until W_0 does not change more than $\varepsilon \leq 10^6$

Compute β_1 given W_0

It is pretended that the realized replenishment lead times are independent and identically distributed. The local warehouse behaves then as an M|G|c|c queue; an Erlang loss system. Each unit on stock, is considered as a server. There are S_1 servers, demand arrives with rate m_1 and each 'server' is occupied for LT_1 time units on average after a demand occurred. Demand that cannot be met from stock, is satisfied from the CW or the supplier and can thus be regarded as lost demand for the local warehouse; there are no backorders. The percentage of accepted customers in this Erlang loss system is therefore equal to the fill rate.

$$\beta_1 = 1 - L(S_1, (m_1 \cdot LT_1)) \tag{2}$$

Where

$$L(S_1, m_1 \cdot LT_1) = \frac{S_1^{m_1 \cdot LT_1} \Big/ m_1 \cdot LT_1 \; !}{\sum_{x=0}^{m_1 \cdot LT_1} \frac{S_1^x}{x!}} \tag{3}$$

Step 2 is executed by substituting in (13) and (15) into (14)

Compute W_0 given β_1

The inventory behavior at the central warehouse is modeled as an Markov process. This implicates two approximation steps:

- All demand streams are independent of each other and independent of the actual inventory,
- The lead time of the central warehouse, L_0, is exponentially distributed

The Markov process is defined by the state space and the arrival and departure rates of all states (see Figure 40). The state space consists of all possibilities for the net inventory. The maximum inventory level equals S_0 and the minimum inventory level equals $-\overline{S} = -\sum_{n=0}^{2} S_n$ because backorders only occur for replenishment orders (emergency shipments are satisfied by the (external) supplier when the central warehouse has no on hand stock). It is assumed that $\beta_2 = 1$, which implicates that $S_2 = \infty$ and $-\overline{S} = -\sum_{n=0}^{2} S_n = -\infty$ [1] The arrival and departure rates are dependent on the demand rate and lead time from the supplier. The arrival rate of 1 new item is dependent on the lead time; $\mu_0 = \frac{1}{L_0}$.

When the inventory level is strictly positive, the demand rate equals

$$\sum_{n=1}^{2} \left[m_n \cdot \beta_n + m_n \cdot (1 - \beta_n) \right] = \sum_{n=1}^{2} m_n = m_0$$

whereas the demand decreases to

$$m_0^{'} = \sum_{n=1}^{2} m_n \cdot \beta_n \tag{4}$$

in case that the inventory level is zero or negative.

[1] The value for infinite is approximated in the calculations. The procedure to approximate $\overline{S} = \infty$ is discussed in the last section of this appendix.

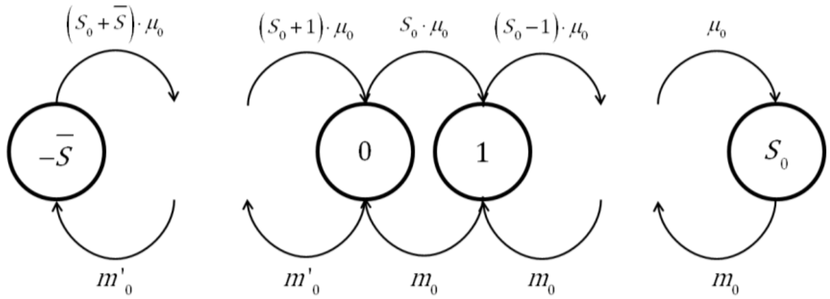


Figure 40 Markov process for the inventory level at the central warehouse

The mean delay W_0 is determined using Little's law,

$$W_0 = \frac{B_0}{m'_0} \tag{5}$$

where B_0 equals the expected amount of backorders. Note that m'_0 is used as the rate, because the focus is here on the part of the model with a negative net inventory. The expected amount of backorders is obtained via the steady state distribution π_x,

$$B_0 = \sum_{x=-\infty}^{-1} (-x)\cdot\pi_x \qquad (6)^2$$

The steady state distribution is found by solving the following linear problem:

$$\pi_x = \begin{cases} \dfrac{m_0'}{(S_0-x)\cdot\mu_0}\cdot\pi_{x+1} & -\infty \le x \le 0 \\ \dfrac{m_0}{(S_0-x)\cdot\mu_0}\cdot\pi_{x+1} & 0 \le x \le S_0 \end{cases} \qquad (7)^3$$

$$\sum_{i=-\infty}^{S_0-1} \pi_x = 1$$

This problem has a unique solution because it consist of $\bar{S}+S$ equations and $\bar{S}+S$ variables.

Step 3 is executed by substituting (16) and (18) into (17)

Calculating θ_1 and γ_1

This section explains how the fraction of the demand that is satisfied by an emergency shipment from the central warehouse and the (external) supplier is approximated. Let IL_0 and IL_1 denote the inventory level of the central warehouse and local warehouse 1 respectively. The fraction of the demand fulfilled by the central warehouse is then equal to:

2 The value for infinite is approximated in the calculations The procedure to approximate $\bar{S}=\infty$ is discussed in the last section of this appendix.

3 The value for infinite is approximated in the calculations. The procedure to approximate $\bar{S}=\infty$ is discussed in the last section of this appendix.

$$\theta_1 = \mathrm{P}(IL_0 > 0, IL_1 = 0)$$
$$= \mathrm{P}(IL_1 = 0 \mid IL_0 > 0) \cdot \mathrm{P}(IL_0 > 0)$$

To approximate the conditional probability $\mathrm{P}(IL_1 = 0 \mid IL_0 > 0)$ it is pretended that the central warehouse has a strictly positive inventory level. This means that the inventory level behaves like an Erlang loss system with an average service time of L_n time units (see step 2 of the algorithm to calculate β_1); $\mathrm{P}(IL_1 = 0 \mid IL_0 > 0) \approx L(S_1, m_1 \cdot L_1)$. The last chance, $\mathrm{P}(IL_0 > 0)$ is estimated using the steady state distribution determined in step 3 of the algorithm to calculate β_1; $\beta_0 := \sum_{x=1}^{S_0} \pi_x$. Thus we obtain:

$$\theta_1 \approx \beta_0 \cdot L(S_1, m_1 \cdot L_1) \qquad (8)$$

The fraction of the demand satisfied by (external) suppliers, γ_1, is estimated by the fact that by definition:

$$\beta_1 + \theta_1 + \gamma_1 = 1 \qquad (9)$$

Approximating the steady state of the CW

The steady state has to be determined for the following Markov process in Figure 41 where $\overline{S} = S_1 + S_2$ and S_2 is unknown.

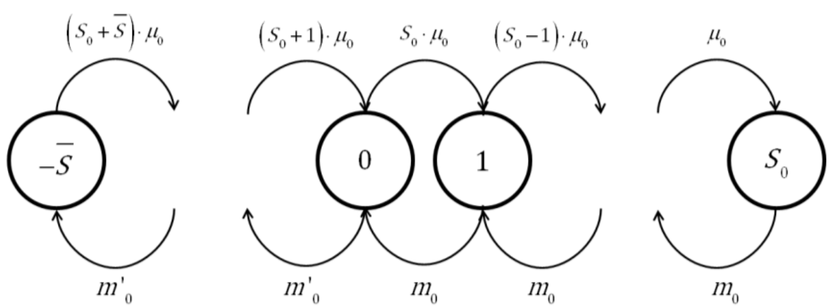


Figure 41 Markov process for the inventory level at the central warehouse

Usual way to determine the steady state

The steady state is determined by summing up the chances that the system is in a certain state expressed in for example the chance that the system is in state S_0.This sum is then divided by the number of states in the Markov process in order to determine the chance that the system is in state S_0. Knowing this state, the steady state probabilities can be determined.

Approximation

The Markov chain here is approximated by adding chances to the sum until the sum does not changes more than 0.0001. This means that the steady state probabilities does not change more than $\frac{0.0001}{\overline{S} + S_0 + 1}$ which is judged to be acceptable.

Appendix V: MATLAB code

The structure of the programs to evaluate and optimize the base stock levels will be given first. Next the MATLAB code is given.

Evaluation of base stock levels

Figure 42 gives an overview of the structure of the program to evaluate a base stock level. The validation for this model is done in two ways. First the program was developed according to the algorithm described in Özkan et al. (2011). This model is validated using the results described in the paper of Özkan et al. (2011). Then the program is simplified according to the way described in Appendix IV. This simplified model is validated by performing the calculations performed by hand. This is done for all green boxes in Figure 42.

The subprograms that are colored blue are meant to read or write respectively input and output to excel. This is checked visually.

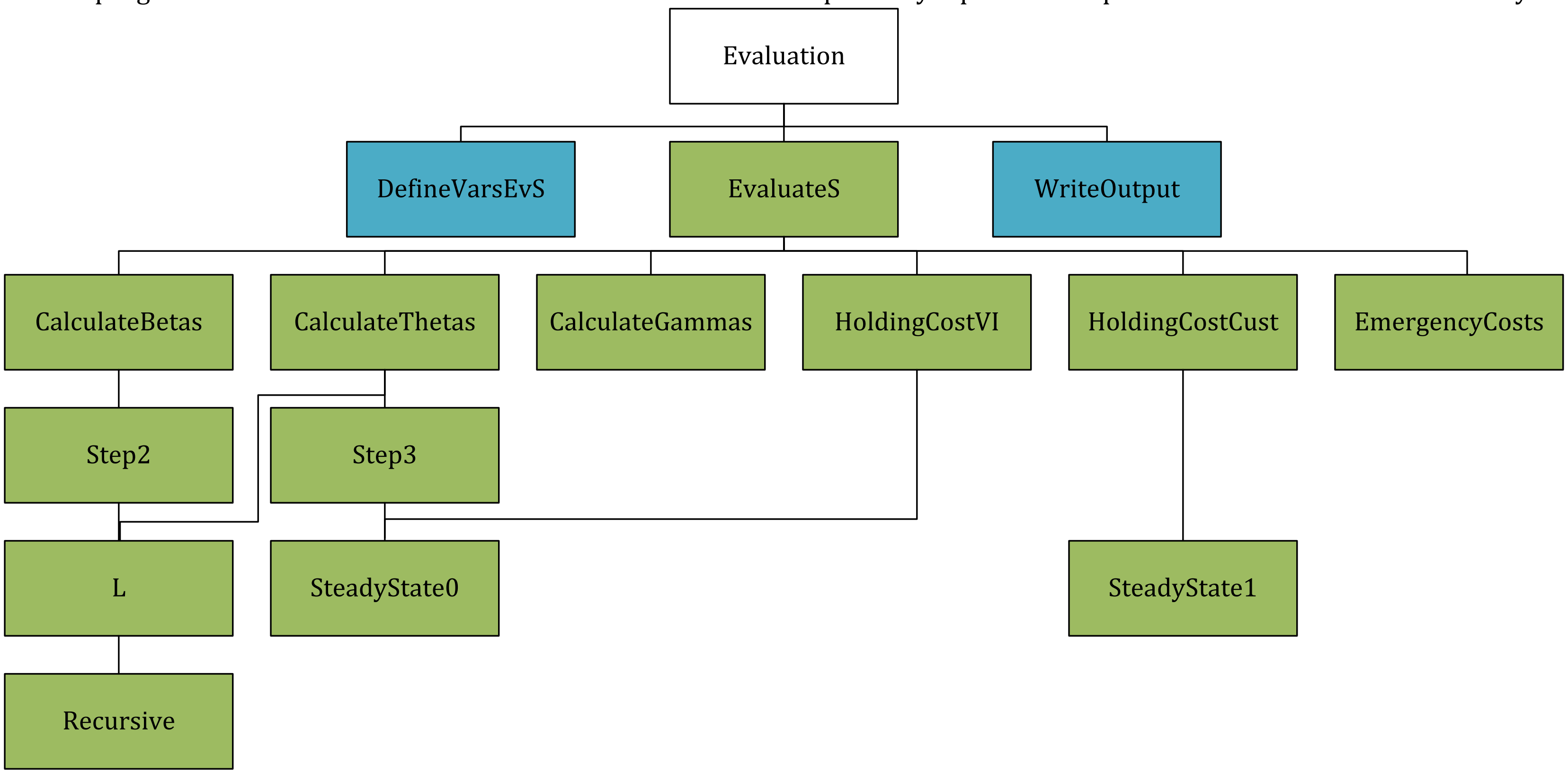


Figure 42 Structure of the program to evaluate the base stock levels

Optimization of base stock levels

Figure 43 gives an overview of the structure of the program to optimize base stock levels. The programs in the green blocks in this structure also occurred in the program to evaluate the base stock levels. These were validated by performing the calculations performed by hand. The subprograms that are colored blue are again meant to read or write respectively input and output to excel. This is checked visually. The purple blocks are programs that form a matrix in which each row represents an option using its building block(s). The program then selects the best option according to certain guidelines. These programs are validated by assigning MATLAB to give the matrix with all options. This matrix is validated by performing the single calculations using its building blocks. Then the selection is validated by doing the selection by hand and comparing the results.

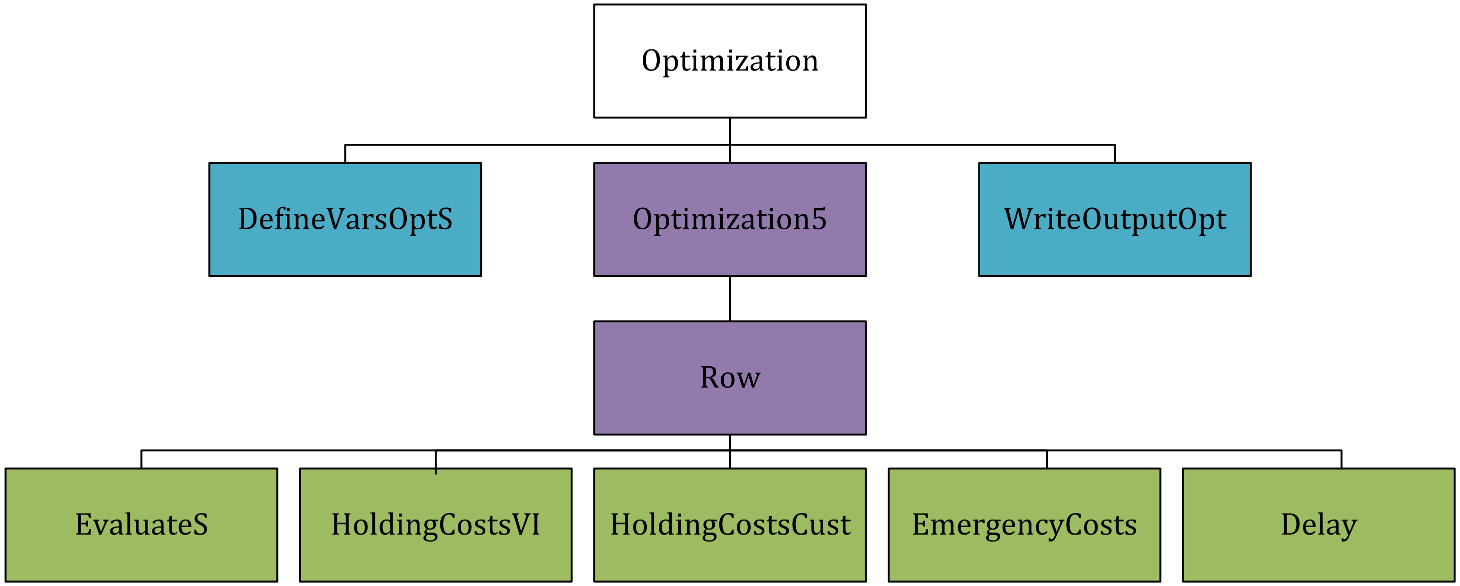


Figure 43 Structure program to optimize base stock levels

Evaluation

```
function [ output_args ] = EvaluationR2()

    V=xlsread('Example.xls','B2:M2');
    S0=V(1,1);
    S1=V(1,2);
    L0=V(1,3);
    L1=V(1,4);
    m1=V(1,5);
    m2=V(1,6);
    h0=V(1,7);
    h1=V(1,8);
    eCWH=V(1,9);
    eSup=V(1,10);
    ELCWH=V(1,11);
    ELsup=V(1,12);

[Beta0, Beta1, Beta2, Theta1, Theta2, Gamma1, Gamma2, W0] =
EvaluateS(S0,S1,L0,L1, m1,m2);

[HCVI] = HoldingCostsVI(h0, S0, S1, L0,L1, m1, m2, Beta1, Beta2,W0);
[HCCust] = HoldingCostsCust(h1, S1, L1, m1, W0);
[TEC] = EmergencyCosts(eCWH,eSup, Theta1, Gamma1,m1 );
[D] = Delay(ELCWH,ELsup, Theta1, Gamma1,m1 );

Q= [Beta0, Beta1, Theta1, Gamma1, D,HCVI, HCCust, TEC, Beta2,Theta2, Gamma2,
W0];

    xlswrite('Example.xls', Q, 'N2:Y2');

end
```

EvaluateS

```
function [Beta0, Beta1, Beta2, Theta1, Theta2, Gamma1, Gamma2, W0] =
EvaluateS(S0,S1,L0,L1, m1,m2)

    [Beta0, Beta1, Beta2,W0]= calculateBetas(S0,S1,L0,L1,m1,m2);

    [Theta1, Theta2]= calculateThetas(Beta0,S1,L1,m1);

    [Gamma1, Gamma2] = calculateGammas(Beta1,Theta1);

    %[HCVI] = HoldingCostsVI(h0, S0, S1, S2,L0,L1, m1, m2, Beta1, Beta2,W0);
    %[HCCust] = HoldingCostsCust(h1, S1, L1, m1, W0);
    %[TEC] = EmergencyCosts(eCWH,eSup, Theta1, Gamma1,m1 );

    %[D] = Delay(ELCWH,ELsup, Theta1, Gamma1,m1 );
end
```

CalculateBetas

```
function [Beta0, Beta1, Beta2,W0] = calculateBetas(S0,S1,L0,L1, m1,m2)

    W0=0;
    deltaW0=10^6;

    while deltaW0 > 0.000000001
        W0old=W0;

        [Beta1, Beta2]=Step2(S1,L1,m1,W0);

        [W0,Beta0]=Step3(S0,S1,L0, m1,m2, Beta1,Beta2);

        deltaW0=abs(W0-W0old);

    end

end
```

CalculateThetas

```
function [Theta1,Theta2] = calculateThetas(Beta0,S1,L1,m1)

    rho1=m1*L1;

    Theta1=Beta0*L(S1,rho1);
    Theta2=0;

end
```

CalculateGammas

```
function [Gamma1, Gamma2] = calculateGammas(Beta1, Theta1)

    Gamma1= 1-Beta1-Theta1;
    Gamma2=0;

end
```

HoldingCostVI

```
function [HCVI] = HoldingCostsVI(h0, S0, S1, L0,L1, m1, m2, Beta1, Beta2,W0)
    LT1=L1+W0;

    [SS0] = SteadyState0(S0, S1, L0, m1, m2, Beta1, Beta2);
    q=size(SS0);
    l=q(1,1);
    S2=l-S1-S0-1;
    help0= [zeros((S1+S2+1),1);(1:S0)'];
    %help1= (0:S1)';

    AS0=sum(help0.*SS0)       ;          % amount on stock at location 0

    AP=m1*Beta1*LT1    ;               % amount in pipeline
```

```
    HCVI=(AS0+AP)*h0    ;               % Total amount on stock against price loc
0

end
```

HoldingCostCust

```
function [HCCust] = HoldingCostsCust(h1, S1, L1, m1, W0)

    LT1=L1+W0;

    [SS1] = SteadyState1(S1,LT1, m1);

    help1= (0:S1)';

    AS1=sum(help1.*SS1)    ;            % amount on stock at location 1

    HCCust= AS1*h1;

end
```

EmergencyCosts

```
function [ ec] = EmergencyCosts(eCWH,eSup, Theta1, Gamma1,m1 )
%UNTITLED3 Summary of this function goes here
%   Detailed explanation goes here

    ec= (Theta1*eCWH +Gamma1*eSup)*m1;

end
```

Step2

```
function [Beta1,Beta2] = Step2( S1, L1,m1,W0 )

    LT1=L1+W0;

    rho1=m1*LT1;

    Beta1=1-L(S1,rho1);
    Beta2=1;

end
```

Step3

```
function [W0,Beta0]=Step3(S0, S1, L0, m1, m2, Beta1, Beta2)

    [x] = SteadyState0(S0, S1, L0, m1, m2, Beta1, Beta2);
    q=size(x);
    l=q(1,1);
    S2=l-S1-S0-1;
    Sbar=S1+S2;
    m00= (Beta1*m1 + Beta2*m2)       ;    %getal
```

```
    y= x(1:Sbar)                ;                       %kolom lengte Sbar
    h1=Sbar:-1:1                  ;                     %rij lengte Sbar
    B0=sum(y'.*h1)                 ;                    %getal
    W0=B0/m00(1,1)                 ;                    %getal

    z= x((Sbar+2):(S0+Sbar+1))       ;                  %kolom lengte Sbar
    Beta0=sum(z)                     ;                  %getal

end
```

L

```
function [L] = L(S,rho)

   [teller]= recursief(rho,S);

    n=zeros(1,1);
    n(1)=1      ; %x=0
    for x=1:S;
        n(x+1)=n(x)+recursief(rho,x);
    end
    noemer=n(S+1);
    L=teller/noemer;

end
```

SteadyState0

```
function [A] = SteadyState0(S0,S1, L0,m1,m2, beta1,beta2 )
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here

mu0=1/L0;
m0=m1+m2;
m00=beta1*m1+beta2*m2;
som=1;
pi=1;
Sbar=S1;


for i=S0-1:-1:(-Sbar-1)
    if i>-1
        m=m0;
    else m=m00;
    end

    piplus1=pi;
    somold=som;
    pi=(m/((S0-i)*mu0))*piplus1;

    som=som+pi;
    t=i;
    d=som-somold;
end
```

```
    while d>0.0001
        t=t-1;
        piplus1=pi;
        somold=som;
        pi=(m00/((S0-t)*mu0))*piplus1;

        som=som+pi;
        d=som-somold;
    end

Z=1/som;
pi=Z;

Q=S0+1-t;
q=S0+1-t;
A=zeros(Q,1);
A(q,1)=Z;

for i=S0-1:-1:t
        if i>-1
        m=m0;
    else m=m00;
        end

    piplus1=pi;
    pi=(m/((S0-i)*mu0))*piplus1;
    q=q-1;
    A(q)=pi;
end

end
```

SteadyState1

```
function [x] = SteadyState1(S1,LT1, m1)
    m =ones(1,S1)*(m1)          ;                   %vector lengte s1

    mu1 = 1/LT1      ;                                    %getal

    A=eye(S1+1)       ;                             %matrix l=b=S1+1
    %1 op diagonaaal
    A(end,:)=1        ;                                  %matrix l=b=S0+Sbar+1
    %laatste regel =1

    h=0:(S1-1)         ;                          %vector lengte s1
    y=-(m./((S1 - h)*mu1))     ;                         %vector lengte S1

    A=A+diag(y,1)      ;                                 %matrix l=b=S0+Sbar+1
    % waardes boven diagonaal invullen

    b=zeros(S1+1,1)      ;                          %kolom lengte S0+1
    b(end,1)=1;
    % onderste in kolom 1 maken
```

```
    x=linsolve(A,b)     ;                                  %kolom lengte
S0+Sbar+1
    % oplossen

end
```

Recursive

```
function [a] = recursief( rho, s )
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here
t=zeros(1,1);
t(1)=1;
for i=1:s
    t(i+1)=(rho/i)* t(i);
end

a=t(s+1);

end
```

Delay

```
function [ D] = Delay(ELCWH,ELsup, Theta1, Gamma1,m1 )
%UNTITLED3 Summary of this function goes here
%   Detailed explanation goes here

    D= (Theta1*ELCWH +Gamma1*ELsup)*m1;

end
```

Optimization5

```
function [Q] = Optimization5(L0,L1, m1,m2, h0, h1,ELCWH,ELsup, eCWH,eSup,
Dmax,Beta0min)

Z=zeros((round((m1+m2)*L0))*5,7);

D=1000;
TC=1000000;
HCmin=0;
i=-1;
Beta0=0;
    while ((D>Dmax) || (HCmin<TC) || (Beta0<Beta0min))
        i=i+1;                    %i=Stot
        TCold=TC;
        [R ] = Row(i,L0,L1, m1,m2, h0, h1,ELCWH,ELsup, eCWH,eSup,
Dmax,Beta0min);
        Beta0=R(1,3)   ;
        D=R(1,7);
        HCmin=h0*i-h0*(m1+m2)*L0-h1*m1*(L0+L1);
        TC=R(1,6);

        if TC>TCold
            TC=TCold;
```

```
        end

        Z(i+1,:)=R;

    end
    % matrix volgorde [S0,S1,Beta0,HC,ec,TC,D]
    % Choose best 1
    q=size(Z);
    l=q(1,1);

    TC=1000000;
    for i=1:l
        TCold=TC;
        if ((Z(i,7)<=Dmax) && (Z(i,3)>=Beta0min) && (Z(i,6)<TCold))
                S0=Z(i,1);
                S1=Z(i,2);
                Beta0=Z(i,3);
                HC=Z(i,4);
                ec=Z(i,5);
                TC=Z(i,6);
                D=Z(i,7);
        end

    end
    Q=[S0,S1,Beta0, HC,ec, TC, D];

end
```

Row

```
function [R ] = Row(Stot,L0,L1, m1,m2, h0, h1,ELCWH,ELsup, eCWH,eSup,
Dmax,Beta0min)
T=zeros((Stot+1),7);


 % matrix invullen,  kolom1=S0, k2=S1, k3=Hc, k4=D
for i=0:Stot
    S0=Stot-i;
    S1=i;
    [Beta0, Beta1, Beta2, Theta1, ~, Gamma1, ~, W0]= EvaluateS(S0,S1,L0,L1,
m1,m2);
    [HCVI] = HoldingCostsVI(h0, S0, S1, L0,L1, m1, m2, Beta1, Beta2,W0);
    [HCCust] = HoldingCostsCust(h1, S1, L1, m1, W0);
    [ec] = EmergencyCosts(eCWH,eSup, Theta1, Gamma1,m1 );
    [D] = Delay(ELCWH,ELsup, Theta1, Gamma1,m1 );
    HC=HCVI+HCCust;
    TC=HC+ec;

    T(i+1,:)=[S0,S1,Beta0, HC,ec, TC,D];


end

%Beste optie kiezen
q=size(T);
```

```
l=q(1,1);
TC=100000;
for i=1:l
    if ((T(i,7)<=Dmax) && (T(i,6)<=TC) && (T(i,3)>=Beta0min))
            S0=T(i,1);
            S1=T(i,2);
            Beta0=T(i,3);
            HC=T(i,4);
            ec=T(i,5);
            TC=T(i,6);
            D=T(i,7);
   end
end
R=[S0,S1,Beta0, HC,ec, TC, D];

end
```

Appendix VI: Results potential attractiveness dynamic base stock levels

Beta0 min=0.92					Csup=300				Csup=3000							
					Ccw=100				Ccw=100				Ccw=1200			
					h=0.5		h=50		h=0.5		h=50		h=0.5		h=50	
Dmax	ELsup	Elcw	m1min	m1max	S1min	S1max	S1min	S1max	S1min	S1max	S1min	S1max	S1min	S1max	S1min	S1max
0.0001	0.29	0.14	0.01	0.011	1	1	1	1	1	1	1	1	1	1	1	1
				0.02	1	1	1	1	1	1	1	1	1	2	1	1
				0.11	1	2	1	2	1	2	1	2	1	3	1	2
			0.08	0.088	2	2	2	2	2	2	2	2	2	2	2	2
				0.16	2	3	2	3	2	3	2	3	2	3	2	3
				0.18	2	3	2	3	2	3	2	3	2	3	2	3
			0.3	0.33	4	4	4	4	4	4	4	4	4	4	4	4
				0.6	4	5	4	5	4	5	4	5	4	5	4	5
				0.4	4	4	4	4	4	4	4	4	4	4	4	4
		0.5	0.01	0.011	1	1	1	1	1	1	1	1	1	1	1	1
				0.02	1	2	1	2	1	2	1	2	1	2	1	2
				0.11	1	3	1	3	1	3	1	3	1	3	1	3
			0.08	0.088	3	3	3	3	3	3	3	3	3	3	3	3
				0.16	3	3	3	3	3	3	3	3	3	3	3	3
				0.18	3	3	3	3	3	3	3	3	3	3	3	3
			0.3	0.33	4	4	4	4	4	4	4	4	4	4	4	4
				0.6	4	6	4	6	4	6	4	6	4	6	4	6
				0.4	4	4	4	4	4	4	4	4	4	4	4	4
	1	0.14	0.01	0.011	1	1	1	1	1	1	1	1	1	1	1	1
				0.02	1	1	1	1	1	1	1	1	1	2	1	1
				0.11	1	3	1	3	1	3	1	3	1	3	1	3
			0.08	0.088	2	2	2	2	2	2	2	2	2	2	2	2
				0.16	2	3	2	3	2	3	2	3	2	3	2	3
				0.18	2	3	2	3	2	3	2	3	2	3	2	3
			0.3	0.33	4	4	4	4	4	4	4	4	4	4	4	4
				0.6	4	5	4	5	4	5	4	5	4	5	4	5
				0.4	4	4	4	4	4	4	4	4	4	4	4	4
		0.5	0.01	0.011	1	1	1	1	1	1	1	1	1	1	1	1
				0.02	1	2	1	2	1	2	1	2	1	2	1	2
				0.11	1	3	1	3	1	3	1	3	1	3	1	3
			0.08	0.088	3	3	3	3	3	3	3	3	3	3	3	3
				0.16	3	3	3	3	3	3	3	3	3	3	3	3
				0.18	3	3	3	3	3	3	3	3	3	3	3	3
			0.3	0.33	4	4	4	4	4	4	4	4	4	4	4	4
				0.6	4	6	4	6	4	6	4	6	4	6	4	6
				0.4	4	4	4	4	4	4	4	4	4	4	4	4
0.05	0.29	0.14	0.01	0.011	1	1	0	0	1	1	0	0	1	1	0	0
				0.02	1	1	0	0	1	1	0	0	1	2	0	0
				0.11	1	2	0	0	1	2	0	0	1	3	0	1
			0.08	0.088	2	2	0	0	2	2	0	0	2	2	1	1
				0.16	2	2	0	0	2	3	0	0	2	3	1	1
				0.18	2	2	0	0	2	3	0	0	2	3	1	1
			0.3	0.33	3	3	0	1	3	4	0	1	4	4	2	2
				0.6	3	4	0	1	3	5	0	2	4	5	2	3
				0.4	3	3	0	0	3	4	0	0	4	4	2	2
		0.5	0.01	0.011	1	1	0	0	1	1	0	0	1	1	0	0
				0.02	1	1	0	0	1	1	0	0	1	2	0	0
				0.11	1	2	0	1	1	2	0	1	1	3	0	1
			0.08	0.088	2	2	0	0	2	2	0	0	2	2	1	1
				0.16	2	2	0	1	2	3	0	1	2	3	1	1
				0.18	2	2	0	1	2	3	0	1	2	3	1	1
			0.3	0.33	3	3	1	1	3	4	1	1	4	4	2	2
				0.6	3	4	1	2	3	5	1	2	4	5	2	3
				0.4	3	3	1	1	3	4	1	1	4	4	2	2
	1	0.14	0.01	0.011	1	1	0	0	1	1	0	0	1	1	0	0
				0.02	1	1	0	0	1	1	0	0	1	2	0	0
				0.11	1	2	0	0	1	2	0	0	1	3	0	1
			0.08	0.088	2	2	0	0	2	2	0	0	2	2	1	1
				0.16	2	2	0	0	2	3	0	0	2	3	1	1
				0.18	2	2	0	0	2	3	0	0	2	3	1	1
			0.3	0.33	3	3	1	1	3	4	1	1	4	4	2	2
				0.6	3	4	1	1	3	5	1	2	4	5	2	3
				0.4	3	3	1	1	3	4	1	1	4	4	2	2
		0.5	0.01	0.011	1	1	0	0	1	1	0	0	1	1	0	0
				0.02	1	1	0	0	1	1	0	0	1	2	0	0
				0.11	1	2	0	1	1	2	0	1	1	3	0	1
			0.08	0.088	2	2	0	0	2	2	0	0	2	2	1	1
				0.16	2	2	0	1	2	3	0	1	2	3	1	1
				0.18	2	2	0	1	2	3	0	1	2	3	1	1
			0.3	0.33	3	3	1	1	3	4	1	1	4	4	2	2
				0.6	3	4	1	2	3	5	1	2	4	5	2	3
				0.4	3	3	1	1	3	4	1	1	4	4	2	2

Beta0 min=0.3

Dmax	ELsup	Elcw	m1min	m1max	Csup=300				Csup=3000							
					Ccw=100				Ccw=100				Ccw=1200			
					h=0.5		h=50		h=0.5		h=50		h=0.5		h=50	
					S1min	S1max	S1min	S1max	S1min	S1max	S1min	S1max	S1min	S1max	S1min	S1max
0.0001 (20 min/year)	0.29	0.14	0.01	0.011	1	1	1	1	1	1	1	1	1	1	1	1
				0.02	1	2	1	2	1	2	1	2	1	2	1	2
				0.11	1	3	1	3	1	3	1	3	1	3	1	3
			0.08	0.088	3	3	3	3	3	3	3	3	3	3	3	3
				0.16	3	3	3	3	3	4	3	3	3	4	3	3
				0.18	3	4	3	4	3	4	3	4	3	4	3	4
			0.3	0.33	4	5	4	5	5	5	4	5	5	5	4	5
				0.6	4	6	4	6	5	7	4	6	5	7	4	6
				0.4	4	4	4	4	5	5	4	4	5	5	4	4
		0.5	0.01	0.011	1	1	1	1	1	1	1	1	1	1	1	1
				0.02	1	2	1	2	1	2	1	2	1	2	1	2
				0.11	1	3	1	3	1	3	1	3	1	3	1	3
			0.08	0.088	3	3	3	3	3	3	3	3	3	3	3	3
				0.16	3	3	3	3	3	4	3	3	3	4	3	3
				0.18	3	4	3	4	3	4	3	4	3	4	3	4
			0.3	0.33	4	5	4	5	5	5	4	5	5	5	4	5
				0.6	4	6	4	6	5	7	4	6	5	7	4	6
				0.4	4	5	4	5	5	5	4	5	5	5	4	5
	1	0.14	0.01	0.011	2	2	2	2	2	2	2	2	2	2	2	2
				0.02	2	2	2	2	2	2	2	2	2	2	2	2
				0.11	2	3	2	3	2	3	2	3	2	3	2	3
			0.08	0.088	3	3	3	3	3	3	3	3	3	3	3	3
				0.16	3	4	3	4	3	4	3	4	3	4	3	4
				0.18	3	4	3	4	3	4	3	4	3	4	3	4
			0.3	0.33	5	5	5	5	5	5	5	5	5	5	5	5
				0.6	5	7	5	7	5	7	5	7	5	7	5	7
				0.4	5	5	5	5	5	5	5	5	5	5	5	5
		0.5	0.01	0.011	2	2	2	2	2	2	2	2	2	2	2	2
				0.02	2	2	2	2	2	2	2	2	2	2	2	2
				0.11	2	3	2	3	2	3	2	3	2	3	2	3
			0.08	0.088	3	3	3	3	3	3	3	3	3	3	3	3
				0.16	3	4	3	4	3	4	3	4	3	4	3	4
				0.18	3	4	3	4	3	4	3	4	3	4	3	4
			0.3	0.33	5	5	5	5	5	5	5	5	5	5	5	5
				0.6	5	7	5	7	5	7	5	7	5	7	5	7
				0.4	5	5	5	5	5	5	5	5	5	5	5	5
0.05 (18.3 days/ Year)	0.29	0.14	0.01	0.011	1	1	0	0	1	1	0	0	1	1	0	0
				0.02	1	1	0	0	1	2	0	0	1	2	0	0
				0.11	1	2	0	0	1	3	0	1	1	3	0	1
			0.08	0.088	2	2	0	0	3	3	1	1	3	3	1	1
				0.16	2	3	0	0	3	4	1	2	3	4	1	2
				0.18	2	3	0	0	3	4	1	2	3	4	1	2
			0.3	0.33	4	4	1	1	5	5	2	3	5	5	2	3
				0.6	4	5	1	2	5	7	2	4	5	7	2	4
				0.4	4	4	1	1	5	5	2	2	5	5	2	2
		0.5	0.01	0.011	1	1	0	0	1	1	0	0	1	1	0	0
				0.02	1	1	0	0	1	2	0	0	1	2	0	0
				0.11	1	2	0	0	1	3	0	1	1	3	0	1
			0.08	0.088	2	2	0	0	3	3	1	1	3	3	1	1
				0.16	2	3	0	1	3	4	1	2	3	4	1	2
				0.18	2	3	0	1	3	4	1	2	3	4	1	2
			0.3	0.33	4	4	1	1	5	5	2	3	5	5	2	3
				0.6	4	5	1	2	5	7	2	4	5	7	2	4
				0.4	4	4	1	1	5	5	2	2	5	5	2	3
	1	0.14	0.01	0.011	1	1	0	0	1	1	0	0	1	1	0	0
				0.02	1	1	0	0	1	2	0	0	1	2	0	0
				0.11	1	2	0	1	1	3	0	1	1	3	0	1
			0.08	0.088	2	2	1	1	3	3	1	1	3	3	1	1
				0.16	2	3	1	1	3	4	1	2	3	4	1	2
				0.18	2	3	1	1	3	4	1	2	3	4	1	2
			0.3	0.33	4	4	2	2	5	5	2	3	5	5	2	3
				0.6	4	5	2	3	5	7	2	4	5	7	2	4
				0.4	4	4	2	2	5	5	2	2	5	5	2	3
		0.5	0.01	0.011	1	1	0	0	1	1	0	0	1	1	0	0
				0.02	1	1	0	0	1	2	0	0	1	2	0	0
				0.11	1	2	0	1	1	3	0	1	1	3	0	1
			0.08	0.088	2	2	1	1	3	3	1	1	3	3	1	1
				0.16	2	3	1	1	3	4	1	2	3	4	1	2
				0.18	2	3	1	1	3	4	1	2	3	4	1	2
			0.3	0.33	4	4	2	2	5	5	2	3	5	5	2	3
				0.6	4	5	2	3	5	7	2	4	5	7	2	4
				0.4	4	4	2	2	5	5	2	2	5	5	2	3

Appendix VII: Results cost savings by dynamic base stock levels

							Constant base stock level						Dynamic base stock level					
							Holding Costs (€/year)			Total cost (€/year)			Holding Costs (€/year)			Total cost (€/year)		
D_{max}	El^{cw}	C^{sup}	C^{cw}	h	$m1_{min}$	$m1_{max}$	min	max	avg	min	max	avg	min	max	avg	min	max	avg
0.0001 20.05493 min/year	0.14	300	100	0.5	0.01	0.11	€ 49	€ 52	€ 50	€ 51	€ 53	€ 52	€ 26	€ 51	€ 46	€ 26	€ 53	€ 47
					0.08	0.16	€ 74	€ 76	€ 75	€ 74	€ 76	€ 75	€ 49	€ 75	€ 66	€ 51	€ 75	€ 67
					0.3	0.6	€ 114	€ 122	€ 118	€ 116	€ 122	€ 119	€ 93	€ 117	€ 105	€ 95	€ 118	€ 106
				50	0.01	0.11	€ 4,909	€ 5,173	€ 5,041	€ 4,913	€ 5,173	€ 5,042	€ 2,574	€ 5,120	€ 4,607	€ 2,574	€ 5,120	€ 4,609
					0.08	0.16	€ 7,374	€ 7,587	€ 7,480	€ 7,375	€ 7,587	€ 7,481	€ 4,945	€ 7,502	€ 6,614	€ 4,948	€ 7,502	€ 6,615
					0.3	0.6	€ 11,402	€ 12,201	€ 11,801	€ 11,404	€ 12,201	€ 11,802	€ 9,282	€ 11,721	€ 10,502	€ 9,285	€ 11,722	€ 10,503
		3000	100	0.5	0.01	0.11	€ 49	€ 52	€ 50	€ 52	€ 63	€ 55	€ 26	€ 51	€ 46	€ 28	€ 63	€ 51
					0.08	0.16	€ 74	€ 76	€ 75	€ 76	€ 76	€ 76	€ 49	€ 75	€ 66	€ 55	€ 76	€ 70
					0.3	0.6	€ 114	€ 122	€ 118	€ 119	€ 122	€ 121	€ 93	€ 117	€ 105	€ 98	€ 121	€ 110
				50	0.01	0.11	€ 4,909	€ 5,173	€ 5,041	€ 4,922	€ 5,173	€ 5,045	€ 2,574	€ 5,120	€ 4,607	€ 2,576	€ 5,120	€ 4,612
					0.08	0.16	€ 7,374	€ 7,587	€ 7,480	€ 7,377	€ 7,587	€ 7,482	€ 4,945	€ 7,502	€ 6,614	€ 4,955	€ 7,502	€ 6,618
					0.3	0.6	€ 11,402	€ 12,201	€ 11,801	€ 11,409	€ 12,201	€ 11,804	€ 9,282	€ 11,721	€ 10,502	€ 9,293	€ 11,724	€ 10,507
			1200	0.5	0.01	0.11	€ 75	€ 78	€ 76	€ 76	€ 78	€ 77	€ 26	€ 75	€ 50	€ 33	€ 77	€ 59
					0.08	0.16	€ 74	€ 76	€ 75	€ 76	€ 81	€ 78	€ 50	€ 75	€ 70	€ 68	€ 81	€ 77
					0.3	0.6	€ 114	€ 122	€ 118	€ 121	€ 132	€ 124	€ 94	€ 119	€ 109	€ 102	€ 132	€ 119
				50	0.01	0.11	€ 4,909	€ 5,173	€ 5,041	€ 4,954	€ 5,173	€ 5,056	€ 2,574	€ 5,120	€ 4,607	€ 2,581	€ 5,121	€ 4,623
					0.08	0.16	€ 7,374	€ 7,587	€ 7,480	€ 7,381	€ 7,587	€ 7,484	€ 4,945	€ 7,502	€ 6,614	€ 4,976	€ 7,504	€ 6,625
					0.3	0.6	€ 11,402	€ 12,201	€ 11,801	€ 11,421	€ 12,201	€ 11,808	€ 9,282	€ 11,721	€ 10,502	€ 9,312	€ 11,727	€ 10,516
	0.5	300	100	0.5	0.01	0.11	€ 75	€ 78	€ 76	€ 75	€ 78	€ 76	€ 26	€ 76	€ 55	€ 26	€ 76	€ 55
					0.08	0.16	€ 74	€ 76	€ 75	€ 74	€ 76	€ 75	€ 74	€ 76	€ 75	€ 74	€ 76	€ 75
					0.3	0.6	€ 140	€ 148	€ 144	€ 140	€ 148	€ 144	€ 94	€ 140	€ 114	€ 96	€ 140	€ 114
				50	0.01	0.11	€ 7,507	€ 7,773	€ 7,640	€ 7,507	€ 7,773	€ 7,640	€ 2,574	€ 7,560	€ 5,474	€ 2,574	€ 7,560	€ 5,474
					0.08	0.16	€ 7,374	€ 7,587	€ 7,480	€ 7,375	€ 7,587	€ 7,481	€ 7,374	€ 7,587	€ 7,480	€ 7,375	€ 7,587	€ 7,481
					0.3	0.6	€ 14,002	€ 14,801	€ 14,401	€ 14,002	€ 14,801	€ 14,401	€ 9,441	€ 14,002	€ 11,368	€ 9,443	€ 14,002	€ 11,369
		3000	100	0.5	0.01	0.11	€ 75	€ 78	€ 76	€ 76	€ 78	€ 77	€ 26	€ 76	€ 55	€ 28	€ 76	€ 56
					0.08	0.16	€ 74	€ 76	€ 75	€ 76	€ 76	€ 76	€ 74	€ 76	€ 75	€ 76	€ 76	€ 76
					0.3	0.6	€ 140	€ 148	€ 144	€ 141	€ 148	€ 144	€ 94	€ 140	€ 114	€ 98	€ 141	€ 116
				50	0.01	0.11	€ 7,507	€ 7,773	€ 7,640	€ 7,508	€ 7,773	€ 7,640	€ 2,574	€ 7,560	€ 5,474	€ 2,576	€ 7,561	€ 5,475
					0.08	0.16	€ 7,374	€ 7,587	€ 7,480	€ 7,377	€ 7,587	€ 7,482	€ 7,374	€ 7,587	€ 7,480	€ 7,377	€ 7,587	€ 7,482
					0.3	0.6	€ 14,002	€ 14,801	€ 14,401	€ 14,002	€ 14,801	€ 14,401	€ 9,441	€ 14,002	€ 11,368	€ 9,447	€ 14,002	€ 11,371
			1200	0.5	0.01	0.11	€ 75	€ 78	€ 76	€ 76	€ 78	€ 77	€ 26	€ 76	€ 55	€ 33	€ 77	€ 59
					0.08	0.16	€ 74	€ 76	€ 75	€ 76	€ 81	€ 78	€ 74	€ 76	€ 75	€ 76	€ 81	€ 78
					0.3	0.6	€ 140	€ 148	€ 144	€ 142	€ 148	€ 145	€ 94	€ 140	€ 114	€ 102	€ 142	€ 121
				50	0.01	0.11	€ 7,507	€ 7,773	€ 7,640	€ 7,509	€ 7,773	€ 7,641	€ 2,574	€ 7,560	€ 5,474	€ 2,581	€ 7,561	€ 5,478
					0.08	0.16	€ 7,374	€ 7,587	€ 7,480	€ 7,381	€ 7,587	€ 7,484	€ 7,374	€ 7,587	€ 7,480	€ 7,381	€ 7,587	€ 7,484
					0.3	0.6	€ 14,002	€ 14,801	€ 14,401	€ 14,004	€ 14,801	€ 14,402	€ 9,441	€ 14,002	€ 11,368	€ 9,456	€ 14,004	€ 11,375

							Constant base stock level						Dynamic base stock level					
							Holding Costs (€/year)			Total cost (€/year)			Holding Costs (€/year)			Total cost (€/year)		
D_{max}	El^{cw}	C^{sup}	C^{cw}	h	$m1_{min}$	$m1_{max}$	min	max	avg	min	max	avg	min	max	avg	min	max	avg
0.05	0.14	300	100	0.5	0.01	0.11	€ 49	€ 52	€ 50	€ 51	€ 53	€ 52	€ 25	€ 50	€ 37	€ 26	€ 53	€ 42
18.25					0.08	0.16	€ 48	€ 50	€ 49	€ 51	€ 59	€ 55	€ 48	€ 50	€ 49	€ 51	€ 59	€ 55
dgn/yr					0.3	0.6	€ 88	€ 96	€ 92	€ 95	€ 101	€ 97	€ 67	€ 91	€ 79	€ 77	€ 101	€ 91
				50	0.01	0.11	€ 0	€ 0	€ 0	€ 59	€ 650	€ 355	€ 0	€ 0	€ 0	€ 59	€ 650	€ 355
					0.08	0.16	€ 0	€ 0	€ 0	€ 473	€ 944	€ 709	€ 0	€ 0	€ 0	€ 473	€ 944	€ 709
					0.3	0.6	€ 1,612	€ 1,986	€ 1,789	€ 2,432	€ 2,983	€ 2,670	€ 0	€ 1,900	€ 1,458	€ 1,807	€ 2,983	€ 2,565
		3000	100	0.5	0.01	0.11	€ 49	€ 52	€ 50	€ 52	€ 63	€ 55	€ 25	€ 51	€ 42	€ 28	€ 63	€ 49
					0.08	0.16	€ 74	€ 76	€ 75	€ 76	€ 76	€ 76	€ 49	€ 74	€ 57	€ 55	€ 76	€ 67
					0.3	0.6	€ 114	€ 122	€ 118	€ 119	€ 122	€ 121	€ 4	€ 35	€ 15	€ 1	€ 2	€ 2
				50	0.01	0.11	€ 0	€ 0	€ 0	€ 158	€ 1,701	€ 934	€ 0	€ 0	€ 0	€ 158	€ 1,701	€ 934
					0.08	0.16	€ 0	€ 0	€ 0	€ 1,245	€ 2,449	€ 1,850	€ 0	€ 0	€ 0	€ 1,245	€ 2,449	€ 1,850
					0.3	0.6	€ 3,770	€ 4,424	€ 4,090	€ 4,649	€ 5,047	€ 4,788	€ 1,979	€ 9,275	€ 4,835	€ 0	€ 73	€ 35
			1200	0.5	0.01	0.11	€ 75	€ 78	€ 76	€ 76	€ 78	€ 77	€ 26	€ 75	€ 50	€ 33	€ 77	€ 59
					0.08	0.16	€ 74	€ 76	€ 75	€ 76	€ 81	€ 78	€ 50	€ 75	€ 70	€ 68	€ 81	€ 77
					0.3	0.6	€ 114	€ 122	€ 118	€ 121	€ 132	€ 124	€ 94	€ 119	€ 109	€ 102	€ 132	€ 119
				50	0.01	0.11	€ 2,337	€ 2,574	€ 2,452	€ 2,581	€ 3,126	€ 2,769	€ 0	€ 2,473	€ 1,603	€ 690	€ 3,126	€ 2,368
					0.08	0.16	€ 2,234	€ 2,403	€ 2,317	€ 2,833	€ 3,827	€ 3,285	€ 2,234	€ 2,403	€ 2,317	€ 2,833	€ 3,827	€ 3,285
					0.3	0.6	€ 6,235	€ 7,004	€ 6,616	€ 6,961	€ 7,167	€ 7,036	€ 4,018	€ 6,385	€ 4,917	€ 5,187	€ 7,167	€ 6,252
	0.5	300	100	0.5	0.01	0.11	€ 49	€ 52	€ 50	€ 51	€ 53	€ 52	€ 25	€ 50	€ 37	€ 26	€ 53	€ 42
					0.08	0.16	€ 48	€ 50	€ 49	€ 51	€ 59	€ 55	€ 48	€ 50	€ 49	€ 51	€ 59	€ 55
					0.3	0.6	€ 88	€ 96	€ 92	€ 95	€ 101	€ 97	€ 67	€ 91	€ 79	€ 77	€ 101	€ 91
				50	0.01	0.11	€ 2,337	€ 2,574	€ 2,452	€ 2,405	€ 2,574	€ 2,480	€ 0	€ 2,337	€ 389	€ 59	€ 2,405	€ 647
					0.08	0.16	€ 2,234	€ 2,403	€ 2,317	€ 2,372	€ 2,440	€ 2,401	€ 0	€ 2,332	€ 1,522	€ 473	€ 2,403	€ 1,764
					0.3	0.6	€ 3,770	€ 4,429	€ 4,091	€ 4,162	€ 4,495	€ 4,300		€ 1,900	€ 4,149	€ 3,286	€ 2,418	€ 4,310
		3000	100	0.5	0.01	0.11	€ 49	€ 52	€ 50	€ 52	€ 63	€ 55	€ 25	€ 51	€ 42	€ 28	€ 63	€ 49
					0.08	0.16	€ 74	€ 76	€ 75	€ 76	€ 76	€ 76	€ 49	€ 74	€ 57	€ 55	€ 76	€ 67
					0.3	0.6	€ 114	€ 122	€ 118	€ 119	€ 122	€ 121	€ 70	€ 116	€ 96	€ 96	€ 121	€ 109
				50	0.01	0.11	€ 2,337	€ 2,574	€ 2,452	€ 2,515	€ 2,576	€ 2,537	€ 0	€ 2,337	€ 389	€ 158	€ 2,546	€ 1,075
					0.08	0.16	€ 2,234	€ 2,403	€ 2,317	€ 2,518	€ 2,653	€ 2,573	€ 0	€ 2,332	€ 1,522	€ 1,245	€ 2,653	€ 2,188
					0.3	0.6	€ 3,770	€ 4,429	€ 4,091	€ 4,649	€ 5,047	€ 4,781	€ 1,900	€ 4,149	€ 3,286	€ 3,264	€ 5,047	€ 4,380
			1200	0.5	0.01	0.11	€ 75	€ 78	€ 76	€ 76	€ 78	€ 77	€ 26	€ 75	€ 50	€ 33	€ 77	€ 59
					0.08	0.16	€ 74	€ 76	€ 75	€ 76	€ 81	€ 78	€ 50	€ 75	€ 70	€ 68	€ 81	€ 77
					0.3	0.6	€ 114	€ 122	€ 118	€ 121	€ 132	€ 124	€ 94	€ 119	€ 109	€ 102	€ 132	€ 119
				50	0.01	0.11	€ 2,337	€ 2,574	€ 2,452	€ 2,581	€ 3,126	€ 2,769	€ 0	€ 2,473	€ 1,603	€ 690	€ 3,126	€ 2,368
					0.08	0.16	€ 2,234	€ 2,403	€ 2,317	€ 2,833	€ 3,827	€ 3,285	€ 2,234	€ 2,403	€ 2,317	€ 2,833	€ 3,827	€ 3,285
					0.3	0.6	€ 6,235	€ 7,004	€ 6,616	€ 6,961	€ 7,167	€ 7,036	€ 4,018	€ 6,385	€ 4,917	€ 5,187	€ 7,167	€ 6,252

							% Change						Absolute change					
							Holding Costs			Total Costs			Holding Costs			Total Costs		
D_{max}	El^{cw}	C^{sup}	C^{cw}	h	$m1_{min}$	$m1_{max}$	min	max	avg	min	max	avg	min	max	avg	min	max	avg
0.0001 20.05493 min/year	0.14	300	100	0.5	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 23	-€ 1	-€ 4	-€ 25	€ 0	-€ 4
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	-€ 1	-€ 9	-€ 23	-€ 1	-€ 8
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 21	-€ 5	-€ 13	-€ 20	-€ 4	-€ 12
				50	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,335	-€ 53	-€ 433	-€ 2,338	-€ 53	-€ 433
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,429	-€ 85	-€ 866	-€ 2,427	-€ 85	-€ 866
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,120	-€ 479	-€ 1,300	-€ 2,119	-€ 479	-€ 1,299
		3000	100	0.5	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 23	-€ 1	-€ 4	-€ 24	€ 0	-€ 4
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	-€ 1	-€ 9	-€ 20	€ 0	-€ 6
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 21	-€ 5	-€ 13	-€ 21	-€ 1	-€ 10
				50	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,335	-€ 53	-€ 433	-€ 2,347	-€ 53	-€ 433
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,429	-€ 85	-€ 866	-€ 2,422	-€ 85	-€ 864
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,120	-€ 479	-€ 1,300	-€ 2,116	-€ 477	-€ 1,297
			1200	0.5	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 49	-€ 3	-€ 26	-€ 43	-€ 1	-€ 18
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	€ 0	-€ 4	-€ 8	€ 0	-€ 1
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 20	-€ 3	-€ 9	-€ 19	€ 0	-€ 5
				50	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,335	-€ 53	-€ 433	-€ 2,373	-€ 52	-€ 432
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,429	-€ 85	-€ 866	-€ 2,405	-€ 84	-€ 859
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,120	-€ 479	-€ 1,300	-€ 2,109	-€ 474	-€ 1,292
	0.5	300	100	0.5	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 49	-€ 2	-€ 22	-€ 49	-€ 2	-€ 21
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 46	-€ 8	-€ 30	-€ 44	-€ 8	-€ 30
				50	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 4,933	-€ 213	-€ 2,167	-€ 4,933	-€ 213	-€ 2,166
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 4,560	-€ 799	-€ 3,033	-€ 4,559	-€ 799	-€ 3,033
		3000	100	0.5	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 49	-€ 2	-€ 22	-€ 48	-€ 2	-€ 20
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 46	-€ 8	-€ 30	-€ 43	-€ 7	-€ 28
				50	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 4,933	-€ 213	-€ 2,167	-€ 4,932	-€ 213	-€ 2,165
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 4,560	-€ 799	-€ 3,033	-€ 4,556	-€ 798	-€ 3,031
			1200	0.5	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 49	-€ 2	-€ 22	-€ 43	-€ 1	-€ 18
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 46	-€ 8	-€ 30	-€ 40	-€ 6	-€ 24
				50	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 4,933	-€ 213	-€ 2,167	-€ 4,928	-€ 212	-€ 2,162
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 4,560	-€ 799	-€ 3,033	-€ 4,547	-€ 797	-€ 3,027

							% Change						Absolute change					
							Holding Costs			Total Costs			Holding Costs			Total Costs		
D_{max}	El^{cw}	C^{sup}	C^{cw}	h	$m1_{min}$	$m1_{max}$	min	max	avg	min	max	avg	min	max	avg	min	max	avg
0.05 18.25 dgn/yr	0.14	300	100	0.5	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	-€ 2	-€ 13	-€ 25	€ 0	-€ 10
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 21	-€ 5	-€ 13	-€ 18	€ 0	-€ 6
				50	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	-€ 1	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 1,612	-€ 86	-€ 331	-€ 626	€ 0	-€ 104
		3000	100	0.5	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	-€ 1	-€ 9	-€ 24	€ 0	-€ 6
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 25	-€ 2	-€ 17	-€ 20	€ 0	-€ 9
					0.3	0.6	-€ 1	-€ 1	-€ 1	-€ 1	-€ 1	-€ 1	-€ 110	-€ 87	-€ 103	-€ 118	-€ 120	-€ 119
				50	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 1	€ 0	-€ 1	-€ 1	-€ 1	-€ 1,791	€ 4,851	€ 745	-€ 4,649	-€ 4,974	-€ 4,753
			1200	0.5	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 49	-€ 3	-€ 26	-€ 43	-€ 1	-€ 18
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	€ 0	-€ 4	-€ 8	€ 0	-€ 1
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 20	-€ 3	-€ 9	-€ 19	€ 0	-€ 5
				50	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 2,337	-€ 100	-€ 849	-€ 1,891	€ 0	-€ 401
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,218	-€ 619	-€ 1,699	-€ 1,773	€ 0	-€ 784
	0.5	300	100	0.5	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	-€ 2	-€ 13	-€ 25	€ 0	-€ 10
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 21	-€ 5	-€ 13	-€ 18	€ 0	-€ 6
				50	0.01	0.11	-€ 1	€ 0	-€ 1	-€ 1	€ 0	-€ 1	-€ 2,337	-€ 237	-€ 2,063	-€ 2,346	-€ 169	-€ 1,832
					0.08	0.16	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 2,234	-€ 71	-€ 795	-€ 1,899	-€ 37	-€ 637
					0.3	0.6	-€ 1	-€ 1	€ 0	€ 0	€ 0	€ 0	-€ 3,770	-€ 2,529	€ 59	-€ 876	-€ 2,077	€ 10
		3000	100	0.5	0.01	0.11	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	-€ 1	-€ 9	-€ 24	€ 0	-€ 6
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 25	-€ 2	-€ 17	-€ 20	€ 0	-€ 9
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 44	-€ 6	-€ 22	-€ 23	-€ 1	-€ 12
				50	0.01	0.11	-€ 1	€ 0	-€ 1	-€ 1	€ 0	-€ 1	-€ 2,337	-€ 237	-€ 2,063	-€ 2,357	-€ 29	-€ 1,462
					0.08	0.16	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 2,234	-€ 71	-€ 795	-€ 1,273	€ 0	-€ 385
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 1,870	-€ 279	-€ 804	-€ 1,384	€ 0	-€ 401
			1200	0.5	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 49	-€ 3	-€ 26	-€ 43	-€ 1	-€ 18
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 24	€ 0	-€ 4	-€ 8	€ 0	-€ 1
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 20	-€ 3	-€ 9	-€ 19	€ 0	-€ 5
				50	0.01	0.11	-€ 1	€ 0	€ 0	-€ 1	€ 0	€ 0	-€ 2,337	-€ 100	-€ 849	-€ 1,891	€ 0	-€ 401
					0.08	0.16	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0
					0.3	0.6	€ 0	€ 0	€ 0	€ 0	€ 0	€ 0	-€ 2,218	-€ 619	-€ 1,699	-€ 1,773	€ 0	-€ 784

Appendix VIII: Selection of a VI product

Below the requirements for the selection of a product will be given. The requirements are first discussed with G.J. van Houtum to get an expert opinion, and then they are brought in to a session with Erlend Hessel, Huub Peeters and Katja Kleinveld. They are the managers of the departments within the business unit Customer Services and it is assumed that they have a good view on the products sold by VI and what is important when analyzing these products. The goal of this session was to choose the most appropriate VI system. First the requirements were discussed and slightly adapted. Then a matrix was formed with all VI products on the top row and the selection criteria in the first column. The requirements will be discussed short below. Hard requirements need to be true, for normal requirements it is nice if they are true and the soft requirements are used as a ranking criteria for the products for which the hard and normal requirement hold.

Hard requirements

- Many similar products in the field

  To be able to derive the demand distribution
- Data available from the moment of installation of the product

  To be able to observe changes in the demand distribution during lifetime
- CMo applicable

  For scenario 3 CMo has to be applicable
- System is in the sold for more than 7 years

  The demand for spare parts usually occurs in phases, after 5 years of operating another interesting great demand occurs usually.
- Turnover rate spare parts

  Some products are that good that they do never fail, then it makes no sense to do research to the spare parts because there will be no data to analyze.

Normal requirements

- High percentage of critical items that is VI specific

  This makes the analysis more valuable because there is more information
- Contains spare parts that fail due to wear (IFR)

  Required for scenario 2

Soft requirements

- A high required availability

  If this is not the case, it is not important whether there are enough spare parts available
- Expensive spare parts

  If this is not the case, a bulk of spare parts could be stocked without causing high costs
- Installed at customers having a VI site based maintenance team/consignment stock

  This will give the opportunity get additional information
- The expectation is that this product is sold often in the future

  This makes the analysis more valuable

Based on the matrix shown in Figure 44 and the discussion it is found that the Posisorter and the Vertisorter are good products for this research.

After deeper analysis of the spare parts used for both products, it seemed that only one product on the recommended spare parts lists of the Vertisorter was a VI-item. So the conclusion was made that only the Posisorter is appropriate for this study.

	Posisorter	Vertisorter	Loopsorter	Tubtrax	Bagtrax	Crane	CHCD	Check-in
Many similar products in the field								
Data available from the moment of installation of the product								
System is in the sold for more than 7 years								
High turnover rate spare parts								
High percentage of critical items that is VI specific								
Contains spare parts that fail due to wear								
Expensive spare parts								
A high required availability								
Installed at customers having a VI site based maintenance team/consignment stock								
The expectation is that this product is sold often in the future								

Figure 44 Matrix to determine product for case-study

Appendix IX: Posisorter

Working of the Posisorter

An overview of a Posisorter is given in Figure 45. The Posisorter is the sorter where all packages are on in this picture. The branches, or chutes in which the packages are sorted, do not belong to the Posisorter.

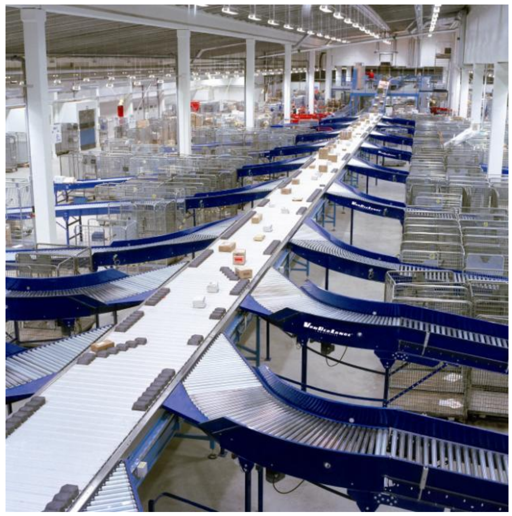


Figure 45 Overview of Posisorter

An overview of a typical Posisorter is given in the picture below. Packages enter the Posisorter at the induct. The sorter then sends the packages into the right chutes. Packages which are not sorted will end up in the overflow. The Posisorter in the picture above and Figure 46below have chutes on both sites. It is also possible that the sorter has chutes at only one site.

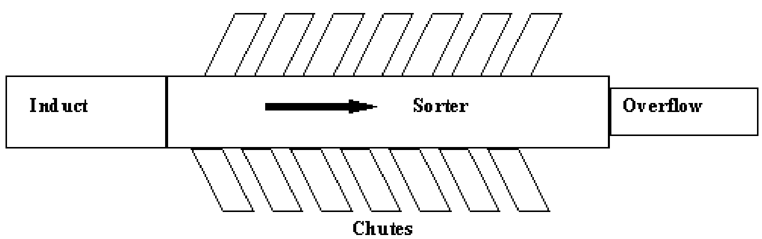


Figure 46 Schematic view on the Posisorter

Figure 47 shows how the packages are sorted; the 'black boxes', called Divert Shoes, push the package into the right shoot.

Figure 47 Sorting a package

Items studied of the Posisorter

The items studied are the Crossing, the Divert Shoe, the Divert Switch, the Merge and the Proximity Switch. The function of these items will be discussed using Figure 48. This is a picture of a Posisorter of which some of the panels on which the packages are transported are removed to be able to look inside the sorter.

The function of the Divert Shoe is to push the packages into the chutes. The Divert Shoes do have pins on their bottom side. These pins do slide through the rails that are assembled at each side of the sorter and go across the sorter to the other side. A Divert Shoe, will usually slide through a rails at one of the sides of the sorter. When a package has to be sorted out, a Divert Switch is will direct a Divert Shoe from one side to the other to push a package into a chute. A Divert Switch is the mechanical part and the Proximity Switch will control this part. The Divert Switch and the Proximity switch do occur on both sides of the sorter.

When a Divert Shoe has moved from one side of the sorter to the other side, a Merge will take care over a smooth enter of the Divert Shoe into the rail that is assembled along the other side of the sorter.

It can be seen in the picture that these rails cross each other. A Crossing makes sure that the pins of the Diver Shoe smoothly pass this crossing.

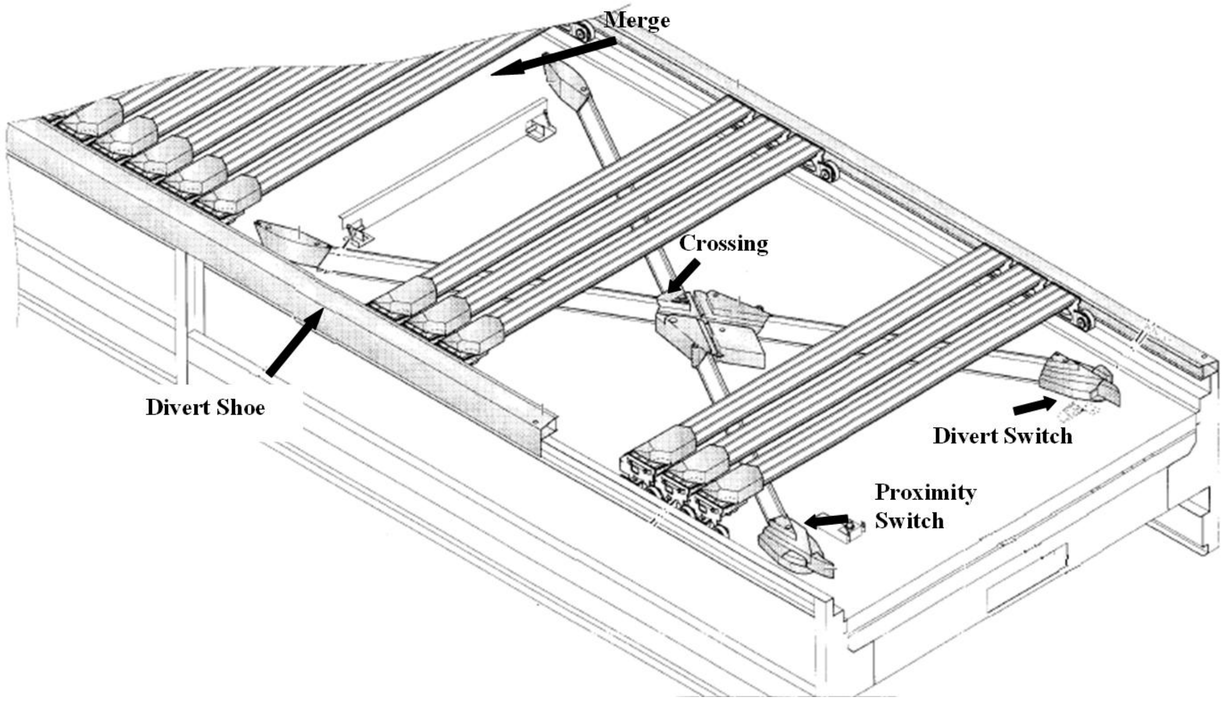


Figure 48 Items in the Posisorter

Appendix X: Data selection

Selection step 1

The recommended spare part lists of 4 projects with an Posisorter were used to specify the spare parts of an Posisorter. Only items which were classified as VIN (Vanderlande Normal), VIS (Vanderlande Specific) or PLA (plastics) were kept in the selection. VIN and VIS spare parts need to be bought at VI, plastics can theoretically be bought at external suppliers when a mold is arranged but it is assumed that these items are always bought at VI.

Selection step 2

A first step in combining these datasets, was to filter out all sales activities for the VI-spare parts of the Posisorter selection. Unfortunately this did not provide a good overview; there were VI-spare parts on the list that were sold for other purposes than replacing the item in the Posisorter and sales activities were missing. Almost all Posisorters are customized, leading to different items in different Posisorters. It therefore occurs that items with a similar function and a similar failure behavior do have different item numbers.

The first problem, that sales occurred that were not used for Posisorters, occurred only for wheels. It is resolved by deleting all items that were bought by customers not having an Posisorter.

The fact that there were multiple item numbers for items with a similar function and failure behavior, led to the development of categories of VI-spare parts.

The problem that the overview was not complete is solved by using the field 'item description' in the sales database. For all items in the subset, search is done based on the description to find similar items with different item numbers. To be sure that the function and failure behavior is equal to the other items in the category, the drawings of the single components were used and if necessary expert knowledge was used. By doing this search, another problem occurred. Although it is prescribed by VI to exchange only the complete assembly, it turned out that some customers do buy components of the assembly. It was decided to add the orders of this components to the category of the assembly because the whole assembly was needed strictly spoken.

Selection step 3

It is decided whether spare parts orders were placed for planned preventive maintenance, revisions or big crashes based on the order quantity. A demand occurrence was considered to fall in this category when the order quantity was bigger than the maximum quantity to be stored on site.

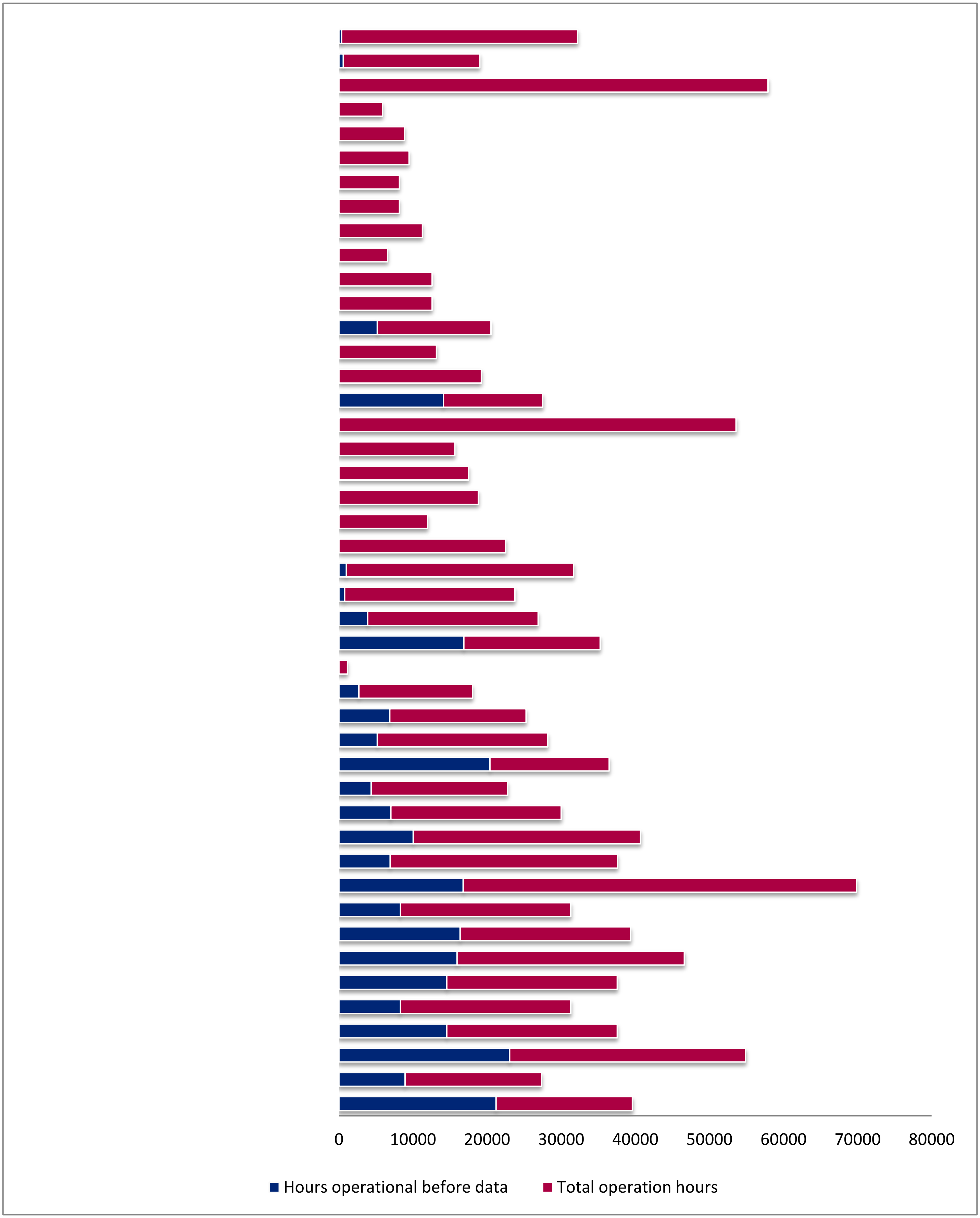
For all customers in the sample, extra information had to be gained via the service account managers (SAMs), which led to a limited size of the sample. For the 73 customers which created 80% of the total demand of the spare parts sales (excluding the orders with high order quantity), the service account managers were requested for the extra information. If there was no response within a week, a first reminder was sent and a second reminder was sent after 2 weeks. Customers of which the SAM did not react were left outside the sample. Some SAMs did advise to add some site that they knew to the selection. In this way a random selection of 55 customers was made.

The criticality of the items was judged by E. Hessel. All VI-spare parts were divided in three categories;

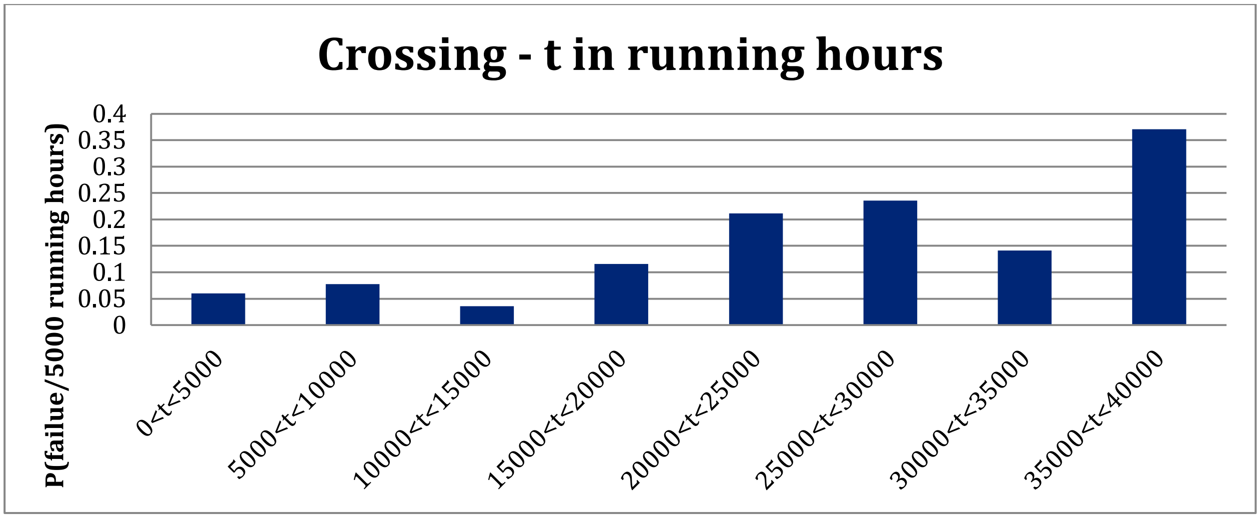
- Category 1: Failure of the items lead to stoppage of the whole Posisorter
- Category 2: Failure of the item leads to loss of capacity; 1 or multiple shoots become unavailable
- Category 3: Failure of the items leads to more noise, or other non-desirable things, but the Posisorter can run for several weeks in this state.

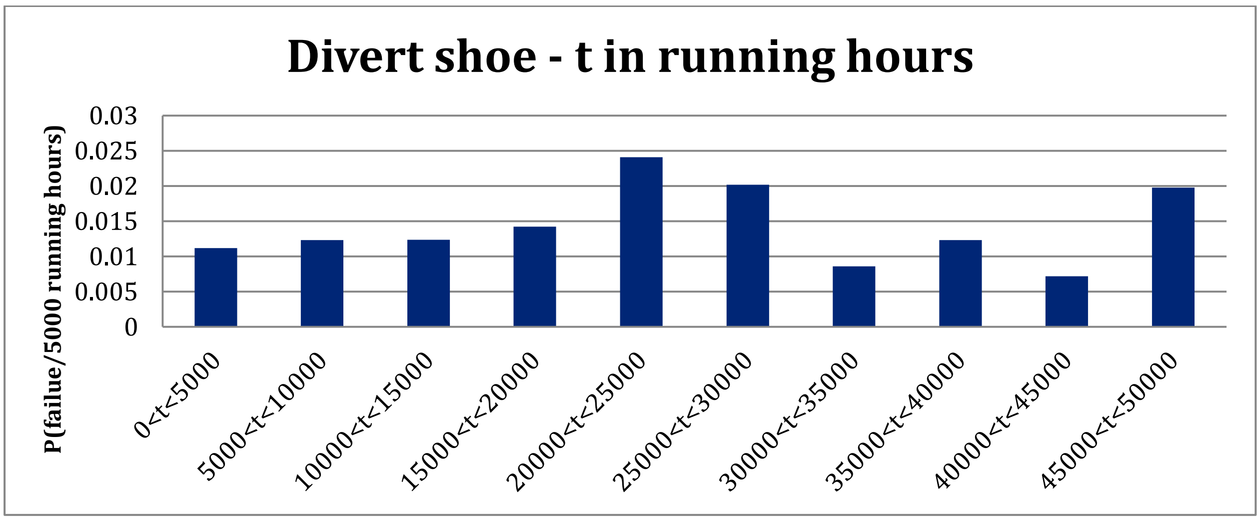
All items of category 3 were left outside the analysis.

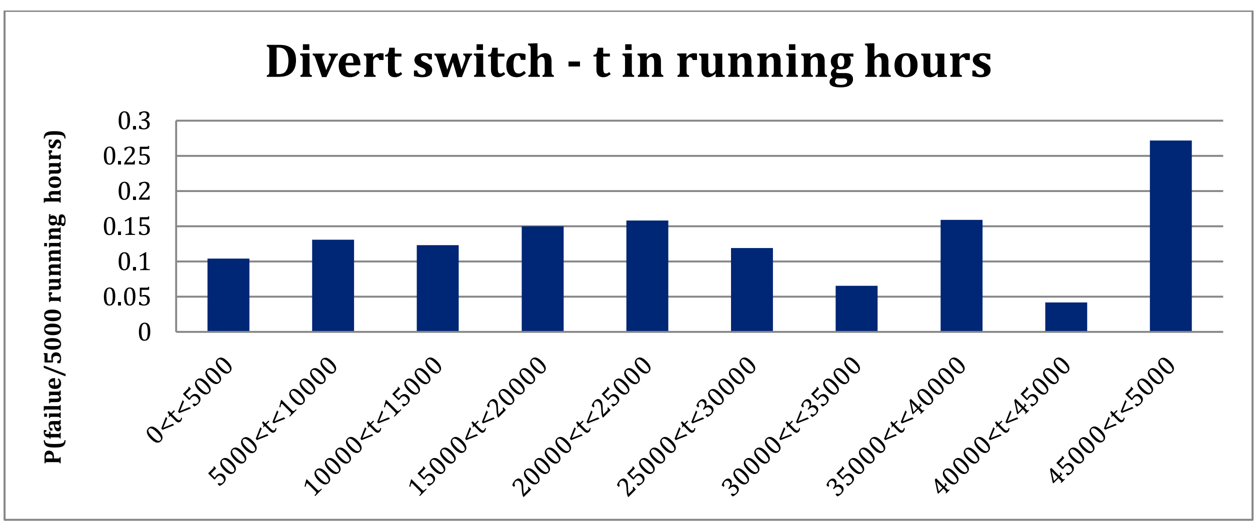
Appendix XI: Overview of customers in analysis

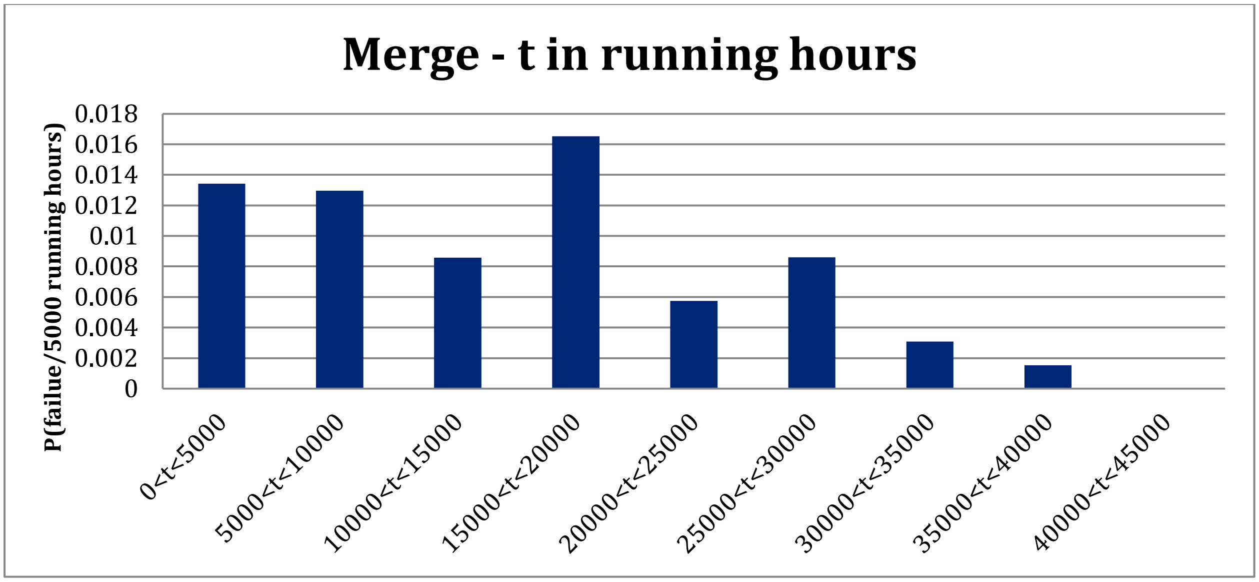


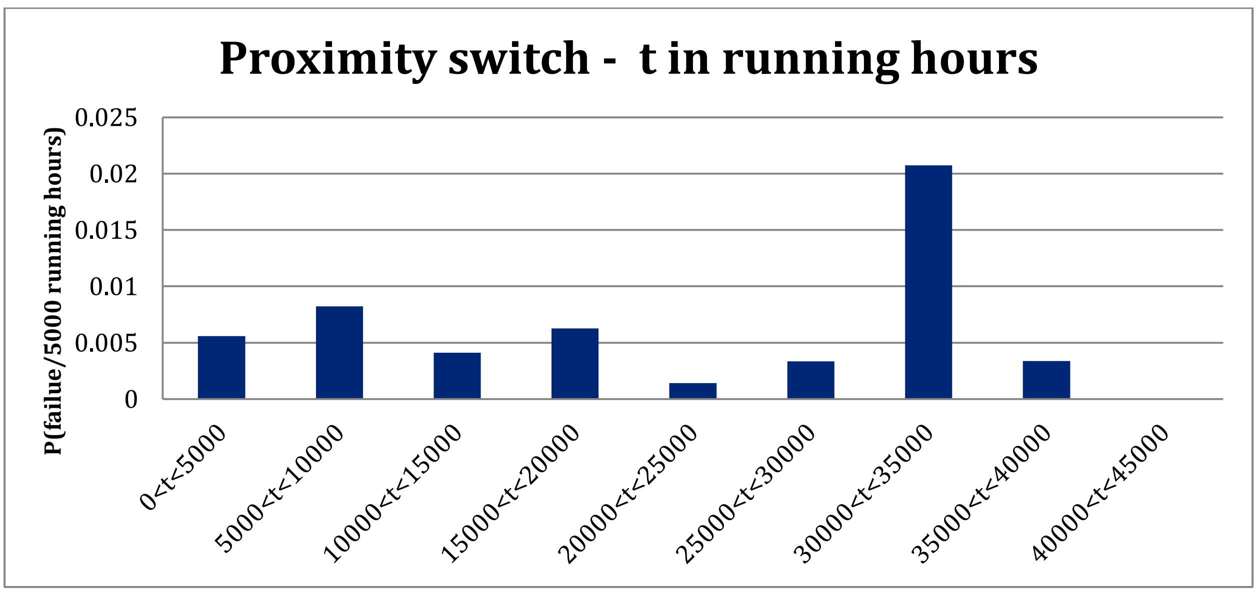
Appendix XII: Graphs demand items Posisorter








Merge - t in running hours
P(failue/5000 running hours)
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0<t<5000
5000<t<10000
10000<t<15000
15000<t<20000
20000<t<25000
25000<t<30000
30000<t<35000
35000<t<40000
40000<t<45000


Proximity switch - t in running hours
P(failue/5000 running hours)
0.025
0.02
0.015
0.01
0.005
0
0<t<5000
5000<t<10000
10000<t<15000
15000<t<20000
20000<t<25000
25000<t<30000
30000<t<35000
35000<t<40000
40000<t<45000

Appendix XIII: Fitting an empirical distribution to the demand

Crossing

The transformation using $\sqrt{x}$ resulted in the best fit for the crossing. The SPSS output is given below:

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,845[a]	,714	,667	,08047

a. Predictors: (Constant), VAR00001

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	,097	1	,097	15,012	,008[a]
	Residual	,039	6	,006		
	Total	,136	7			

a. Predictors: (Constant), VAR00001
b. Dependent Variable: VAR00004

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	,180	,057		3,152	,020
	VAR00001	9,622E-7	,000	,845	3,874	,008

a. Dependent Variable: VAR00004

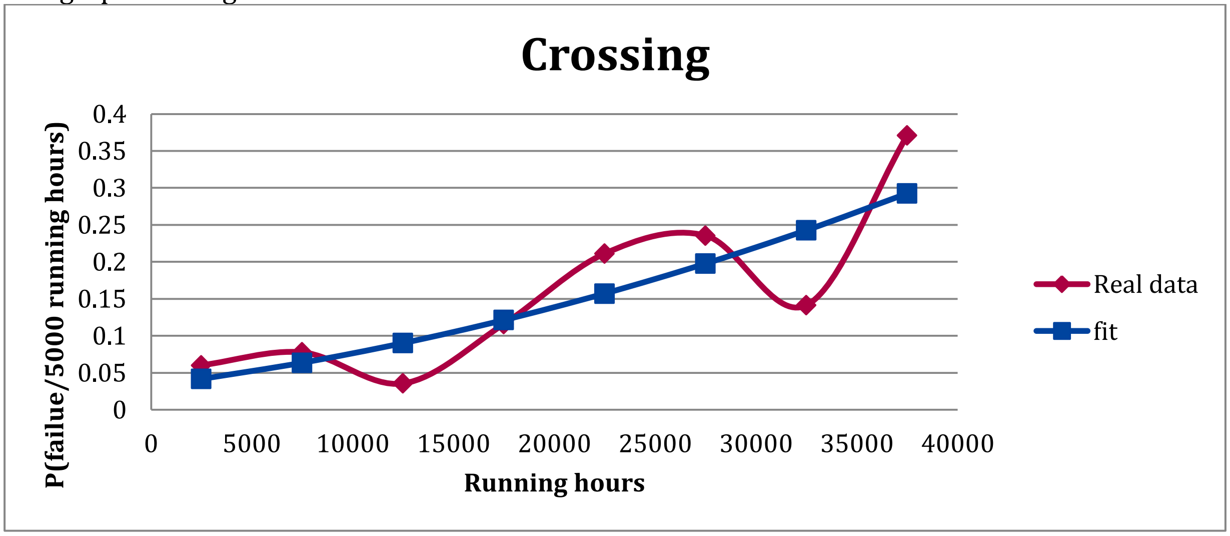
Because of the transformation, the equation to determine the chance on failure of a crossing is:

$$\sqrt{P(failure/5000runninghours)_{crossing}} = 0.18 + 9.622*10^{-6}*t$$

Resulting in the following formula:

$$P(failure/5000runninghours)_{crossing} = (0.18 + 9.622*10^{-6}*t)^2$$

The graph below gives an overview of the fit of this function.



Divert shoe

For the regression analysis only the data points till 30000 running hours are used. The transformation using $\sqrt{x}$ resulted in the best fit for the divert shoe as well. The results are given below.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,863[a]	,745	,681	,01126

a. Predictors: (Constant), VAR00001

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	,001	1	,001	11,673	,027[a]
	Residual	,001	4	,000		
	Total	,002	5			

a. Predictors: (Constant), VAR00001
b. Dependent Variable: VAR00004

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	,096	,009		10,386	,000
	VAR00001	1,839E-7	,000	,863	3,417	,027

a. Dependent Variable: VAR00004

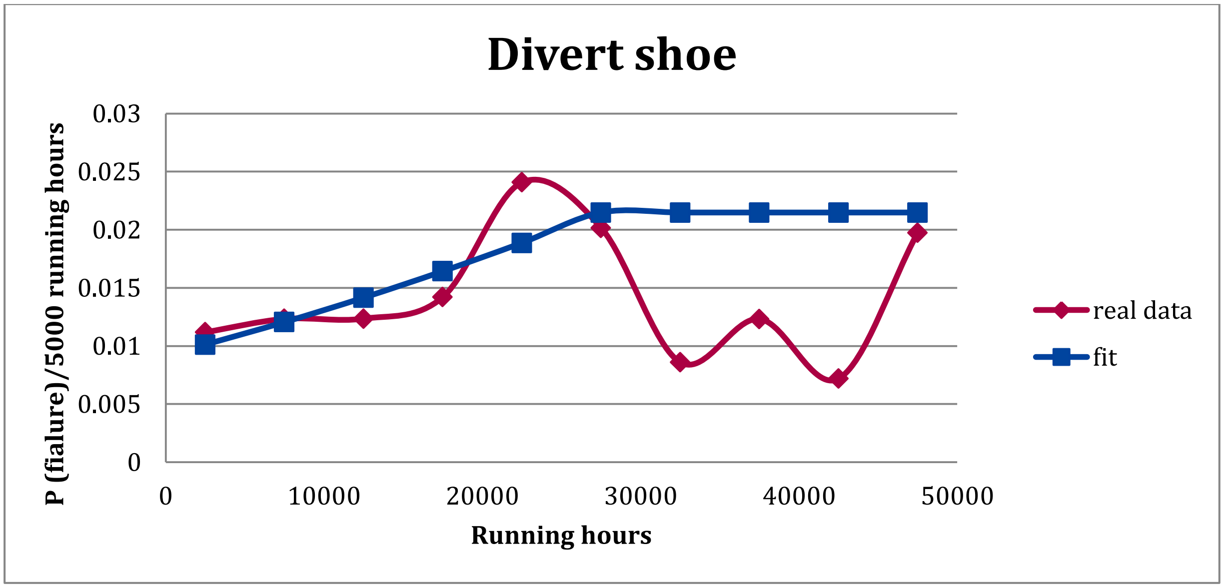
Because of the transformation, the equation to determine the chance on failure of a crossing is:

$$\sqrt{P(failure/5000 runninghours)_{divertshoe}} = \begin{cases} 0.096 + 1.839 * 10^{-6} * t & t \leq 30000 \\ \sqrt{0.02148} & t > 30000 \end{cases}$$

Resulting in the following formula:

$$P(failure/5000 runninghours)_{divertshoe} = \begin{cases} (0.096 + 1.839 * 10^{-6} * t)^2 & t \leq 30000 \\ 0.02148 & t > 30000 \end{cases}$$

The graph below gives an overview of the fit of this function.



Divert switch

For the regression analysis the data point 30,000<t<35,000 running hours was deleted. The original data (without transformation) resulted in the best fit for the divert switch. The results are given below.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,655[a]	,429	,315	,01761

a. Predictors: (Constant), VAR00001

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	,001	1	,001	3,763	,110[a]
	Residual	,002	5	,000		
	Total	,003	6			

a. Predictors: (Constant), VAR00001
b. Dependent Variable: VAR00002

Coefficients[a]

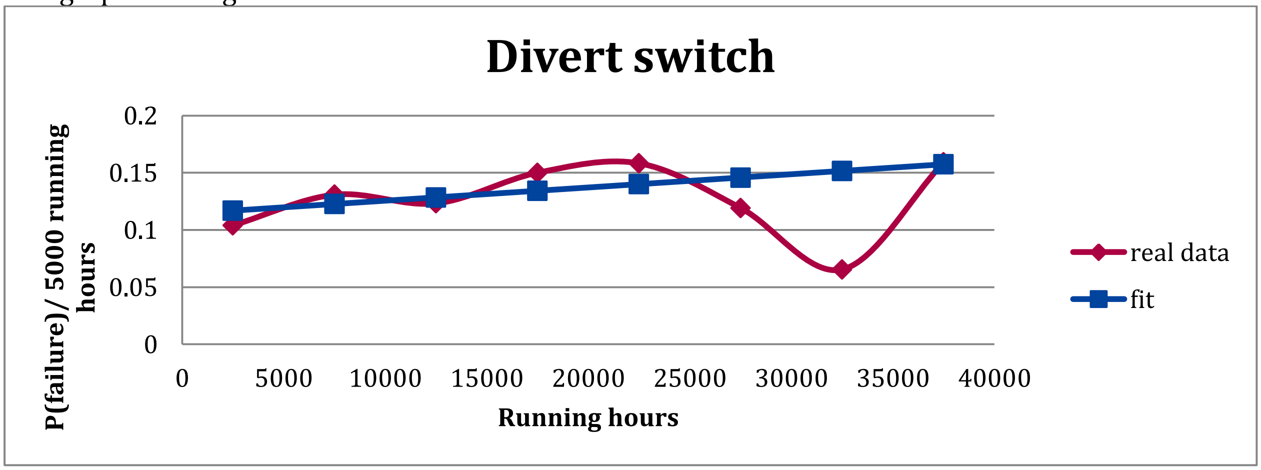
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	,114	,013		8,937	,000
	VAR00001	1,157E-7	,000	,655	1,940	,110

a. Dependent Variable: VAR00002

Based on this regression analysis, the formula to determine the change of failure of a divert switch is equal to:

$$P(failure/5000 runninghours)_{divertswitch} = (0.114 + 1.157 * 10^{-6} * t)$$

The graph below gives an overview of the fit of this function.

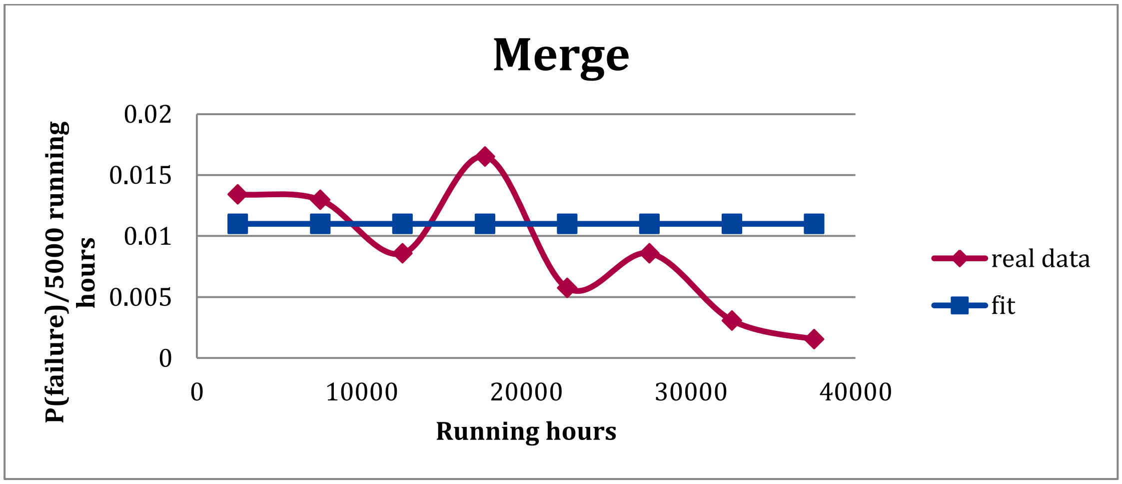


Merge

For the merge, a constant demand rate had to be forced. Therefore no regression analysis is performed. Taking the average of the selected data points resulted in this formula:

$$P(failure/5000 runninghours)_{merge} = 0.0011$$

In the graph below it can be seen how this fits to the real data.

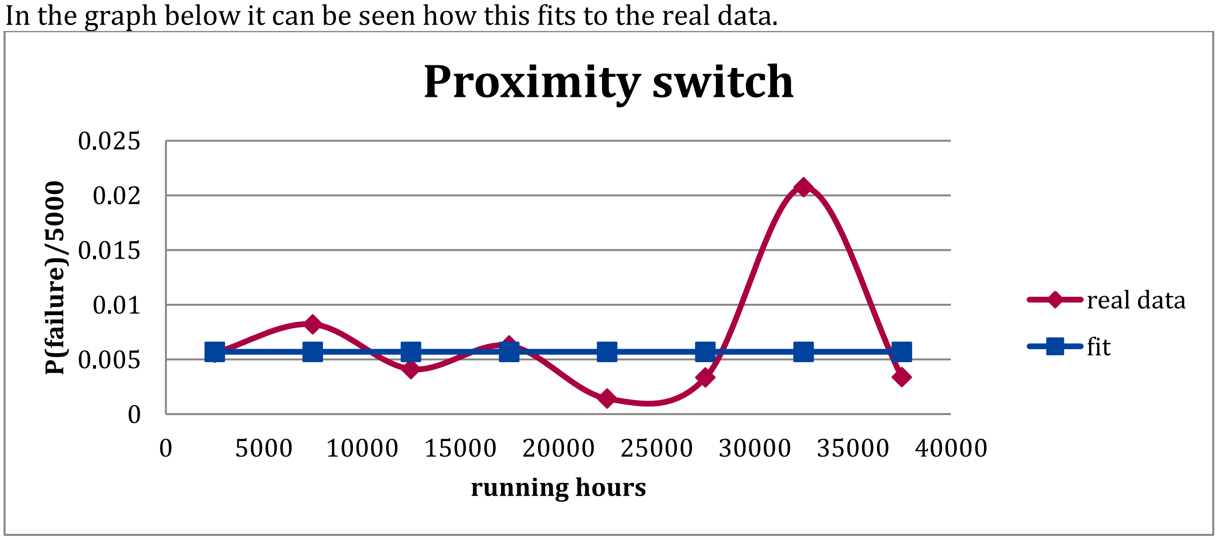


Proximity switch

For the proximity switch, a constant demand rate had to be forced as well. Therefore no regression analysis is performed. Taking the average of the selected data points resulted in this formula:

$$P(failure/5000 runninghours)_{proximityswitch} = 0.0057$$

In the graph below it can be seen how this fits to the real data.



Appendix XIV: Results Evaluation

Current usage supply chain

Crossing

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
0<t<5000	2.53%	99.98%	0.00%	0.02%	2.35E-06			
5000<t<10000	2.51%	99.96%	0.00%	0.04%	8.32E-06			
10000<t<15000	2.48%	99.92%	0.00%	0.08%	2.35E-05			
15000<t<20000	2.45%	99.86%	0.00%	0.14%	5.67E-05			
20000<t<25000	2.42%	99.77%	0.00%	0.23%	1.22E-04			
25000<t<30000	2.38%	99.65%	0.00%	0.35%	2.39E-04			
30000<t<35000	2.34%	99.48%	0.00%	0.52%	4.35E-04			
35000<t<40000	2.29%	99.25%	0.00%	0.75%	7.48E-04			
40000<t<45000	2.24%	98.97%	0.00%	1.03%	1.22E-03			

Divert shoe

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
0<t<5000	0.00%	97.32%	0.00%	2.68%	4.93E-04			
5000<t<10000	0.00%	96.82%	0.00%	3.18%	6.97E-04			
10000<t<15000	0.00%	96.29%	0.00%	3.71%	9.56E-04			
15000<t<20000	0.00%	95.72%	0.00%	4.28%	1.28E-03			
20000<t<25000	0.00%	95.11%	0.00%	4.89%	1.68E-03			
25000<t<30000	0.00%	94.47%	0.00%	5.53%	2.16E-03			
30000<t<35000	0.00%	94.47%	0.00%	5.53%	2.16E-03			
35000<t<40000	0.00%	94.47%	0.00%	5.53%	2.16E-03			
40000<t<45000	0.00%	94.47%	0.00%	5.53%	2.16E-03			

Divert switch

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
0<t<5000	12.22%	99.69%	0.01%	0.31%	5.37E-04			
5000<t<10000	12.18%	99.66%	0.01%	0.34%	6.19E-04			
10000<t<15000	12.14%	99.62%	0.01%	0.37%	7.09E-04			
15000<t<20000	12.10%	99.59%	0.01%	0.40%	8.07E-04			
20000<t<25000	12.06%	99.56%	0.01%	0.43%	9.14E-04			
25000<t<30000	12.02%	99.52%	0.01%	0.47%	1.03E-03			
30000<t<35000	11.98%	99.48%	0.01%	0.51%	1.15E-03			
35000<t<40000	11.94%	99.44%	0.01%	0.55%	1.29E-03			
40000<t<45000	11.90%	99.40%	0.01%	0.58%	1.43E-03			

Merge

Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
94.99%	100.00%	0.00%	0.00%	1.04E-14	€ 27.14		

Proximity switch

Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
99.33%	99.90%	0.10%	0.00%	2.62E-07	€ 172.80		

New usage supply chain

Crossing

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
0<t<5000	93.11%	100.00%	0.00%	0.00%	4.57E-08			
5000<t<10000	93.03%	100.00%	0.00%	0.00%	1.64E-07			
10000<t<15000	92.93%	99.99%	0.01%	0.00%	4.70E-07			
15000<t<20000	92.81%	99.99%	0.01%	0.00%	1.16E-06			
20000<t<25000	92.68%	99.98%	0.02%	0.00%	2.54E-06			
25000<t<30000	92.52%	99.97%	0.02%	0.01%	5.10E-06			
30000<t<35000	92.34%	99.96%	0.04%	0.01%	9.55E-06			
35000<t<40000	92.15%	99.94%	0.05%	0.01%	1.69E-05			
40000<t<45000	91.93%	99.91%	0.07%	0.02%	2.86E-05			

Divert shoe

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
0<t<5000	100.00%	99.22%	0.78%	0.00%	1.54E-05			
5000<t<10000	100.00%	99.07%	0.93%	0.00%	2.19E-05			
10000<t<15000	100.00%	98.91%	1.09%	0.00%	3.01E-05			
15000<t<20000	100.00%	98.74%	1.26%	0.00%	4.05E-05			
20000<t<25000	100.00%	98.55%	1.45%	0.00%	5.33E-05			
25000<t<30000	100.00%	98.35%	1.65%	0.00%	6.90E-05			
30000<t<35000	100.00%	98.35%	1.65%	0.00%	6.90E-05			
35000<t<40000	100.00%	98.35%	1.65%	0.00%	6.90E-05			
40000<t<45000	100.00%	98.35%	1.65%	0.00%	6.90E-05			

Divert switch

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
0<t<5000	100.00%	99.95%	0.05%	0.00%	4.50E-06			
5000<t<10000	100.00%	99.94%	0.06%	0.00%	5.20E-06			
10000<t<15000	100.00%	99.94%	0.06%	0.00%	5.96E-06			
15000<t<20000	100.00%	99.93%	0.07%	0.00%	6.79E-06			
20000<t<25000	100.00%	99.92%	0.08%	0.00%	7.69E-06			
25000<t<30000	100.00%	99.92%	0.08%	0.00%	8.67E-06			
30000<t<35000	100.00%	99.91%	0.09%	0.00%	9.73E-06			
35000<t<40000	100.00%	99.90%	0.10%	0.00%	1.09E-05			
40000<t<45000	100.00%	99.90%	0.10%	0.00%	1.21E-05			

Merge

Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
100.00%	100.00%	0.00%	0.00%	4.28E-15	€ 59.13		

Proximity switch

Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
99.33%	99.90%	0.10%	0.00%	2.62E-07	€ 172.80		

Appendix XV: Results optimization constant base stock levels

Crossing

The optimal base stock level for the CW was 26, for the stock point on site 2.

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
0<t<5000	99.10%	100.00%	0.00%	0.00%	1.78E-08			
5000<t<10000	99.08%	100.00%	0.00%	0.00%	6.35E-08			
10000<t<15000	99.07%	99.99%	0.01%	0.00%	1.81E-07			
15000<t<20000	99.04%	99.99%	0.01%	0.00%	4.42E-07			
20000<t<25000	99.02%	99.98%	0.02%	0.00%	9.62E-07			
25000<t<30000	98.99%	99.97%	0.03%	0.00%	1.92E-06			
30000<t<35000	98.95%	99.96%	0.04%	0.00%	3.56E-06			
35000<t<40000	98.91%	99.94%	0.06%	0.00%	6.23E-06			
40000<t<45000	98.87%	99.92%	0.08%	0.00%	1.04E-05			

Divert shoe

The optimal base stock level for the CW was 200, for the stock point on site 20.

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI*	H costs cust.*	Em costs
0<t<5000	98.88%	100.00%	0.00%	0.00%	7.43E-08			
5000<t<10000	98.87%	100.00%	0.00%	0.00%	1.26E-07			
10000<t<15000	98.86%	99.99%	0.01%	0.00%	2.03E-07			
15000<t<20000	98.85%	99.99%	0.01%	0.00%	3.18E-07			
20000<t<25000	98.83%	99.99%	0.01%	0.00%	4.82E-07			
25000<t<30000	98.82%	99.99%	0.01%	0.00%	7.11E-07			
30000<t<35000	98.80%	99.98%	0.02%	0.00%	1.03E-06			
35000<t<40000	98.79%	99.98%	0.02%	0.00%	1.45E-06			
40000<t<45000	98.77%	99.97%	0.03%	0.00%	2.00E-06			

*costs need to be multiplied by 10

Divert switch

The optimal base stock level for the CW was 118, for the stock point on site 2.

period	Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
0<t<5000	98.71%	99.95%	0.05%	0.00%	6.94E-06			
5000<t<10000	98.70%	99.94%	0.06%	0.00%	8.03E-06			
10000<t<15000	98.69%	99.93%	0.06%	0.00%	9.23E-06			
15000<t<20000	98.68%	99.93%	0.07%	0.00%	1.05E-05			
20000<t<25000	98.67%	99.92%	0.08%	0.00%	1.20E-05			
25000<t<30000	98.67%	99.92%	0.08%	0.00%	1.35E-05			
30000<t<35000	98.66%	99.91%	0.09%	0.00%	1.52E-05			
35000<t<40000	98.65%	99.90%	0.10%	0.00%	1.70E-05			
40000<t<45000	98.64%	99.89%	0.10%	0.00%	1.90E-05			

Merge

The optimal base stock level for the CW was 25, for the stock point on site 1.

Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
99.84%	100.00%	0.00%	0.00%	4.45E-15			

Proximity switch

The optimal base stock level for the CW was 25, for the stock point on site 1.

Beta0	Beta1	Theta1	Gamma1	Delay	H costs VI	H costs cust.	Em costs
99.33%	99.90%	0.10%	0.00%	2.62E-07			

Appendix XVI: Results optimization dynamic base stock levels

Crossing

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	25.00	1.00	98.42%	99.51%	0.48%	0.01%	7.67E-06			
5000<t<10000	27.00	1.00	99.49%	99.26%	0.74%	0.01%	1.50E-05			
10000<t<15000	26.00	2.00	99.07%	99.99%	0.01%	0.00%	1.81E-07			
15000<t<20000	26.00	2.00	99.04%	99.99%	0.01%	0.00%	4.42E-07			
20000<t<25000	26.00	2.00	99.02%	99.98%	0.02%	0.00%	9.62E-07			
25000<t<30000	26.00	2.00	98.99%	99.97%	0.03%	0.00%	1.92E-06			
30000<t<35000	26.00	2.00	98.95%	99.96%	0.04%	0.00%	3.56E-06			
35000<t<40000	26.00	2.00	98.91%	99.94%	0.06%	0.00%	6.23E-06			
40000<t<45000	26.00	2.00	98.87%	99.92%	0.08%	0.00%	1.04E-05			

Divert switch

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	118.00	2.00	98.71%	99.95%	0.05%	0.00%	6.94E-06			
5000<t<10000	118.00	2.00	98.70%	99.94%	0.06%	0.00%	8.03E-06			
10000<t<15000	118.00	2.00	98.69%	99.93%	0.06%	0.00%	9.23E-06			
15000<t<20000	118.00	2.00	98.68%	99.93%	0.07%	0.00%	1.05E-05			
20000<t<25000	118.00	2.00	98.67%	99.92%	0.08%	0.00%	1.20E-05			
25000<t<30000	118.00	2.00	98.67%	99.92%	0.08%	0.00%	1.35E-05			
30000<t<35000	118.00	2.00	98.66%	99.91%	0.09%	0.00%	1.52E-05			
35000<t<40000	120.00	2.00	98.65%	100.00%	0.00%	0.00%	2.80E-07			
40000<t<45000	118.00	3.00	98.64%	100.00%	0.00%	0.00%	3.24E-07			

Appendix XVII: Sensitivity analysis case study

Case I: Extreme low demand during lead time

Item	# in system	Lead time	Daily running hours
Crossing	5	28	5.143
Divert switch	24	28	5.143
Divert shoe	567 (57)	28	5.143

Crossing

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			
5000<t<10000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			
10000<t<15000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			
15000<t<20000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			
20000<t<25000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			
25000<t<30000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			
30000<t<35000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			
35000<t<40000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			
40000<t<45000	21,00	1,00	98,45%	99,93%	0,07%	0,00%	1,34E-07			

Divert shoe

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			
5000<t<10000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			
10000<t<15000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			
15000<t<20000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			
20000<t<25000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			
25000<t<30000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			
30000<t<35000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			
35000<t<40000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			
40000<t<45000	20,00	1,00	98,92%	99,78%	0,21%	0,00%	1,33E-06			

Divert switch

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			
5000<t<10000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			
10000<t<15000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			
15000<t<20000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			
20000<t<25000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			
25000<t<30000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			
30000<t<35000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			
35000<t<40000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			
40000<t<45000	58,00	2,00	98,84%	99,99%	0,01%	0,00%	2,06E-07			

Case II: Extreme high demand during lead time

Crossing

Item	# in system	Lead time	Daily running hours
Crossing	34	35	20.252
Divert switch	126	63	20.252
Divert shoe	3713	28	20.252

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	26,00	2,00	99,02%	99,98%	0,02%	0,00%	8,75E-07			
5000<t<10000	26,00	2,00	99,02%	99,98%	0,02%	0,00%	8,75E-07			
10000<t<15000	26,00	3,00	99,02%	100,00%	0,00%	0,00%	5,52E-09			
15000<t<20000	26,00	3,00	99,02%	100,00%	0,00%	0,00%	5,52E-09			
20000<t<25000	26,00	3,00	99,02%	100,00%	0,00%	0,00%	5,52E-09			
25000<t<30000	27,00	3,00	99,46%	100,00%	0,00%	0,00%	4,88E-09			
30000<t<35000	28,00	3,00	99,71%	100,00%	0,00%	0,00%	4,53E-09			
35000<t<40000	27,00	4,00	99,46%	100,00%	0,00%	0,00%	2,25E-11			
40000<t<45000	28,00	4,00	99,71%	100,00%	0,00%	0,00%	2,06E-11			

Divert shoe

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	20,00	3,00	98,52%	100,00%	0,00%	0,00%	5,14E-07			
5000<t<10000	21,00	3,00	99,22%	100,00%	0,00%	0,00%	4,43E-07			
10000<t<15000	21,00	3,00	99,22%	100,00%	0,00%	0,00%	4,43E-07			
15000<t<20000	21,00	3,00	99,22%	100,00%	0,00%	0,00%	4,43E-07			
20000<t<25000	21,00	3,00	99,22%	100,00%	0,00%	0,00%	4,43E-07			
25000<t<30000	21,00	3,00	99,22%	100,00%	0,00%	0,00%	4,43E-07			
30000<t<35000	21,00	4,00	99,22%	100,00%	0,00%	0,00%	6,36E-09			
35000<t<40000	21,00	4,00	99,22%	100,00%	0,00%	0,00%	6,36E-09			
40000<t<45000	22,00	4,00	99,61%	100,00%	0,00%	0,00%	5,74E-09			

Divert switch

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	121,00	4,00	98,55%	99,99%	0,01%	0,00%	1,07E-05			
5000<t<10000	122,00	4,00	98,86%	99,99%	0,01%	0,00%	9,56E-06			
10000<t<15000	124,00	4,00	99,31%	99,99%	0,01%	0,00%	7,91E-06			
15000<t<20000	122,00	5,00	98,86%	100,00%	0,00%	0,00%	4,78E-07			
20000<t<25000	122,00	5,00	98,86%	100,00%	0,00%	0,00%	4,78E-07			
25000<t<30000	122,00	5,00	98,86%	100,00%	0,00%	0,00%	4,78E-07			
30000<t<35000	122,00	5,00	98,86%	100,00%	0,00%	0,00%	4,78E-07			
35000<t<40000	123,00	5,00	99,11%	100,00%	0,00%	0,00%	4,27E-07			
40000<t<45000	123,00	5,00	99,11%	100,00%	0,00%	0,00%	4,27E-07			

Case III: Costs for emergency shipments

For all emergency shipments a fee of € 100 is calculated

Crossing

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	25.00	1.00	98.42%	99.51%	0.48%	0.01%	7.67E-06			
5000<t<10000	27.00	1.00	98.40%	100.00%	0.00%	0.00%	7.35E-08			
10000<t<15000	26.00	2.00	99.07%	99.99%	0.01%	0.00%	1.81E-07			
15000<t<20000	26.00	2.00	99.04%	99.99%	0.01%	0.00%	4.42E-07			
20000<t<25000	26.00	2.00	99.02%	99.98%	0.02%	0.00%	9.62E-07			
25000<t<30000	26.00	2.00	98.99%	99.97%	0.03%	0.00%	1.92E-06			
30000<t<35000	26.00	2.00	98.95%	99.96%	0.04%	0.00%	3.56E-06			
35000<t<40000	26.00	2.00	98.91%	99.94%	0.06%	0.00%	6.23E-06			
40000<t<45000	26.00	2.00	98.87%	99.92%	0.08%	0.00%	1.04E-05			

Divert shoe

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			
5000<t<10000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			
10000<t<15000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			
15000<t<20000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			
20000<t<25000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			
25000<t<30000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			
30000<t<35000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			
35000<t<40000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			
40000<t<45000	20.00	2.00	98.89%	100.00%	0.00%	0.00%	5.61E-08			

Divert switch

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
5000<t<10000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
10000<t<15000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
15000<t<20000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
20000<t<25000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
25000<t<30000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
30000<t<35000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
35000<t<40000	120.00	2.00	99.23%	99.95%	0.05%	0.00%	5.50E-06			
40000<t<45000	118.00	3.00	98.72%	100.00%	0.00%	0.00%	7.64E-08			

Case IV: Minimum holding costs

Crossing

A reduction of 7.6% in holding costs was used as input

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	25.00	1.00	98.42%	99.51%	0.48%	0.01%	7.67E-06			
5000<t<10000	27.00	1.00	99.49%	99.26%	0.74%	0.01%	1.50E-05			
10000<t<15000	26.00	2.00	99.07%	99.99%	0.01%	0.00%	1.81E-07			
15000<t<20000	26.00	2.00	99.04%	99.99%	0.01%	0.00%	4.42E-07			
20000<t<25000	26.00	2.00	99.02%	99.98%	0.02%	0.00%	9.62E-07			
25000<t<30000	26.00	2.00	98.99%	99.97%	0.03%	0.00%	1.92E-06			
30000<t<35000	26.00	2.00	98.95%	99.96%	0.04%	0.00%	3.56E-06			
35000<t<40000	26.00	2.00	98.91%	99.94%	0.06%	0.00%	6.23E-06			
40000<t<45000	26.00	2.00	98.87%	99.92%	0.08%	0.00%	1.04E-05			

Divert switch

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
5000<t<10000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
10000<t<15000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
15000<t<20000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
20000<t<25000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
25000<t<30000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
30000<t<35000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
35000<t<40000	120.00	2.00	99.23%	99.95%	0.05%	0.00%	5.50E-06			
40000<t<45000	118.00	3.00	98.72%	100.00%	0.00%	0.00%	7.64E-08			

Case V: Maximum holding costs

Crossing

An increase of 398.5% in holding costs was used as input

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	25.00	1.00	98.42%	99.51%	0.48%	0.01%	7.67E-06			
5000<t<10000	27.00	1.00	99.49%	99.26%	0.74%	0.01%	1.50E-05			
10000<t<15000	26.00	2.00	99.07%	99.99%	0.01%	0.00%	1.81E-07			
15000<t<20000	26.00	2.00	99.04%	99.99%	0.01%	0.00%	4.42E-07			
20000<t<25000	26.00	2.00	99.02%	99.98%	0.02%	0.00%	9.62E-07			
25000<t<30000	26.00	2.00	98.99%	99.97%	0.03%	0.00%	1.92E-06			
30000<t<35000	26.00	2.00	98.95%	99.96%	0.04%	0.00%	3.56E-06			
35000<t<40000	26.00	2.00	98.91%	99.94%	0.06%	0.00%	6.23E-06			
40000<t<45000	26.00	2.00	98.87%	99.92%	0.08%	0.00%	1.04E-05			

Divert switch

An increase of 42% in holding costs was used as input.

period	S0	S1	Beta0	Beta1	Theta1	Gamma1	Delay	Holding costs VI	Holding costs cust.	Total Emergency costs
0<t<5000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
5000<t<10000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
10000<t<15000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
15000<t<20000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
20000<t<25000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
25000<t<30000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
30000<t<35000	118.00	2.00	98.72%	99.95%	0.05%	0.00%	6.43E-06			
35000<t<40000	120.00	2.00	99.23%	99.95%	0.05%	0.00%	5.50E-06			
40000<t<45000	118.00	3.00	98.72%	100.00%	0.00%	0.00%	7.64E-08			

Appendix XVIII: Feasible area and optimal solution

It may be clear that the usage of dynamic base stock levels creates more possible solutions than usage of constant base stock levels. How this effects the results will be explained using Figure 49. Let the black lines define the feasible area, the red points are the possible solutions when constant base stock levels are used and the blue points represent the extra possible solutions that are added by use of dynamic base stock levels. Let the optimization take place in the direction of the lower left corner.

When using constant base stock levels, the red dashed encircled point will be chosen as the most optimal feasible solution. By enabling dynamic base stock levels the blue encircled point also becomes an option which is better because is has lower costs and still falls within the feasible area. This solution is however not directly superior to the solution found with constant base stock levels because a movement to the non-optimal direction took place on one axis.

By limiting the feasible area exactly at the point where the solution of scenario II was found, this will most probably also be the best feasible solution with use of dynamic base stock levels because it is on the boundary.

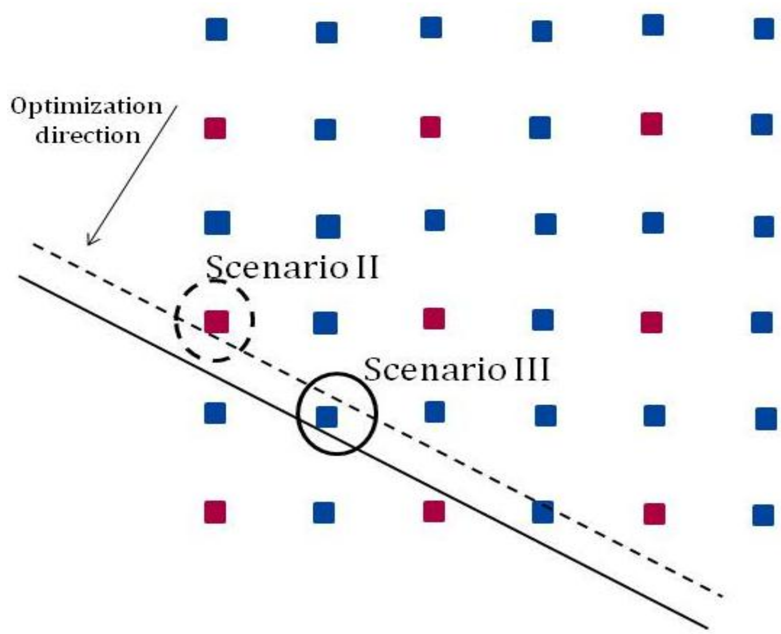
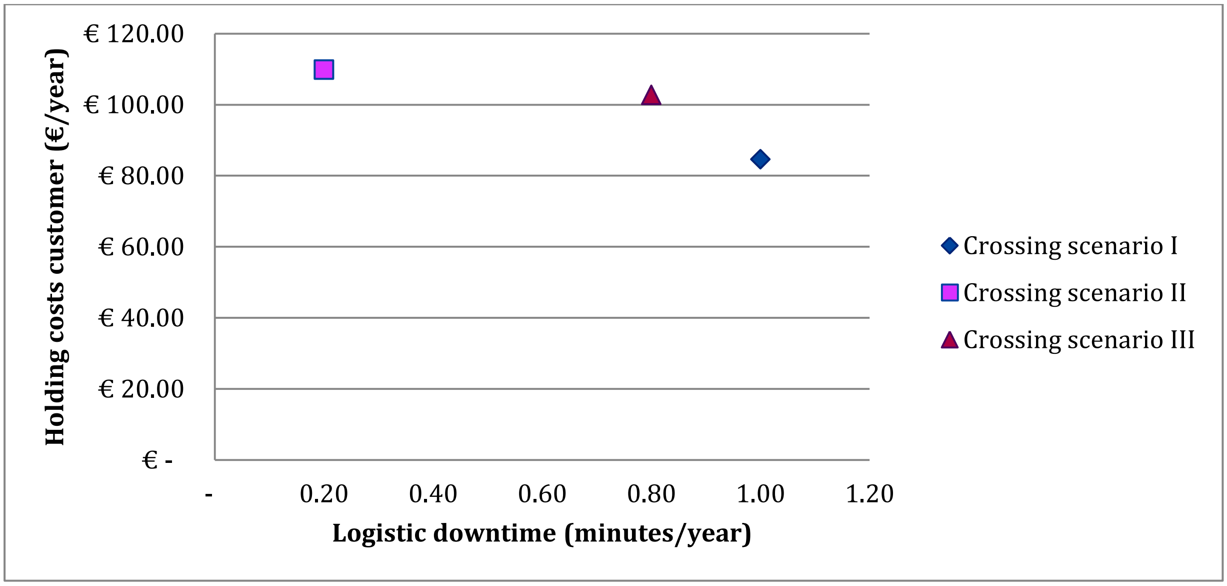


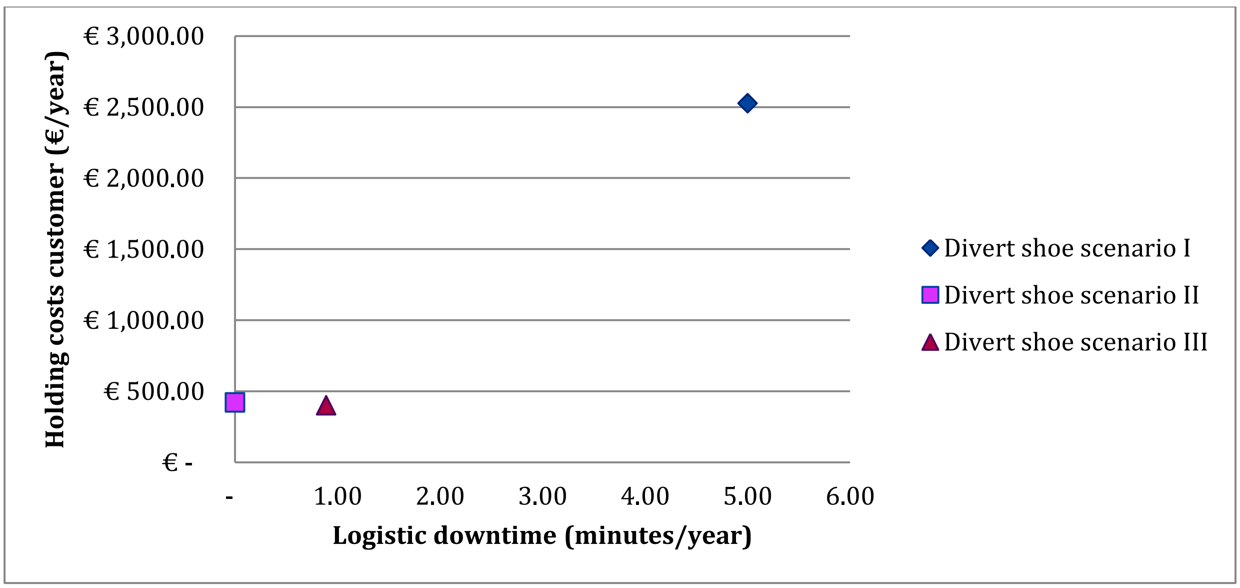
Figure 49 Feasible area and optimal solution

Appendix XIX: Comparison of scenario I, II and III for VI items

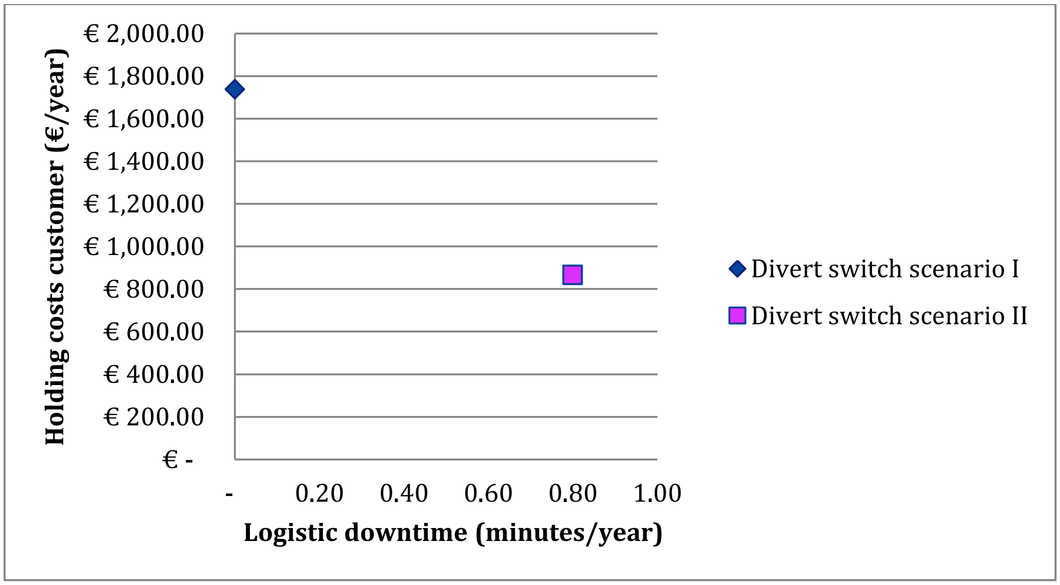
Crossing



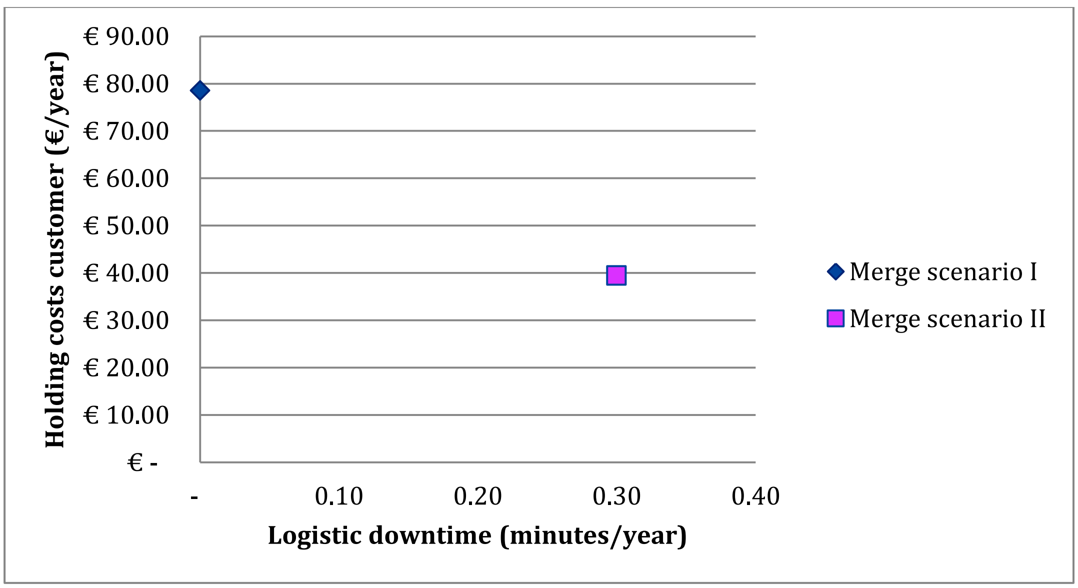
Divert shoe



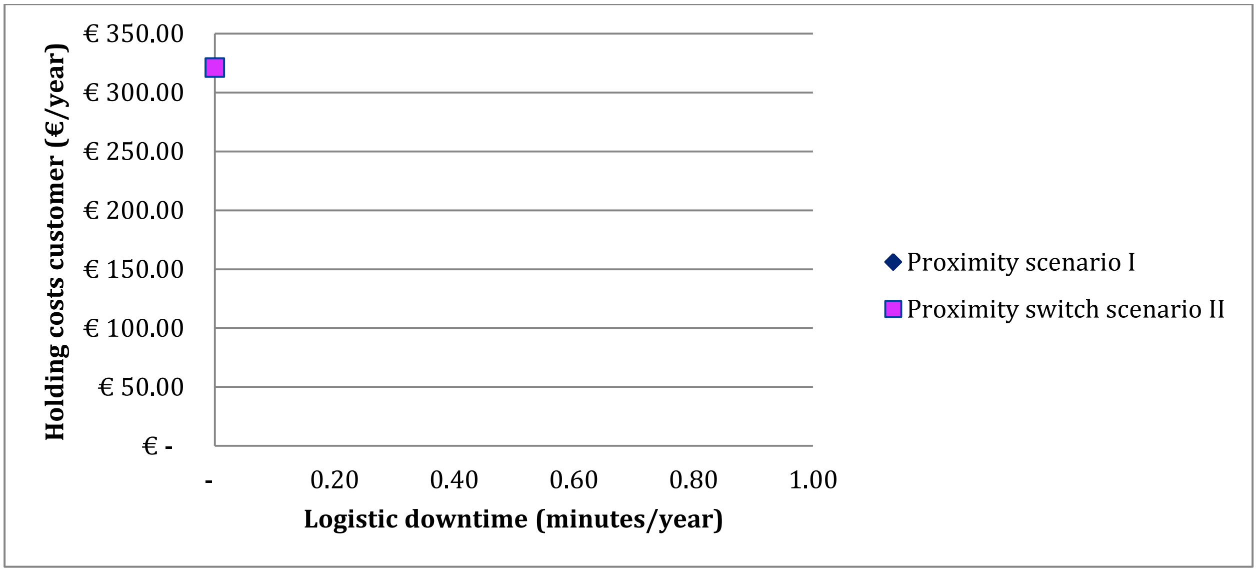
Divert switch



Merge



Proximity switch



Note that the analysis of both scenarios resulted in the same performance.

Appendix XX: Extra possibilities due to (remote) condition monitoring (CM)

This Appendix will give a short overview about opportunities that can occur for VI when applying remote CM. Condition monitoring is already used within VI. Engineers determine whether an item should be replaced during the periodical service checks based on the condition of an item. Remote CM means that not only the current status of an item is taken into account, but that the information about the current status can be read remote.

The first section gives some opportunities of CM at VI. The second section gives an overview of steps that need to be made by VI in order to get more insights in the effect of the application of CM to their systems.

Opportunities for VI due to the application of (remote) CM

Remote condition monitoring could be really useful for VI because failure of items is dependent on the environment and the way the system is handled. The systems of VI are installed in many different environments and all customers have different usage profile. This makes it complicated to forecast failures based on historical data. The variation in the data will be relatively large, which causes a large confidence interval and relatively 'safe' choices in service optimization problems.

Stadhouders (2011) identified the possibility to use available operational data to predict a failure for the scanner of a crane. He showed that VI could determine the physical state of this part from operational data in order to determine the health of the system. Based on this state upcoming failures can be prevented or maintenance could be planned according to the state of a certain part.

As such, the planning regarding the availability of spare parts could also be made based on this physical state. It is known that failures are originated from two sources, wear and crashes. Condition monitoring will only help to reduce the effects of failures caused by wear. With the data that is currently available it cannot be easily defined which part of the failures are caused by crashes and which part is caused by wear.

Introducing remote CM at VI

A first difficulty for the development of remote condition monitoring is that data is necessary to analyze the opportunities that there are for VI. This data is not collected yet. In order to get budget to gather this data, a case study is required. And for this case study data is necessary making the circle complete. This circle thinking is probably caused by the fact that there is no real trigger within VI to optimize maintenance because most customers do pay the service engineers per hour. However, with the increasing amount of service contracts, maintenance is sold against a fixed price increasingly. To be prepared for this evolvement, it would is recommended to find out whether (remote) condition monitoring provides opportunities.

As a starting point to break through this circular thinking, a roadmap should be developed. The steps that should be taken to be able to estimate the potential of CM are:

1. Find an indicator for failure
2. Start collecting data about this indicator manually. Let service engineers measure this indicator every time they visit a site for a periodic maintenance visit.
3. Collect data about the failures that occurred
4. Analyze the data
5. Make a case study

If there is a positive result, this will be a trigger to convince the organization to invest in further development of (remote) CM. Presumably, the amount of customers having a contract with a fixed price for maintenance is increased by that time which will create a trigger to optimize maintenance as well. These steps should however be interpreted by maintenance experts of VI in order to develop a real roadmap. Many parts of this roadmap are open, e.g.: should this first analysis be done for one or more item(s), how to select the items, focus on one indicator or multiple indicators per item what is the time frame necessary to get reliable results?

CM at the items studied

As discussed above, data should be gathered to be able to gain benefits of condition monitoring. These are the (expected) indicator for failure and the moment at which the item failed. When speaking about the Posisorter, carrier tracking will be necessary in order to know exactly which item is replaced at which moment. To be able to come up with a good indicator, expert knowledge is necessary. The items and the question for possible indicators is brought into discussion with to Posisorter experts. The information gathered about the failure behavior of the items is given below.

Crossing

Early signs of wear out can be obtained visually by looking for minor cracks. It seems hard to give a strict guideline for these cracks and even harder to obtain early signs of wear out remote.

Divert shoe

It might be possible to predict failure of a shoe by a sensor measuring the power to move a shoe. An increase in the power necessary to move the shoe indicates wear on the shoe. This sensor could be placed on the presort because almost all shoes are sorted here.

Divert switch

Wear of the divert switch is now measured by measuring the depth of the point where the pin slides through the switch. A possibility would be to gather all these measures to be able to find a threshold for the failure. Another possibility is to use the same sensor measuring the power to move a shoe because the higher the required power, the more wear appears on the divert switch. This does not directly indicate whether the divert shoe is worn out, but is can be helpful to prevent major wear.

Merge

The merge is an item that typically fails by crashes, which are by definition unpredictable.

Proximity switch

Is a sensor itself, maybe a pattern can be found when storing the information from this sensor an analyzing the correctness.

Tension/End pulley

The vibration of the pulley will be an indicator for failure. This can also be measured with a sensor.

In the discussion with the experts it also seemed that a good estimation of the working of an Posisorter can be obtained by measuring the current that is used to drive the Posisorter. This should be measured three times: without using the divert, with using all diverts and by using only the presort. An increase in the current indicates an increase in the resistance. This resistance is either caused by wear or by dirt. If those three measurements are executed each period maintenance check, an indication about the wear and dirt can be determined.