Design of a spare part inventory control system for Vlisco Helmond

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Design of a spare part inventory control system for Vlisco Helmond

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Abstract

In this master thesis, a framework to determine the optimal inventory policy and corresponding control parameter values given a service constraint for spare parts has been developed for Vlisco.

The framework has to operate in an environment with scarcity of data. Methods are therefore developed to determine the downtime costs (i.e. unavailability costs of the spare parts) in phases to be able to further optimize the inventory in each phase. Furthermore the framework includes a simulation model that determines the optimal inventory control parameter values based on the total relevant costs (replenishment, holding and unavailability costs) and the service constraint; a maximum machine waiting time.
Executive summary

This master thesis report is the result of a research executed at Vlisco, Helmond for the final phase of the master Operations Management & Logistics at the Eindhoven University of Technology. Vlisco is a designer and manufacturer of unique textiles for the African market. The scope of this research is spare part management for the manufacturing location in Helmond.

Research goal

To maintain a high availability of the machines it is important that spare parts are available, as these assist the maintenance department in keeping the manufacturing systems (i.e. machines) available (Kennedy et al., 2002). The maintenance and manufacturing department have service constraints regarding this availability.

The influence of the spare part inventory control on total relevant costs and availability has not been subject to an extensive research at Vlisco. Total relevant costs consist of the following: unavailability costs, inventory holding costs and replenishment cost. Vlisco presumed that there was an inventory of spare parts of €2 million, however a stocktaking started in June 2013 showed that this was 3 times higher. Currently Vlisco has around 6000 different spare parts on stock with a total value of €6 million. The availability agreements for the machines have been met, but whether these availability goals are met with optimal level of spare parts is unknown. The formulated research goal is therefore:

“Develop a framework that determines the optimal inventory policy and parameter values such that the total relevant costs are minimized given a service constraint”

The inventory policy defines at which point in time an inventory replenishment should be initiated and what the replenishment quantity should be (Silver et al., 1998).

Method

An inventory policy was selected for Vlisco based on a literature review. It was concluded that the \((R, s, S)\) policy is most suitable for Vlisco. Every \(R\) days the inventory position is checked and if it is equal or below the reorder level \(s\) the inventory level is increased to level \(S\).

To be able to reach the objective with the selected policy an understanding is required about the following aspects: 1) the service measure, 2) what the total relevant costs are at Vlisco and 3) the demand of the spare parts

1) The selected service measure is a maximum machine waiting time, since this specifies in which time window spare parts should be delivered such that the required availability of the machines is met.

2) The holding costs and replenishment costs were determined. It was detected that the unavailability costs were not available and a method was developed to determine these costs in 3 phases. In each phase more data becomes available, which gives the opportunity to already partially (sub) optimize the inventory with minimal effort (i.e. time, costs) without having to wait until all required data is available.

3) It was concluded that at Vlisco 4 demand patterns exist:
   - Smooth demand: few or no periods with zero demand and the variability of the demand sizes is low
   - Erratic demand: few zero or no periods with zero demand, but the demand size variability is high
- **Intermittent demand**: many periods with zero demand and low demand size variability.
- **Lumpy demand**: many periods with zero demand and a high demand size variability.

Next a method is required to determine the optimal parameter values \( R, s \) and \( S \). A simulation model was created, that is capable to deal with the different demand patterns, minimizing the total relevant costs given a maximum machine waiting time.

Vlisco was interested whether classification could reduce time and ensure selecting the correct inventory control policy for the different spare parts. Since one policy is used and the model is capable to deal with the different demand patterns it was concluded that classification is unnecessary. Furthermore with 6000 parts on stock and an unknown amount of spare parts not on stock, Vlisco was interested in an implementation plan that describes the order of analysing the parts such that it is as efficient as possible. The phases of the determination of the unavailability costs are developed such that this information is retrieved as efficiently as possible, therefore this method will also dictate the order of analysing the parts.

**Results**

The goal of this research is to create a framework that determines the optimal inventory policy parameter values such that total relevant costs are minimized given a service constraint.

The framework described in the previous section was applied to 5 spare parts. Due to the no insight of how the current policy operates and exactly performs, a comparison was made based on an approximation of the current situation. 1 part showed a cost saving of 33% and a reduction of inventory on capital of 43%. The remaining parts showed a bigger cost saving but an increase of inventory to prevent unavailability costs. In the approximation for the current situation unavailability costs were incurred. However this is in contradiction with the actual situation, because according to Vlisco no costs are incurred due to insufficient inventory. In discussion with the maintenance manager it is concluded that this is caused because: data is not available at the moment or unreliable data (wrongly registered demand) is used.

Additionally the model showed that the current policy to maintain only inventory for corrective demand is not always optimal. The model is applied separately for the corrective demand and the total demand (corrective and preventive), which made comparison possible. The case analysis of 5 parts showed that for 4 of them the yearly cost can be reduced. The reduction varied from 13.53% up to 1153.48%.

Given the premises can be concluded that the developed framework determines the optimal parameter values such that the total relevant costs are minimized and the service constraint is met as long the correct values of the input variables is used.
Recommendations
The most important recommendations are described below:

1. **Use the developed inventory control model to determine the parameters values**
The inventory model created in this research has been automated in Microsoft Excel. With the tool Vlisco can determine what the optimal reorder level and order up to level is for every spare part. Results described above have shown that it is beneficial to determine the inventory control parameter values with the provided tool.

2. **Improve data availability**
The input of the tool, such as the demand and several cost variables are used to determine the parameter values. Sensitivity analysis showed that deviation of the real value can result in wrongly estimated parameter values, with as result that these are not optimal. Since at Vlisco certain data is missing or not reliable the performance of the method is less accurate. Vlisco should therefore make sure:
   - demand of the spare parts is correctly registered by its employees
   - demand of pumps and rollers is registered differently, such that these can be analysed as well
   - all elements (e.g. product damage, deterioration) of holding costs are registered
   - unavailability costs are available

3. **Use phases to determine the unavailability costs**
In the previous recommendation the need of data availability was emphasized. Vlisco should use the developed method to determine the unavailability costs, since this method is developed in a matter that it will retrieve the data as efficient as possible. The method will result that in each phase the inventory can be further optimized

4. **Consider to keep inventory for preventive and corrective demand**
Vlisco has the policy to only keep inventory for corrective maintenance and for preventive maintenance the spare parts are always ordered. The results described above show that this policy not always results in minimal costs. For each part it should therefore be evaluated if it is beneficial to have inventory only for corrective demand or inventory for preventive and corrective demand.

5. **Standardize the parts used in the machines**
Vlisco should standardize its parts where possible. When different parts (e.g. bearing x and bearing y) are used on several locations, but for this function 1 part would satisfy the need, only 1 part should be used (e.g. bearing x) for all locations. A case analysis showed that when 2 different parts are replaced by 1 the total relevant costs would be reduced from €280.15 to €156.3 per year. The average capital on stock would be reduced from €704.14 to €369.56. In brief this would mean a cost reduction of 43.0% and a reduction of capital on stock of 47.9%.
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<td>--------------------------------------------------------------------------------------------------------</td>
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<tr>
<td>Backorder</td>
<td>Backorders is the demand that has not yet been delivered to the machine due to fact that the inventory on hand (physical inventory) was not sufficient when the demand arrived</td>
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<tr>
<td>Consequential downtime</td>
<td>the part of downtime that results into costs (i.e. loss of production)</td>
<td></td>
</tr>
<tr>
<td>Delay time</td>
<td>time period that order is delayed after the replenishment decision</td>
<td></td>
</tr>
<tr>
<td>Demand pattern</td>
<td>Describes the arrival time and size of demand for a spare part</td>
<td></td>
</tr>
<tr>
<td>Downtime</td>
<td>Time a machine is out of service and does not generate output</td>
<td></td>
</tr>
<tr>
<td>Downtime costs</td>
<td>Cost of lost production; it is the cost incurred, on a per unit time basis, by not having a machine in service</td>
<td></td>
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<td>Erratic demand</td>
<td>few or no periods with zero demand, but the demand size variability is high</td>
<td></td>
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<tr>
<td>Holding costs</td>
<td>Cost to keep and a spare part on stock</td>
<td></td>
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<td>Intermittent demand</td>
<td>Many periods with zero demand and low demand size variability.</td>
<td></td>
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<tr>
<td>Inventory control policy</td>
<td>Defines at which point in time an inventory replenishment should be initiated and what the replenishment quantity should be</td>
<td></td>
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<tr>
<td>Inventory control system</td>
<td>Decides which spare parts to stock, at which stocking location and in what quantities</td>
<td></td>
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<tr>
<td>Inventory on hand</td>
<td>Number of units of a product that is physically present at the inventory location</td>
<td></td>
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<tr>
<td>Inventory on order</td>
<td>Number of units that has been ordered from a supplier but has not yet arrived on the inventory location</td>
<td></td>
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<tr>
<td>Inventory position</td>
<td>Sum of the net inventory and the Inventory on order.</td>
<td></td>
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<tr>
<td>Lumpy demand</td>
<td>Many periods with zero demand and a high demand size variability.</td>
<td></td>
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<tr>
<td>Machine demand</td>
<td>Demand of spare parts of a machine</td>
<td></td>
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<tr>
<td>Machine waiting time</td>
<td>Time a machine has to wait on the fulfilment of an machine order</td>
<td></td>
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<tr>
<td>Margin</td>
<td>The proportion of money left over from revenues after accounting for the cost of goods sold</td>
<td></td>
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<tr>
<td>Mean time to repair (MTTR)</td>
<td>Time to remove a part, install a part and to configure the machine such that the machine is ready to be setup for production.</td>
<td></td>
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<tr>
<td>Net inventory</td>
<td>The difference between the inventory on hand and the backorders.</td>
<td></td>
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<td>Non-consequential downtime</td>
<td>The part of downtime that does not result into costs (i.e. no loss of production)</td>
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<td>Order quantity</td>
<td>Fixed number of spare parts that are ordered.</td>
<td></td>
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<tr>
<td>Order up to level</td>
<td>A quantity of spare parts is ordered to raise the inventory position up to this level</td>
<td></td>
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<tr>
<td>Reorder level</td>
<td>Spare parts are ordered when the inventory position of spare parts is below this level when monitored</td>
<td></td>
</tr>
<tr>
<td>Replenishment costs</td>
<td>Cost to replenish the inventory of a spare part</td>
<td></td>
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- **Replenishment order**: Order placed at supplier to replenish the inventory of spare parts
- **Review period**: Period each time the inventory position is monitored
- **Risk period**: Review period plus the delivery lead time which the inventory should protect against demand variations
- **Service level agreement**: Agreement between maintenance and manufacturing department that describes the target service levels or service constraints, maintenance activities and the responsibilities
- **Service level constraint**: The minimal required level of service
- **Setup Time**: Time needed to set up a machine (e.g. heat an oven or fill a bath) before production can start.
- **Shutdown time**: Time needed to shut down a machine (e.g. cooldown an oven or empty a bath) before repair can be executed.
- **Smooth demand**: Few or no periods with zero demand and the variability of the demand sizes is low
- **Spare parts**: Pieces of a machine that are purchable to replace defective parts
- **Technical availability**: Planned production time minus downtime due to technical failures
- **Total relevant costs**: Cost that influence the decisions regarding inventory control, consisting out of: unavailability costs, inventory holding costs and replenishment cost
- **Unavailability costs**: Costs caused when a spare part is not readily available
- **Undershoot**: Difference between the reorder point and the inventory position of moment of the replenishment decision
1. Introduction
This first chapter provides an introduction to Vlisco (1.1) the maintenance of the machines responsible for the production process (1.2) and the problem (1.3).

1.1. Vlisco
The research is executed at Vlisco, a designer and manufacturer of unique textiles for the African market. Every centimetre of fabric is unique due to a special wax process, which originates from batik techniques. With these unique textiles Vlisco has become market leader in African Prints and the textiles are sold in more than 30 African countries.

The Vlisco Group manufactures these textiles at 3 locations: Helmond (the Netherlands), Tema (Ghana) and Abidjan (Ivory Coast). The scope of this research is on the manufacturing location in Helmond.

1.2. Maintenance of machines
Downtime of the production process of the textiles is costly with circa € 11 thousand per hour. Therefore to maintain high availability of the manufacturing systems, the maintenance department is responsible for the technical availability of the machines. Technical availability is the planned production time minus downtime due to technical failures (Figure 1). The maintenance of the machines is documented in a service level agreement between the manufacturing and maintenance department. This agreement describes the target service levels or service constraints (e.g. response time, technical availability), when maintenance activities (e.g. inspections, cleaning, preventive replacements) are executed and the responsibilities. The capacity and importance of the machines are different and therefore the service level agreements also differ per machine (shown in Appendix 1). In total the maintenance department is responsible for 120 machines. To maintain a high availability of these machines it is important that spare-parts are available, as these assist the maintenance department in keeping the manufacturing systems (i.e. machines) available (Kennedy et al., 2002).

<table>
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<th>Available machine time (24 hrs/day)</th>
<th>Planned production time</th>
<th>No production time planned</th>
</tr>
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<tr>
<td>Technical availability</td>
<td>Technical Failures</td>
<td></td>
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Figure 1 Technical availability

1.3. Problem introduction
In the previous paragraph the maintenance of machines was introduced and the importance of spare parts explained. The research area of this project is concerned with the inventory control of these spare parts. In this paragraph the cause of the research will be discussed and the arguments leading to the research question.

1.3.1. Inventory control of spare parts
An inventory control system is concerned with decisions regarding which spare parts to stock, at which stocking location and in what quantities (Driessen et al., 2014). The right level of stock is a trade-off between the inventory holding costs and unavailability costs (Cavalieri et al., 2008). Figure 2 illustrates this, as the curves of both costs move along an opposite direction. However often in practice there is an absence of an uniform quantitative method, which leads usually to an excess of locked up financial resources by holding inventory or risking unavailability of important parts (Molenaers et al., 2012)
The influence of the inventory control on total relevant costs and availability has not been subject to an extensive research at Vlisco. Here, total relevant costs consist of the following: unavailability costs, inventory holding costs and replenishment cost. Vlisco assumed that there was an inventory of spare parts of €2 million, however a stocktaking started in June 2013 showed that this was 3 times higher. Currently Vlisco has around 6000 different spare parts on stock with a total value of €6 million. The availability agreements for the machines have been met, but whether these availability goals are met with optimal level of spare parts is unknown. Additionally, Vlisco plans to apply investments constraints to the spare-parts budget. This implies a limit for future replenishments of spare-parts while service constraints still need to be met. These premises ask for analysis of the current inventory control of Vlisco.

1.3.2. Current inventory control of spare parts

Characteristics of a specific spare part determine the way of control (Huiskonen, 2001), with a high variety of characteristics the control of spare part inventory demands for different policies (An inventory policy defines the decision rules at which point in time an inventory replenishment should be initiated and what the replenishment quantity should be (Silver et al., 1998)). The control inventory can be defined according to the following distinctions; an inventory control policy and the inventory control policy parameter values.

An inventory control policy encompasses types of methods to determine the moment to initiate a re-order of spare parts or the size of the re-order. The differences in of re-order moment between inventory control policies range from periodic reviews in which the decision to order spare parts is made every n periods, to continuously monitored spare parts levels, which allows instant ordering of spare parts once a certain number spare parts are left in stock. Otherwise, inventory control policies differ from each other in the way the size of the re-order is determined. These methods range from re-ordering up until a certain stock level to re-ordering the same amount of parts overtime a re-order is initiated.

Where inventory control policies determine how a re-order is initiated, the inventory control policy parameter value determines when this moment is initiated, i.e. every two weeks the inventory level is checked.

Maintenance engineers are responsible for the inventory control. In the current inventory control policy Vlisco makes the differentiation between parts for preventive and corrective maintenance. In principle only stock is kept for corrective maintenance. The decisions are taken according the same approach, namely every maintenance engineer decides for each machine based on experience how much stock is kept. The decision criteria differ for each
maintenance engineer, criteria used are: the risk of a failure, amount of parts in a machine, the lead time and the lifetime of a part. There is no structured method applied, which updates the inventory decisions and these decisions are not documented. The consequence of this policy is that the stock is sufficiently large such that it can always satisfy the demand. Further due to the missing insight why parts are stocked and with modifications of machines there could be parts that are obsolete (i.e. not required anymore). Analyses showed that 664 parts on stock haven’t been demanded for the last 4 years, indicating possible obsolete parts. Besides the high inventory there, may be risk of long downtime as there is no inventory of certain parts. This concerns mainly parts with very low demand, where the supply situation could have changed. The maintenance engineers are aware of this situation and acknowledge the need for improvements. These premises lead to the following problem statement:

“Does the current inventory control of Vlisco optimize the inventory of spare parts in terms of total relevant cost given service constraints?”

1.4. Summary current situation

In this chapter the reader is introduced into the problem statement. Vlisco needs to keep a high availability of different types of machines with different importance as downtimes are costly. The inventory control of spare parts to facilitate the maintenance department is unstructured and there is no insight in stocking decisions. There is no assessment of the trade-off between holding and unavailability costs. This leads to high inventories and a possible risk of no inventory of certain parts. Concluding, there is an absence of a structured uniform quantitative method which optimized the total relevant costs given service constraints.
2. Research design
Based on the problem introduced in the previous chapter the project objective, deliverables and restrictions are formulated in respectively paragraph 2.1, 2.2 and 2.3. Finally the research questions are described and the approach is explained.

2.1. Project objective
The final objective of the project is to answer the question stated in chapter 1.3.2. A structured quantitative method should determine the inventory control system which optimizes the total relevant costs given service constraints. Therefore the project objective is defined as:

“Develop a framework that determines the optimal policy parameter values such that total relevant costs are minimized given a service constraint”

2.2. Project deliverables
- Develop a software tool to determine the policy parameters values
- Vlisco currently classifies spare parts into classes; this research should investigate the use of classification.

2.3. Project restrictions
- Floor stocks (bolts, nuts etc.) are under responsibility of a supplier and will therefore not be investigated. This research project will only analyze the remaining parts.
- Dependent on the market situation the availability of a machine becomes more or less important, since the downtime costs change. The solution has to be capable to cope with changes in downtime costs according to the market situation.

2.4. Research questions
Based on the project objective and the deliverables the research questions can be formulated to guide the research.

First needs to be determined what inventory control policy Vlisco can use, it needs to be investigated what policies exist according to literature. Secondly, it can be determined which of the found policies are realistic to be applied at Vlisco within the time constraint of the project. Based on this premise the following research question is formulated:

1) Which inventory control policies are realistic to be implemented at Vlisco?
   a) Which inventory control policies are available in literature?
   b) Which inventory control policies can be applied at Vlisco?

How to manage the stock of spare parts is determined by the inventory control policy. Before the parameter values can be determined, additional information is required. Literature globally describes 3 inventory control elements which define the context in which inventory control policies operate. These are; the demand patterns of spare parts, the total relevant costs and the service constraint for spare parts. Therefore, the first research question is;

2) What is the context in which the inventory control policies must operate?
   a. With what service constraint should the spare part policy operate?
b. What are the relevant costs for spare parts management for Vlisco?
c. What demand patterns do the spare-parts at Vlisco exhibit?

With the key elements and an inventory control policy, the parameter values of the policies need to be determined. Therefore, a literature research will be done to determine a method to find the optimal parameter values for the inventory control policy. This method needs to be able to cope with the situation at Vlisco, therefore will first the characteristics of the inventory system be analysed. Thereafter the literature search will be executed to determine which methods can be applied by Vlisco. This premise leads to the third research question:

3) How can Vlisco determine the optimal inventory control policy parameter value for its spare parts?
   a) What are the characteristics of the inventory system at Vlisco?
   b) What methods exist in literature to determine the optimal inventory control policy parameter values that meet the characteristics of the inventory system at Vlisco?

Due to the large number of spare-parts (circa 6000) Vlisco wants to investigate the possibility to use a classification method. By classifying spare-parts Vlisco wants to reduce the effort that comes with selecting an inventory control policy per spare part. Therefore, the objective is to determine whether a classification of spare parts is required and if so, how it can be improved such that spare parts can be managed accordingly. This premise leads to the following research question:

4) How can the method of Vlisco for classifying its spare parts be improved and is it necessary?
   a) How does Vlisco currently classify its spare parts?
   b) Which criteria are appropriate to classify spare parts according to literature?

With the inventory control policy and model determined it can be applied on the parts of Vlisco. With circa 6000 different types of spare parts currently on stock with a net worth of €6 million and an unknown amount of spare parts not on stock that could imply a risk in terms of high downtimes, time and economic resources are insufficient to analyse them all within a short time-span (e.g. < 1 year). Consequently, this ask for a implementation plan for Vlisco that allows for quick results to cover the highest risks but leads to optimal results in due time.

5) How can spare parts be selected for analysis?

Once the inventory control system has been defined, machine revision or changing market situations can have as result that the defined inventory policies and parameter values are no longer optimal. To prevent the inventory control system to be outdated, it will be investigated what should trigger a reconsideration of the inventory controls system.

6) When should the inventory control system of Vlisco be reconsidered?
2.5. Report structure
In the previous paragraph the research questions have been formulated. Within this paragraph the general approach is described to answer the research questions. Figure 3 shows the corresponding chapter that answers the formulated research questions.

Chapter 1 and 2 cover the problem statement and research design of this research.

Within chapter 3 research question 1 is answered. First the possible inventory control policies are determined according to a literature research. The inventory control policies are reviewed on their applicability for Vlisco, and an inventory policy is selected
Chapter 4 covers the key elements needed to meet the research objective and thereby answering research question 2. First the service measure that is suited for Vlisco is selected. Thereafter the total relevant costs at Vlisco are described. Finally the demand at Vlisco is analysed. Since the unavailability costs are not directly available a method should be developed to obtain these costs, which is dealt with in chapter 4.

In chapter 6 the method how to determine the optimal parameter values is explained; a uniquely developed simulation model that can perform the necessary calculations such that the optimal parameter values are selected. The requirements for a simulation model are clarified in chapter 7. With this conclusion research question 3 is answered.

Chapter 8 covers research question 4 and determines if classification is needed at Vlisco such that selecting an inventory control policy for spare parts can be simplified. Criteria are determined and evaluated if these are beneficial for Vlisco.

In chapter 9 the order of analysing the spare parts are described and thus answering research question 5. The developed method guides Vlisco to determine the inventory control parameter values for its spare parts in a timely fashion.

Finally a sensitivity analysis is described which forms the basis to answer research question 6. The sensitivity analysis gives insight in the model parameter and their influences on the inventory control policies and the results. Based on the sensitivity analysis a reconsideration period can be determined such that the inventory control policy and parameter values will always be up to date.

Finally in chapter 11 the results for several parts are discussed and in chapter 12 the conclusions and recommendations are given.

2.6. Chapter Conclusion

In this chapter the design of the research has been explained to realize the objective to minimize the total relevant costs given a service constraint. Research questions have been formulated and the structure of this report has been clarified. In the next chapter the first research question will be answered.
3. Inventory control policy selection
In this chapter the research question “Which inventory control policies are realistic to be implemented at Vlisco?” is answered. To select the inventory control policy the design principles of an inventory control system are clarified. Next it is explained how an inventory policy operates and which policies are suggested by literature. Subsequently it is discussed which inventory control policy are realistic to be implemented at Vlisco and a selection is made.

3.1. Define design principals of inventory control system
When developing a spare-part inventory system two principals have to be considered (Van Houtum and Kranenburg, 2015):

(i) **Avoid decompositions into lower-level constraints and integrate decisions as far as possible**, hence no service constraints on machine level are translated into separate service constraints for spare parts. This is possible as Vlisco is only interested in whether or not the system is working and not in the performance of separate spare-parts.

(ii) **Create as much pooling effect as possible for the spare parts**: the demand process of spare parts is stochastic (volatile) and requires buffers. When demand is bundled (e.g. inventory is kept one location and not separate for each machine) less buffering is needed.

Principle (i) facilitates the use of multi-item approach (system approach), which makes it possible to keep relatively low stock on expensive parts and high on cheap parts, but achieve similar performance on machine availability. To achieve as much pooling effect (ii) as possible, there are two methods; inventory centralization and lateral shipments (Wang and Yue, 2015). This gives the following possible solutions for Vlisco (Van Houtum and Kranenburg, 2015; Wang and Yue, 2015):

- Item approach; joint inventory for different machines with common components
- Multi-item approach (system approach); machine service constrains set, but keep relatively low stock for expensive items and relatively high on cheap items
- Joint inventory between several company locations by use of emergency and lateral shipments
- Joint inventory that serves multi-companies by use of emergency and lateral shipments

Given the fact that at Vlisco the locations of all spare parts still have to be determined and the time constrain of the project, it is only possible to focus on the item approach.
3.2. Functioning of inventory control policies

An inventory policy defines the decision rules at which point in time an inventory replenishment should be initiated and what the replenishment quantity should be (Silver et al., 1998). To initiate the replenishment the inventory position is monitored. In this paragraph the inventory position monitoring and decision rules (control parameters) are discussed.

3.2.1. Inventory position monitoring

To determine whether a replenishment is needed the inventory position needs to be monitored. During this monitoring the height of the inventory position is checked. The inventory position is determined by the inventory on hand, inventory on order, the net inventory and the backorders. Each of these terms is explained below:

- **$I_{OH_t} = \text{inventory on hand at time } t$ (physical inventory)**
  The inventory on hand is the number of units of a product that is physically present at the inventory location.

- **$I_{OO_t} = \text{inventory on order at time } t$**
  The inventory on order is the total number of units that has been ordered from a supplier but has not yet arrived on the inventory location. It could be the case that multiple orders are outstanding.

- **$B_{O_t} = \text{backorders at time } t$**
  Backorders is the demand that has not yet been delivered to machines due to fact that the inventory on hand (physical inventory) was not sufficient when the demand arrived and is waiting for the replenishment of the inventory (i.e. inventory on order)

- **$N_{I_t} = \text{Net inventory at time } t$**
  The net inventory is the difference between the inventory on hand and the backorders ($N_{I_t} = I_{OH_t} - B_{O_t}$).

Resulting in the inventory position:

- **$I_{P_t} = \text{inventory position at time } t$**
  The inventory position at time $t$ is the sum of the net inventory and the orders on order.

$$I_{P_t} = N_{I_t} + I_{OO_t} = I_{OH_t} - B_{O_t} + I_{OO_t} \quad (3.1)$$

There are two possibilities for monitoring the inventory position; continuous and periodically. With continuous review the inventory position is always known, while with periodic review the inventory position is determined each period. Continuous review and ordering will reduce the needed safety stock (and thus holding costs). The inventory control system only needs to guard against demand variations during the delivery lead-time ($L_T$). With periodic review the extra uncertain period is the review period ($R$), thus the system needs to guard against demand variations during $R + L_T$, i.e. risk period. Periodic review will reduce the cost for inventory monitoring (inspections).

Vliisco uses scanners to update the inventory on hand and therefore in theory the inventory position can be updated continuously, however the data is only updated at the end of the day (23:59 hours), further the system does not provide a solution to automatically send a replenishment order. Once or twice a week, a warehouse employee checks if there are order suggestions and forwards the orders to the suppliers. Consequence is that although the inventory position is monitored continuously the replenishments are initiated with a review period. Given the premises only policies with a review period are evaluated hereafter.

3.2.2. Control parameters

The control parameters are related to (Silver et al., 1998):

1. at which point in time an inventory replenishment should be initiated (when), and
2. what the replenishment quantity should be (how much)

| Inventory control policy selection | 23 |
3.2.2.1. **Point in time a replenishment is initiated**

When the inventory position is checked, a decision needs to be made whether replenishment is initiated or not. The following control parameters are available:

- **Reorder level** ($s$): order spare-parts when inventory position of spare-parts drops below level $s$.

There are parts that have periods with zero demand. Then it may be useful to delay the replenishment order and achieve a lower total cost (Moinzadeh, 2001; Schultz, 1989). The principle behind this is that due to the delayed replenishment there is less inventory or no inventory and thus lower holding costs.

This requires an extra decision parameter, namely:

- **Delay time** ($de$): time period that order is delayed after the replenishment decision

In Figure 4 is shown what the effect is of using a delay time or not. The figure shows that when a delay time is used, no holding costs are incurred for a longer period of time (marked area), because the moment of ordering is delayed.

![Figure 4 Effect of delay time on holding costs](image-url)
3.2.2.2. **Replenishment quantity**

When a replenishment is initiated there has to be decided how much is ordered. The following control parameters are available:

- Order quantity \( Q \): a fixed order quantity of spare parts.
- Order up to level \( S \): a quantity of spare parts is ordered to raise the inventory position up to level \( S \).

3.3. **Inventory control policies & parameters realistic for Vlisco**

In the previous paragraph the possible inventory monitoring method and control parameters were indicated. First, it was concluded that Vlisco does not continuously monitor its inventory, which, as a result, limits the possible policies to inventory control policies to periodic reviews. With the control parameters in the previous section, the possible inventory control policies further considered listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Inventory policies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodic Review</td>
</tr>
<tr>
<td>( (R, S) ) (R, ( de ), ( S ))</td>
</tr>
<tr>
<td>( (R, Q) ) (R, ( de ), ( Q ))</td>
</tr>
<tr>
<td>( (R, s, Q) ) (R, ( de ), ( s ), ( Q ))</td>
</tr>
<tr>
<td>( (R, s, S) ) (R, ( de ), ( s ), ( S ))</td>
</tr>
</tbody>
</table>

Source: combination of (Moinzadeh, 2001; Silver et al., 1998)

In the following section, the strengths and weakness of the policies listed in Table 1 will be clarified.

3.3.1. **Inventory control policies: a review**

Starting with the \( (R, S) \) policy, each review period there is ordered up to level \( S \) as shown in Figure 5. It is visible that when an order is placed the inventory position goes up to \( S \). After the delivery lead time the inventory on hand is increased by the ordered amount. For a \( (R, Q) \) policy the principle works the same only the ordered amount is \( Q \). Both are known as a replenishment cycle system.

![Figure 5 R,S policy](image-url)
Within the \( (R, s, S) \) policy (shown in Figure 6) after each review period is verified if the inventory position is equal or below the reorder level \( s \). When this is the case there is ordered or up to level \( S \) and the inventory level is increased to \( S \). The inventory on hand is increased when the inventory on order arrives after the delivery lead time. In essence the \( (R, s, Q) \) policy works similar only \( Q \) units are ordered.

![Diagram of inventory level, inventory position (IP), and inventory on hand (IOH)](image)

**Figure 6 \( R,s,S \) policy**

When a delay time is used the policies work the same as the corresponding policy without the delay time, only the moment of ordering is delayed. In Figure 7 an example is shown with the \( (R, de, s, S) \) policy.

![Diagram of inventory level, inventory position (IP), and inventory on hand (IOH)](image)

**Figure 7 \( R,de,s,S \) policy**
3.3.1.1. Policies realistic to be implemented at Vlisco

A replenishment cycle system (i.e. \((R, S)\) and \((R, Q)\)) will result in high replenishment cost when the review period is short and there is frequent demand, because every time a small amount is ordered. Each spare part has its unique demand pattern, it is thus important to determine the correct review period \((R)\). Currently the review period is fixed for all parts within Vlisco. Since Vlisco has 6000 parts with each its unique demand pattern it is not practicable to have different review periods. Vlisco prefers therefore policies that use the same review period. Within the \((R, s, S)\) and \((R, s, Q)\) only a replenishment order is placed when the inventory position is equal or below the reorder point after each review period. The \((R, s, S)\) and \((R, s, Q)\) policies are therefore a better alternative. If a fixed order quantity \(Q\) is used, there is a risk that the inventory on hand lags behind. Meaning when there is high demand during the risk period the inventory on hand is that far decreased the replenishment order cannot fulfil all outstanding backorders or it is very likely new backorders will occur before a new replenishment arrives. Figure 8 shows an example of a \((R, s, Q)\) policy that lags behind.

![Figure 8 R,s,Q policy lagging behind](image-url)

Given the premises the chosen policy is the \((R, s, S)\) policy. The delay time gives the opportunity to further optimise the policy, however since the time constraint of the project the delay time is out of scope. The delay time is therefore for future research.

### 3.4. Chapter conclusion

In this chapter the inventory monitoring method and control parameters were determined. This revealed the possible inventory control policies. After the investigated the strengths and weaknesses of the possible inventory control policies, the \((R, s, S)\) policy has been selected. Therewith answering the research question; “Which inventory control policies are realistic to be implemented at Vlisco?” In the next chapter the context wherein this policy has to operate is discussed.
4. Key elements inventory control at Vlisco

The research objective is described in chapter 2, namely to control the inventory such that the total relevant costs are minimized given a service constraint. To be able to reach this objective an understanding is thus needed about the following aspects; 1) the service measure, 2) what the total relevant costs are at Vlisco and 3) the demand of the spare parts. In this chapter each aspect is therefore clarified.

4.1. Service measure

It is not known beforehand when demand will occur (i.e. it is not beforehand when a certain part will breakdown). Due to this uncertainty caused by the probabilistic demand it is necessary to keep inventory. The service measure determines how much inventory is required.

The service measure defines the required service of the inventory of spare parts, for example; 98% of the demand should be delivered directly out of the inventory on hand. The required service level is thus the constraint that determines the amount of inventory that is needed to meet the required service. The right type of service measure depends on the company situation and their requirements.

In the introduction it has been explained that the availability of spare parts influences the availability of the machines. Vlisco is only interested in whether or not a machine is working and not in the performance of separate spare parts. Preferred is therefore a machine oriented service level, since a machine oriented service level defines the required service of a machine based on the availability of all parts (also known as the system approach). Unfortunately at Vlisco is not known which machine contains which parts, with as consequence that a system approach is not immediately possible. Given the time constrain of this project, a separate service measure for each spare part is therefore suggested. Although this is sub optimal it is the only possible solution at the moment.

An additional criterion for the service measure is that it has to be taken into account that full order fulfilments are required. For example, whenever a press breaks down, it requires two new bearings (i.e. an order exists for two new bearings). Having one bearing on stock means that the order cannot be fulfilled; the press requires two new bearings and will not work on one bearing. Therefore, partial fulfilments of orders are not possible. Service measures suggested by literature such as the fill rate (the fraction of demand delivered directly from inventory) or the ready rate (the fraction of time the net inventory is positive) (Silver et al., 1998) measure the availability of the inventory but not the fulfillment of the order and are therefore not appropriate. The Order fill rate suggested by Larsen et al (2008) measures the percentage of orders that are directly delivered from inventory and is therefore a better alternative.

Demand that is backordered causes the customer (i.e. machine) has to wait. The length of this waiting time is of greater importance than the order fill rate as this contributes to the downtime of the machine, from now called the machine waiting time. With the probability that the machine waiting time is less than a specified time (Kiesmüller and de Kok, 2006; Tempelmeier, 1985) a performance measure is available that specifies time windows wherein orders of a machine should be delivered. The service measure used for Vlisco is defined in equation 4.1.

\[ P(W \leq w_{\text{max}}) \geq p_{\text{min}} \]  \hspace{1cm} (4.1)

where \( w_{\text{max}} = \text{maximum waiting time} \)

\( p_{\text{min}} = \text{minimum probability} \)
With the machine waiting time defined as the service measure for spare parts the total relevant costs are discussed in the next paragraph.

4.2. Total Relevant costs

In this section the relevant costs of inventory control are discussed. Relevant costs for the inventory control are; holding costs, replenishment and unavailability costs (Axsäter, 2006; Silver et al., 1998). For inventory control of spare part emergency shipments are quite common (Kranenburg and Van Houtum, 2007. When an emergency demand exits at Vlisco a carrier is used to speed up delivery, however no contracts exists that arranges emergency shipments, therefore no distinction is made between emergency and normal replenishment costs.

Holding costs are determined by the purchase costs of a spare part and the carrying charge. The carrying charge defines which percentage of the purchase costs are incurred as costs per unit time. How the carrying charge is obtained at Vlisco is described in Appendix C. Replenishment costs are the fixed costs for each replenishment order placed at the supplier. See Appendix D how these are obtained.

The unavailability costs are those costs incurred when a spare-part is not available the moment it is required. To determine the unavailability costs, it must be known what the effect of the failure of a part is on a machine.

4.2.1. Unavailability costs

The unavailability costs of a spare-part is defined by the consequences caused by the failure of a part on the process in case a part is not readily available (Huiskonen, 2001). From the inventory control point of view, most important is how much time there is to react to the demand need, that is, whether the need is immediate or whether there is some reaction time available. This determines whether to use a time buffer or a material buffer against variations in demand.

The reaction time is determined by whether or not a failed part causes downtime (i.e. time a machine does not generate output) and from what moment does the downtime result into costs. Measurement of unavailability costs should therefore indicate from what time the failed part has effect and determine the consequence. To evaluate the unavailability costs the preferred measurement is downtime costs, as it is quantitative and most important it influences the financial performance of the company. Downtime cost is the cost of lost production; it is the cost incurred, on a per unit time basis, by not having a machine in service (Duchessi et al., 1988).

4.2.1.1. Downtime costs

To determine the downtime cost the impact of downtime of a machine on the loss of production has to be determined. In this paragraph all the elements and how to calculate the downtime costs will be explained. First the elements of downtime are discussed. Subsequently, the principle of consequential downtime, nett production rate, costs associated with downtime and the failure effect are explained. Finally the equation is given to calculate the downtime costs.
**Elements of downtime**

Downtime can be split up in the following elements; Shutdown time ($SDT$), Delivery time ($LT$), Mean time to repair ($MTTR$) and Setup time ($ST$), which are shown Figure 9.

<table>
<thead>
<tr>
<th>Downtime</th>
<th></th>
<th>MTTR</th>
<th>Setup time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutdown time</td>
<td>Delivery time</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 9 Elements of downtime*

When a machine part fails, the machine can be required to be shut down, indicated as shutdown time in Figure 9. Once the machine is shut down, maintenance engineers determine what part has failed such that a new part can be ordered – resulting in delivery time. Once the new part has been delivered, the machine can be repaired resulting in MTTR. Once repaired, the machine requires to be configured such that it can resume production, this time is called setup time.

In Figure 9 is assumed that the machine needs to be shut down before a failure can be detected and therefore the shutdown time and delivery time are sequential. However the failure could also be known before the shutdown of a machine, resulting that the shutdown time and delivery time can be in parallel. When these times are in parallel there are 3 scenarios possible; delivery time is bigger, smaller or equal to the shutdown time (Figure 10).

*Figure 10 Scenarios Delivery time vs Shutdown time*

The length of the downtime is then determined by the maximum of shutdown time and delivery time, the $MTTR$ and the setup time, which is shown in Figure 11.

<table>
<thead>
<tr>
<th>Downtime</th>
<th></th>
<th>MTTR</th>
<th>Setup time</th>
</tr>
</thead>
<tbody>
<tr>
<td>max(Shutdown time,Delivery time)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 11 Elements of downtime when shutdown time and delivery time are parallel*

Additionally, a part can be installed on a position in a machine such that the machine does not have to be shut down when repaired, hence shutdown time is 0. The consequence is the downtime will only consist of; delivery time, $MTTR$ and setup time.
The premises show that the downtime of a part depends on in which machine it is installed and what the position is within the machine (i.e. its location). Resulting to the following definitions of the elements of downtime:

- \( DT_{kij} \) = downtime of part \( k \) in machine \( i \) at position \( j \) (hours)
- \( SDT_{kij} \) = shutdown time required for part \( k \) in machine \( i \) at position \( j \) (hours)
- \( ST_{kij} \) = setup time required for part \( k \) in machine \( i \) at position \( j \) (hours)
- \( MTTR_{kij} \) = mean time to repair required for part \( k \) in machine \( i \) at position \( j \) (hours)
- \( LT_k \) = delivery time for part \( k \) (hours)

Downtime can be calculated by equation 4.2 when the machine has to be shut down before a failure can be detected or when there is no shut down needed (i.e. \( SDT_{kij} = 0 \)).

\[
DT_{kij} = SDT_{kij} + LT_k + MTTR_{kij} + ST_{kij} \tag{4.2}
\]

Or when a failure can be detected before shutdown, equation 4.3 has to be used.

\[
DT_{kij} = \max(SDT_{ij}, LT_k) + MTTR_{kij} + ST_{kij} \tag{4.3}
\]

The decision to use equation 4.2 or 4.3 is defined by a Boolean variable \( FDBSD \);

\[
FDBSD_{kij} = \begin{cases} 
1, & \text{failure detected before shutdown} \\
0, & \text{failure detected after shutdown}
\end{cases}
\]

**Consequential and non-consequential downtime**

At Vlisco downtime does not directly result in downtime costs, because machines may have a buffer to absorb downtime (i.e. the reaction time mentioned above). Therefore downtime is split up in non-consequential downtime (\( NCDT \)) and consequential downtime (\( CDT \)). First there is \( NCDT \), until the buffers —are depleted after which downtime results into costs, hence \( CDT \). The relations of these time elements are shown in Figure 13. The machine waiting time described in chapter 4.1 is the non-consequential downtime, since this is the maximum time a machine can wait for a part.

\[
NCDT_i = \sum_{p \in P} \frac{d_{pi}}{\sum_{p \in P} d_{pi}} NCDT_{pi} \tag{4.4}
\]
where:

\[ NCDT_i = \text{demand weighted average non – consequential downtime of machine } i \text{ (hours)} \]
\[ NCDT_{pi} = \text{non – consequential downtime of product } p \text{ of machine } i \text{ (hours)} \]
\[ d_{pi} = \text{demand of product } p \text{ that flows over machine } i \text{ (%)} \]

The downtime minus the no consequential downtime gives the consequential downtime \((CDT_{kij})\) when the downtime is bigger than \(NCDT_i\), else \(CDT_{kij}\) is zero (equation 4.5).

\[ CDT_{kij} = \max(0, DT_{kij} - NCDT_i) \] (4.5)

where;

\[ CDT_{kij} = \text{consequential downtime of part } k \text{ in machine } i \text{ on location } j \text{ (hours)} \]

**Net production rate**

In the production process of Vlisco there always exists a percentage loss, consisting of scrap \((SC_{pi})\) and fents \((F_{pi})\). Scrap is discarded fabric and fents is second quality fabric. The throughput of a machine needs to be adjusted according to the estimated scrap and fents it produces per product such that the nett production rate can be determined (i.e. the ratio usable output per time unit). The throughput \((\lambda_{pi})\) for product \(p\) in a machine is therefore multiplied with the correction for scrap and fents in percentages. This results in the nett production rate \((NP_{pi})\) of a machine.

\[ NP_{pi} = \lambda_{pi} \times (100 - SC_{pi}) \times (100 - F_{pi}) \] (4.6)

where;

\[ \lambda_{pi} = \text{throughput of product } p \text{ in machine } i \text{ (yards/hour)} \]
\[ NP_{pi} = \text{nett production rate of product } p \text{ in machine } i \text{ (yards/hour)} \]
\[ SC_{pi} = \text{percentage scrap of product } p \text{ in machine } i \text{ (%)} \]
\[ F_{pi} = \text{percentage fents of product } p \text{ in machine } i \text{ (%)} \]

**Cost associated with consequential downtime**

To determine the cost per hour of the consequential downtime the nett production and the contribution margin \((CM_{pi})\) of each yard produced are required. The sales department of Vlisco assumes (based on experience) that 10% of the orders can be backlogged and thus compensated; the compensable loss of production by sales \((CLP)\). Multiplying the nett production rate, contribution margin and compensable loss results in the cost rate of a machine \(C_{pi}\) (€/hour).

\[ C_{pi} = NP_{pi} \times CM_{pi} \times (100 - CLP) \] (4.7)

where;

\[ C_{pi} = \text{cost associated with the consequential downtime of product } p \text{ in machine } i \text{ (€/hour)} \]
\[ CM_{pi} = \text{contribution margin of product } p \text{ in machine } i \text{ (€)} \]
\[ CLP = \text{compensable loss of production by sales (％)} \]

The demand weighted average cost associated with consequential downtime becomes:

\[ C_i = \frac{\sum_{p \in P} d_{pi} C_{pi}}{\sum_{p \in P} d_{pi}} \] (4.8)
where;

\[ C_i = \text{demand weighted average cost associated with CDT of machine } i \ (€/hour) \]

**Failure effect**
Not every failed part has as consequence that there arises a total production stop (i.e. the machine to be shut down) the production loss can be partial or non-existent due to the position of the part within the machine. Therefore, the effect of a failed part on the throughput of the machine requires to be incorporated. A method to do so will now be introduced.

Failure mode and effect analysis (FMEA) is a method to analyse equipment failures and their consequences on production, safety and environment (Diallo et al., 2009). The method identifies potential failure modes and the subsequent step is to identify the root causes of these failure modes and initiate corrective actions. However, in this research, the goal is to identify the consequence of a failed part on production, i.e. the failure effect. To achieve this, a machine should be decomposed into parts and the function of the part should be related to the total function of the machine. This gives insight in what effect the failure of a part has on the total machine and its throughput. Bearing this in mind, this requires a (1) decomposition method and (2) a method that analyses the effect of a failed part. The Hamburger model of Zaal (2011) decomposes a machine into functions and the related parts, Zaal (2011) suggests a Fc-FMEA method that determines the failure modes of a part (and function) and the consequences of the separate failure modes. As these methods fulfil the requirements and are already used by Vlisco to determine the maintenance activities, this method is used in this research.

**1) Decomposition method**
The decomposition of the machine will be made based on the Hamburger model (Zaal, 2011), which makes the distinction between function \((FU)\), functional requirement \((FR)\) and function solver \((FS)\) (shown in Figure 14). The function is the task a part/machine (function solver) has to fulfill, where the functional requirement describes the expected function fulfilment in normal state of the part/machine.
Figure 14 shows several levels, because the goal is to decompose a machine in such level that spare parts are reached and their impact on the throughput of the machine can be determined. A function should thus be decomposed, until a level is reached where the function solver:

- is maintained by a third party based on a maintenance contract; third party is responsible for the uptime and thus also required inventory
- the part is replaced by a procured or revised part, hence a spare part

To support to which extent the machine needs to be decomposed a decision-logic is designed shown in Figure 15. First the machine is decomposed into a lower level after which is determined whether a failure of this function has impact on the throughput. When there is no impact on the throughput there is verified if the part is a spare part if not the part is further decomposed until the level of a spare part is reached. No thorough analysis of the failure effect is needed, since at a higher level it is already determined that there is no effect on the throughput. However when on a higher level is determined there is an effect on the throughput the function should be decomposed until the part of a spare part is reached. To understand the effect of a failure of the function the Fc-FMEA analysis should be executed as explained below.
Figure 15 Decision logic decomposition

(2) Effect analysis of a failed part
A part has different failure modes. Based on the functional decomposition of a machine a functional failure mode analysis (Fc-FMEA) can be made (Zaal, 2011). In the analysis different failure modes ($FM_2$) are described. For each failure mode the deviation of the function requirements is described and what the effect is. The standard Fc-FMEA used by Vlisco expresses the failure effect based on a 4 point scale a so called severity (Table 2).

<table>
<thead>
<tr>
<th>Value</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>minor</td>
</tr>
<tr>
<td>2</td>
<td>small</td>
</tr>
<tr>
<td>3</td>
<td>big</td>
</tr>
<tr>
<td>4</td>
<td>serious</td>
</tr>
</tbody>
</table>

Table 2 Severity based on standard Fc-FMEA (Zaal, 2011)
The provided severity does not measure the actual effect on the throughput of the machine; it has thus no good practical application. The Fc-FMEA is therefore adjusted and instead of a 4 point scale, the failure effect is expressed in % reduction of the throughput of the machine. Where the reduction can be caused by (Braglia et al., 2004):

- Production loss; failure mode causes direct throughput reduction
- Domino effect; failure mode causes that other parts fail as well, thus the machine is stopped or slowed down to prevent sub sequential costs.
- Environmental issues; failure mode causes environmental contamination, thus the machine is stopped or slowed down to prevent environmental issues
- Safety issues; failure mode causes safety risks, thus the machine is stopped or slowed down to prevent safety issues.

An example of the Fc-FMEA of the function “pressurise”, depicted in Figure 14 is shown in Table 3.

<table>
<thead>
<tr>
<th>$FU_k$</th>
<th>$FR_k$</th>
<th>$FS_k$</th>
<th>$FM_z$</th>
<th>$FF_{zkij}$</th>
<th>$FP_{zkij}$</th>
<th>$FE_{zkij}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurise</td>
<td>80 bar</td>
<td>Pump</td>
<td>Leakage (hole &lt; 5mm)</td>
<td>40 - 60 bar</td>
<td>0.8</td>
<td>50%</td>
</tr>
</tbody>
</table>

Leakage (hole > 5mm) | < 40 bar | 0.2 | 100%

Where

$FU_k =$ function of part $k$
$FR_k =$ function requirement of part $k$
$FS_k =$ function solver $k$ (hence part)
$FM_z =$ failure mode $z$
$FF_{zkij} =$ functional failure of failure mode $z$ of part $k$ in machine $i$ at position $j$
$FP_{zkij} =$ probability that a failure mode $z$ of part $k$ in machine $i$ at position $j$ occurs
$FE_{zkij} =$ failure effect of failure mode $z$ of part $k$ in machine $i$ at position $j$

The function has 2 failure modes, namely a hole bigger than 5mm or smaller than 5 mm. The failure effects of these failure modes are respectively 50% and 100%. To determine the total failure effect the failure effects are weighted with the probability that a certain failure mode occurs. This is done with the following formula:

$$TFE_{kij} = \sum_{z=1}^{N} (FF_{zkij} \times FP_{zkij}), \sum_{z=1}^{N} FP_{zkij} = 1, FP_{zkij} \geq 0 \forall z \hspace{1cm} (4.9)$$

Where

$TFE_{kij} =$ total failure effect of part $k$ in machine $i$ at position $j$

In the example above the hole bigger than and smaller than 5mm occur respectively with a probability of 0.8 and 0.2 ($FP_{zkij}$). The total failure effect becomes thus:

$$TFE_{kij} = 50\% \times 0.8 + 100\% \times 0.2 = 60\%$$

With this analysis the throughput can be adjusted in the calculation of the downtime costs.
Downtime costs of a part on a specific location
With the cost rate and the total failure effect and the consequential downtime the downtime costs can be calculated ($DC_{kij}$) for a part on a specific location.

$$DC_{kij} = TFE_{kij} \times CDT_{kij} \times C_i$$  

(4.10)

Summary downtime costs
The aspects and equations to determine the downtime costs of a failed part have been explained. Required are the following elements of downtime: shutdown time of a machine, delivery time of a part, mean time to repair the part and setup time of a machine. However the downtime does not directly results into costs, therefore with the non-consequential downtime of a machine the consequential downtime can be determined. Further, how to calculate the nett production rate and cost associated with the consequential downtime are clarified in this chapter. Also a method is developed to determine the failure effect of a failed part. This method results into the actual consequence of a failed part on the throughput of a machine and with that the actual downtime costs of a part can be calculated.

Downtime costs for the inventory models
In the case of Vlisco the costs of not having a part readily available (i.e. unavailability costs) are directly related to downtime costs, as not having a part on stock results that a machine is down. As mentioned earlier the downtime costs of a spare part is dependent on the machine where it is installed in and the position of the part within the machine (i.e. the location of the part). In the ideal situation for all parts the downtime costs on each location are known, such that the inventory parameter values can be calculated based on a demand weighted average downtime costs ($DWDC_k$). In equation 4.11 the determination of $DWDC_k$ is shown, where the demand of a part of a specific location is represented by $d_{kij}$ and the downtime costs by $DC_{kij}$.

$$DWDC_k = \text{demand weighted average downtime costs of part } k \text{ (€)}$$

$$d_{kij} = \text{demand of part } k \text{ in machine } i \text{ on position } j$$

$$DC_{kij} = \text{downtime costs of part } k \text{ in machine } i \text{ on position } j \text{ (€)}$$

$$DWDC_k = \sum_{i \in I} \sum_{j \in J} \frac{d_{kij}}{\sum_{i \in I} \sum_{j \in J} d_{kij}} DC_{kij}$$  

(4.11)

However Vlisco does not known the downtime costs of all parts on all locations and therefore a method has been developed to determine the unavailability costs, which is explained in the next chapter.

4.3. Demand
New parts are required whenever old parts are replaced by the maintenance division of Vlisco. When and how many parts are required is called the demand distribution of parts. More precise; a demand pattern describes the arrival time (i.e. when) and the size of the demand (Lengu et al., 2014). The demand distribution influences the inventory policy for the parts and is used to calculate the parameter values of the inventory policy (e.g. re-order levels). In this paragraph is explained which demand patterns exist at Vlisco.

4.3.1. Type of demand patterns
The demand distribution can contain a cyclic (e.g. seasonal effect) and/or a trend pattern. In Appendix F a method is explained how to check for these patterns. It is concluded that the historical demand for parts (i.e. demand data) at Vlisco does not contain cyclic or trend
patterns. Although there is no trend or cyclic pattern there still can be a distinction based on the arrival times and sizes of the demand pattern. According to Syntetos et al., (2005) the following demand patterns exist:

- **Smooth demand**: few or no periods with zero demand and the variability of the demand sizes is low
- **Erratic demand**: few zero or no periods with zero demand, but the demand size variability is high
- **Intermittent demand**: many periods with zero demand and low demand size variability.
- **Lumpy demand**: many periods with zero demand and a high demand size variability.

In Appendix I is the method explained to verify which demand patterns are present. At Vlisco all these patterns exist as shown in Table 4. The inventory control policies and methods to determine the demand distribution should therefore be able to cope with the different distributions. One method will be used to cope with the different demand patterns.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Corrective demand</th>
<th>Total demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>0.4%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Erratic</td>
<td>0.4%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Intermittent</td>
<td>92.6%</td>
<td>87.2%</td>
</tr>
<tr>
<td>Lumpy</td>
<td>6.7%</td>
<td>8.8%</td>
</tr>
</tbody>
</table>

**4.4. Chapter conclusion**

In this chapter the key elements for the inventory control policy at Vlisco were discussed. First a maximum machine waiting time was selected as service measure for inventory control of spare parts. Next all aspects of the total relevant costs (i.e. holding costs, replenishment costs and unavailability costs) at Vlisco were clarified. It was concluded that the ideal approach to determine the unavailability costs is currently not applicable at Vlisco. An alternative method will be discussed in the next chapter. Lastly it was concluded that 4 demand patterns exists at Vlisco and one method will be used to cope with these patterns.
5. Determine unavailability costs
In the previous chapter is explained how in the ideal situation the downtime costs are used to determine the unavailability costs. Since the downtime costs for all parts on each location are not known at Vlisco at this moment, a method has been developed to determine the unavailability costs in 3 phases. This method is explained in this chapter.

5.1. Determine downtime costs in phases
Certain parts are installed in multiple machines on several positions, where the downtime costs for a part differ depending on which machine and position is considered. Selecting a machine at random and analysing its parts would come with the risk of selecting a part with low downtime costs when unavailable. This would result in different inventory parameter values for the inventory policy of the part than for example if a different machine is selected where the part has high downtime costs when unavailable. As a result, downtime costs must be determined for the parts in all machines where the part is situated in, such that unappropriated inventory parameter values can be avoided. Unfortunately the downtime costs and demand of each location are not known at this moment. The data that is available is shown in Table 5.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_i$</td>
<td>Yes</td>
</tr>
<tr>
<td>$FDBSD_{kij}$</td>
<td></td>
</tr>
<tr>
<td>$LT_k$</td>
<td>Yes</td>
</tr>
<tr>
<td>$MTTR_{kij}$</td>
<td></td>
</tr>
<tr>
<td>$NCDT_i$</td>
<td>Yes</td>
</tr>
<tr>
<td>$SDT_{kij}$</td>
<td></td>
</tr>
<tr>
<td>$ST_{kij}$</td>
<td></td>
</tr>
<tr>
<td>$TFE_{kij}$</td>
<td></td>
</tr>
</tbody>
</table>

It can be concluded from Table 5, that a lot of data is missing. As already mentioned in chapter 1.2 parts are situated on more positions within a machine; for example one bearing is situated on more than 80 positions within one machine. Analysing one machine takes 60-80 hours (source: case study at Vlisco, 2015), before the downtime costs of all parts on all positions within the machine are known. Given the fact Vlisco has 120 machines it is not feasible to determine the downtime costs for the parts based on all machines within a short notice. In the most favourable scenario this would take one employee 7200 hours, which are 180 weeks of 40 hours. Therefore a work around scenario has been developed. The method is very extensive and therefore the method is introduced in this chapter and a short summary is given. Details and the exact approach are described in Appendix J.

In 3 phases the ideal situation is reached and the parameter values can be determined based on the demand weighted average downtime costs. The 3 phases give the opportunity to already partially (sub) optimize the inventory with minimal effort (time, costs). Inventory parameter values are namely based on the already available data during each phase. The phases are shown in Figure 16.
First the hypothetical highest downtime costs for a part will be determined in phase 1 which can then be used to determine the inventory parameter values. The hypothetical highest downtime costs is the worst probable case for a part. During phase 2 the machines are analysed and data about the missing downtime elements become available. Due to a smart selection of the order machines are analysed, the actual highest downtime costs of a specific part are obtained in this phase. The highest downtime costs are equal or lower than the hypothetical highest downtime costs, which gives the opportunity to further optimize the inventory. From all parts the downtime costs are saved such that finally in phase 3 all data is available and the demand weighted average downtime costs can be used to fully optimize the inventory parameter values.

For both; phase 1 and 2 the recommended alternative is based on highest downtime costs. By using a (hypothetical) highest downtime costs for a part, it is guaranteed that the inventory is definitely not too low and the main objective of spare parts i.e. keeping the manufacturing systems available (Kennedy et al., 2002) is fulfilled. The solution is not optimal; however, optimality can be achieved as soon as the downtime costs for a part is determined for all locations. In the Appendix F is described which data can be easily obtained, such that the hypothetical highest downtime costs of phase 1 can be calculated. Thereafter, the developed method of phase 2 is explained.

5.2. Chapter conclusion
In this chapter is clarified that in the ideal situation the inventory parameter values are calculated based on demand weighted downtime costs. However obtaining the downtime costs of a part in each machine is time consuming and therefore the parameter values could not be determined in the near future. A method is developed to reach the ideal situation in 3 phases. In phase 1 a hypothetical highest downtime costs of a part is used. Within phase 2 the highest downtime costs of a part are obtained. Finally with the results of phase 2 the demand weighted average can be calculated in phase 3. With the hypothetical and highest downtime costs the worst case is used and this ensures there is sufficient inventory to keep the manufacturing systems available.
6. Inventory model

With the service measure and the total relevant costs the optimal inventory control policy parameter values can be selected. In this chapter the research question: “How can Vlisco select the optimal inventory control policy parameter value for its spare parts?” is answered. The inventory control system of Vlisco is analysed and there is decided that simulation will be used to determine the parameter values. For the extensive analysis see Appendix F. Within this chapter gives is explained how the inventory model works. First the way the model operates is described. Secondly the demand generation is explained. Thirdly is clarified how the costs are calculated and finally the determination of the inventory parameter values is explained.

6.1. Functioning of the model

6.1.1. Modelling of time

In paragraph 3.2.1 is explained that Vlisco uses scanners and the data is only updated at the end of the day. The consequence is that demand of the orders is only registered with a timestamp of a day. It could occur that the same part is demanded on the same day for different machine, which will result in the following 2 deviations if daily demand is modelled as machine orders:

- Insufficient inventory on hand causing 2 machine backorders, while the model creates only 1 machine backorder and downtime costs
- Insufficient inventory on hand causing 1 machine backorder since one of the 2 can be fulfilled, while the model creates 1 machine backorder and downtime costs.

Analysing the data showed that in the last 5 years it only occurred 4 times on 12752 orders which means the probability of occurrence is 0.000314. The influence is therefore considered negligible. Arrival of demand and all related events are therefore modelled on a daily level. Each period \( t \) is a day.

6.1.2. Configuration machine orders

In paragraph 4.1 is already explained that partial delivery of an order will result in that a machine is down. The inventory model should thus only have complete fulfilment of orders and therefore the configuration of the orders is of great importance.

Orders for parts at Vlisco can consist out of:

- Different parts of one or multiple units; an example is when the bearings of a roller are replaced. On both sides of the roller, the bearings and the bearing sleeves that hold the bearing on its place are replaced.
- One part of one or multiple units; an example is when a pump is replaced or when laths of a lathed roller are replaced.

In both situations not being to fulfil the entire order results that a machine remains down. Therefore the inventory of each part function as an assemble-to-order system in which parts are withdrawn from inventory based on order specifications; insufficient stock of one item may cause delays in order fulfilment (Hausman et al., 1998). A more extensive description of assembly to order systems can be found in Appendix F.1.1.

As already mentioned in 4.2.1 locations of all parts are not known, therefore the different configurations of the assemblies are also unknown. Given the premises and the time constraint of the project, the situation where different parts of one or multiple units are demanded is out of scope. The configuration of the machine orders within the model consist therefore out of; one part of one or multiple units.
6.1.3.  Sequence of events

Within the \((R, s, S)\) policy; every \(R\) periods (for example 7 days) the inventory position is compared with the reorder point \(s\). If the inventory position at \(R\) is equal of below the reorder point \(s\) a replenishment order is released that increases the inventory position up the order up to level \((S)\). This order will arrive at the beginning of period \(t + LT + 1\) (\(LT\) is the delivery lead time). For clarity the sequence of events at each period \(t\) is as follows:

1. Arrival of a replenishment order
2. Delivery of waiting machine orders according to the First-come First-served discipline (when necessary)
3. Delivery of the demand of period \(t\)
4. Review of the inventory position and placement of a replenishment order (when necessary)

When a demand arrives from a machine and the demand cannot be fully satisfied the machine waits until there are sufficient spare parts such that the demand can be fulfilled.

6.1.4.  Assumptions

The following assumptions are made:
- Demand does not contain a trend or a cyclic pattern and the demand pattern observed in the past will also occur in the future
- Constant delivery lead time
- No partial deliveries are allowed. Demand of machines experience waiting time until the entire demand can be satisfied.
- Subsequent replenishment orders cannot overtake each other; thus an order placed later cannot arrive earlier.

6.2.  Demand generation

Demand will be generated randomly based on historical data. The selection of the method (approach) is explained in Appendix F. This method has to generate the 2 elements of demand; namely the arrival of the demand and the demand size. The developed method is based on the bootstrap method suggested by Willemain et al. (2004).

The bootstrap method of Willemain et al. (2004) states that the demand data has 2 scenarios, namely no demand or demand with a certain size, which thus represents 2 states; state no demand \((0)\) and state demand \((n)\). Based on the historical data it can be determined what the probability is of going to a different state:
- \(P_{00}\) is the probability of going from no demand to no demand
- \(P_{0n}\) is the probability of going from no demand to demand
- \(P_{n0}\) is the probability of going from demand to no demand
- \(P_{nn}\) is the probability of going from demand to demand

With historical data on daily level the probability of going from state to state is per period of a day. In Figure 17 the state transition diagram is given of going from state to state.
Where \( P_{00} + P_{0n} = 1 \) and \( P_{n0} + P_{nn} = 1 \). With these probabilities of the states the demand can be generated. A random number \( U \) that is uniformly distributed over \((0,1)\) is generated. This is similar to throwing a dice, where all numbers have the same probability and thus a number is selected at random. With the number \( U \) and the previous state the new state is determined. If the previous state \((t - 1)\) has no demand \((0)\) equation 6.1 is used otherwise equation 6.2.

If \( X(t - 1) = 0 \)

\[
X(t) = \begin{cases} 
0, & \text{If } U < P_{00} \\
n, & \text{If } U \geq P_{00}
\end{cases}
\]  \hspace{1cm} (6.1)

If \( X(t - 1) = n \)

\[
X(t) = \begin{cases} 
n, & \text{If } U < P_{nn} \\
0, & \text{If } U \geq P_{nn}
\end{cases}
\]  \hspace{1cm} (6.2)
Different states of demand and no demand can thus be generated for a certain time horizon ($T$), resulting that the arrival of the demand is realized (shown in Figure 18).

<table>
<thead>
<tr>
<th>Time</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>n</td>
</tr>
<tr>
<td>2</td>
<td>o</td>
</tr>
<tr>
<td>3</td>
<td>o</td>
</tr>
<tr>
<td>4</td>
<td>n</td>
</tr>
<tr>
<td>5</td>
<td>o</td>
</tr>
<tr>
<td>6</td>
<td>o</td>
</tr>
<tr>
<td>7</td>
<td>o</td>
</tr>
<tr>
<td>8</td>
<td>o</td>
</tr>
<tr>
<td>9</td>
<td>n</td>
</tr>
<tr>
<td>10</td>
<td>n</td>
</tr>
</tbody>
</table>

*Figure 18 Generate demand arrival*

When a state has demand ($n$) the demand size has to be determined. This is done by randomly selecting a demand size of the observed demand sizes in historical data. Figure 19 gives an example of how this works; the generated demand arrivals are visible on the left size. The observed demand sizes, visible in the middle, are randomly assigned to the states with demand, visible on the right side.

<table>
<thead>
<tr>
<th>Time</th>
<th>State</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>n</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>o</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>o</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>n</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>o</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>o</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>o</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>o</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>n</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>n</td>
<td>1</td>
</tr>
</tbody>
</table>

*Figure 19 Example of creating a demand and no demand sequence*
6.3. Cost calculation

In this paragraph is explained how the total relevant costs are computed. The total relevant costs are the sum of the holding, replenishment and backorder costs.

\[ TRC_{SH} = HC_{SH} + RC_{SH} + BC_{SH} \]  

(6.3)

Where \( TRC_{SH} = \) total relevant costs over the simulation horizon (€)

6.3.1. Holding costs

The holding costs during each period (in the case for Vlisco. each day) are computed by multiplying the inventory on hand at the end of period \( t \) with the price of a spare part and the carrying charge. In Appendix C is clarified how the carrying charge is obtained.

\[ HC_t = IOH_t \times v \times h \]  

(6.4)

Where \( HC_t = \) holding cost at state \( t \) (€)
\( IOH_t = \) inventory on hand at state \( t \) (physical inventory)
\( v = \) spare part price (€/unit)
\( h = \) carrying charge (€/€/t)

With the holding costs of each period the holding cost during the entire simulation run can be determined by summing for the holding cost of \( t = 1 \) up to the simulation horizon.

\[ HC_{SH} = \sum_{t=1}^{SH} HC_t \]  

(6.5)

Where \( HC_{SH} = \) holding costs over the simulation horizon (€)
\( SH = \) simulation horizon

6.3.2. Replenishment costs

Per period it is determined whether there is replenishment via a Boolean variable that defines if a replenishment order is released \( (O_t) \).

\[ O_t = \begin{cases} 
1, & \text{replenishment order} \\
0, & \text{no replenishment order} 
\end{cases} \]

The replenishment costs are computed by summing all the replenishments and multiplying it with the fixed cost per order.

\[ RC_{SH} = A \times \sum_{t=0}^{SH} O_t \]  

(6.6)

Where \( RC_{SH} = \) replenishment costs over the simulation horizon (€)
\( O_t = \) boolean variable defining if a replenishment order is released
\( A = \) fixed cost per order (€/order)

6.3.3. Unavailability costs

The unavailability costs are calculated based on the downtime costs determined in chapter 5. When a machine order cannot be fully satisfied, the machine has to wait. This is determined via equation 6.7. The equation verifies if the inventory on hand minus the demand at period \( t \) is smaller than 0, if yes the demand cannot be fulfilled. Whether a machine order has to wait or not is defined by the Boolean variable \( MOW_t \). The inventory on
hand is measured after a possible replenishment order is received and remaining unfulfilled machine orders are fulfilled.

\[
MOW_t = \begin{cases} 
1, & \text{machine order has to wait} \\
0, & \text{machine order can directly be satisfied} 
\end{cases}
\]

If \( IOH_t - D_t < 0 \)
then \( MOW_t = 1 \)
else \( MOW_t = 0 \)

(6.7)

Where \( IOH_t \) = inventory on hand at time \( t \)
\( D_t \) = demand at time \( t \)
\( MOW_t \) = boolean variable defining if machine order has to wait

The time a machine order has to wait until the demand can be satisfied is defined as the waiting time (\( w \)). Incorporating the waiting time gives the downtime of a machine and is given by equation 6.8.

\[
DT_{kfi} = SDT_i + MTTR_{fi} + w + ST_i
\]

(6.8)

\[
CDT_{kfi} = \max(0, DT_{kfi} - NCDT_i)
\]

(6.9)

\[
DC_{kfi} = CDT_{kfi} \times C_i
\]

(6.10)

The downtime cost can be calculated, by multiplying the downtime costs with the sum of all backorders during the simulation.

\[
BC_{SH} = DC_{kfi} \times \sum_{t=0}^{SH} OB_t
\]

(6.11)

6.4. Determine parameter values

This paragraph explains how each parameter value is obtained based on the total relevant costs and generated demand explained in the previous paragraphs. Which value is used for the review period (\( R \)) is defined by Vlisco, since the inventory position is checked every 4 days as explained in paragraph 3.2.1. The determination of the optimal reorder level (\( s \)) and order-up to level (\( S \)) would require many simulation runs to find the joint optimum. Empirical results show that that the optimal order quantity is nearly independent of the service level requirement (Tijms and Groenevelt, 1984). The parameter values \( s \) and \( S \) can therefore be determined separately, which is explained below

6.4.1. Determine value for \( S \)

In the introduction of this paragraph is explained that \( s \) and \( S \) are determined separately. How these are obtained is in a sequential fashion, first a reorder quantity (\( Q \)) is calculated, subsequently the reorder level (\( s \)) is determined and finally the order up to level (\( S \)) is obtained. The sum of \( s \) and \( Q \) results in the order up to level (\( S \)) as shown in equation 6.12.

\[
S = s + Q
\]

(6.12)

The economic order quantity model is used to determine the optimal \( Q \). Equation 6.13 shows how the optimal \( Q \) is determined and will likely result in a non-integer value. Ideally both integer values surrounding the value are used in the model to determine the best performing
value. For simplicity and since Vlisco is risk averse the result is rounded up to the nearest integer.

\[ Q = \sqrt{\frac{2AE[D_{DH}]}{vh}} \tag{6.13} \]

Where
- \( A = \text{fixed cost per order (€)} \)
- \( E[D_{DH}] = \text{the expected demand during the demand horizon} \)
- \( v = \text{unit cost (€)} \)
- \( h = \text{holding cost (\%/unit time)} \)

Example
- \( A = €100 \)
- \( E[D_{DH}] = 0.077206 \text{ per day} \)
- \( v = €100 \)
- \( h = 0.01 \% \text{ per day} \)

The optimal order quantity is 7 parts as shown in the calculation below.

\[ Q = \sqrt{\frac{2 \times 100 \times 0.077206}{100 \times 0.01}} = 6.213127 \approx 7 \]

The optimal order quantity is determined based on the assumption that demand is constant; so this quantity does not take the variation of the demand into account. Safety stock is thus required to absorb the variation in demand and thus reduce the probability of stock-out occasions and the related machine waiting time. The safety stock is determined by the height of the reorder level \( s \), which is explained in the next paragraph.

6.4.2. Determine value for \( s \)

In this paragraph the method to determine the optimal \( s \)-level based on the maximum machine waiting time will be explained. First is described how to compute the probability of the machine waiting time and finally is clarified how the optimal \( s \)-level is determined.

Machine waiting time probability

When a demand arrives from a machine for a part (i.e. order) and the order cannot be fully satisfied, the machine waits until there are sufficient spare parts such that the order can be fulfilled. Each time a demand has to wait the waiting time is recorded. The number of occurrences of a specific waiting time \((w)\) divided by all the demand occurrences during the simulation time defines the probability of a machine waiting time (equation 6.14).

\[ P(W = w) = \frac{\#(w)}{\# \text{demand occurrences}} \tag{6.14} \]

For the service measure the probability of interest is smaller than a specified value, for example smaller than 1 day. This probability is defined by equation 6.15.

\[ P(W \leq w_z) = \sum_{i=0}^{z} P(W = w_i) \tag{6.15} \]

Determine optimal value for \( s \) level
The service measure defines the optimal reorder level. Goal is to find the lowest reorder level such that the required service level is obtained. A maximum machine order waiting time and a probability are specified and the reorder level is increased such that the constraint will not be violated. The constraint is shown in equation 6.16; find the minimal \( s \) that satisfies that the probability of the machine waiting time \( (P\{W \leq w_{\text{max}}\}) \) is bigger or equal than the required service level \( (p_{\text{min}}) \).

\[
\min \{ s \mid P\{W \leq w_{\text{max}}\} \geq p_{\text{min}} \} \quad (6.16)
\]

The algorithm used to find the optimal \( s \) is described below:

1) Define required service measure for \( w \) and required probability \( p \)
2) Start with \( s = 0 \) if \( P\{W \leq w_{\text{max}}\} \geq p_{\text{min}} \) stop, else go to step 3
3) Increase \( s \) with 1
4) Verify whether \( P\{W \leq w_{\text{max}}\} \geq p_{\text{min}} \) if yes stop else go back to step 3

**Example**

\( R = 7 \)
\( LT = 3 \)
\( Q = 7 \)
\( w_{\text{max}} = 1 \text{ day} \)
\( p_{\text{min}} = 0.95 \)

In the table below the results of the simulation run are shown. When the reorder level is 7 the required probability of 0.95 is met with a maximum waiting time of 1 day.

<table>
<thead>
<tr>
<th>( s )</th>
<th>( P{W \leq w_{\text{max}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.4833</td>
</tr>
<tr>
<td>1</td>
<td>0.6117</td>
</tr>
<tr>
<td>2</td>
<td>0.7067</td>
</tr>
<tr>
<td>3</td>
<td>0.7900</td>
</tr>
<tr>
<td>4</td>
<td>0.8350</td>
</tr>
<tr>
<td>5</td>
<td>0.8933</td>
</tr>
<tr>
<td>6</td>
<td>0.9317</td>
</tr>
<tr>
<td>7</td>
<td><strong>0.9533</strong></td>
</tr>
</tbody>
</table>

Together with the optimal \( Q \) the order op to level can be determined: \( S = Q + s = 7 + 7 = 14 \). Thus the inventory parameter values for this spare part are: \( R = 7 \), \( s = 7 \) and \( S = 14 \).

However when the service constraint is met it is possible that it is still beneficial to increase the reorder level, because the total relevant costs could decrease. The algorithm is extended to determine if a cost optimum can be achieved will satisfying the service level. In equation 6.17 the constraint is shown; find the minimal \( s \) that satisfies that:

- the probability of the machine waiting time \( (P\{W \leq w_{\text{max}}\}) \) is bigger or equal than the required service level \( (p_{\text{min}}) \) and
- the minimal Total relevant costs.

\[
\min \left[ s \mid P\{W \leq w_{\text{max}}\} \geq p_{\text{min}} \cup \min[TRC] \right] 
\]

(6.17)

To make sure the algorithm works in all cases it is important to understand the behaviour of the Total Relevant costs. Hence, required to known whether the cost function is convex, i.e.,
whether there is only one absolute minimum or not (i.e. the function have more minima in the form of local minimums). In figure xx a convex function is shown and a function with several minima and a global minimum.

![Figure 20 Behaviour of the cost function](image)

If the TRC function would be convex, increasing an s level would result that the TRC decreases or increases. Decrease means costs saving and the algorithm could stop until TRC increases.

However, Vlisco does not have a standard convex function. This is caused by the fact that not every increase in of the reorder level (s) results in less back orders. Backorder costs are only prevented if a machine order can be fully delivered. A partial delivery will thus not result in the decrease of the backorder costs. Hence, the TRC would increase due to increasing holding costs and unchanged backorder costs. The backorders will be left unchanged while increasing the s level, until the s level is increased in such an extent that an order can be fully delivered. The consequence of this behaviour is that the TRC function has local minima and a global minimum. An algorithm should search for the global minimum.

The extended algorithm used to find the optimal s is described below:

1) Increase s with 1
2) Verify whether \(TRC(s-1) > TRC(s)\) if yes go back to step 5
3) else save s-1 and \(TRC(s-1)\) as temporary minimum: min_s and \(TRC(\text{min}_s)\) and go to step 7
4) verify if \(BC = 0\) if yes stop else go to step 8
5) Increase s with 1
6) Verify whether \(TRC(s-1) > TRC(s)\) if yes go back to step 8
7) else verify whether \(TRC(s-1) < TRC(\text{min}_s)\) if yes save \(TRC(s-1)\) as temporary minimum: min_s and \(TRC(\text{min}_s)\) and go to step 7

The algorithm makes use of the fact that when the backorder costs are 0 it is certain that all minima are visited, because increasing the inventory will only result in increasing the holding costs.

6.5. Chapter conclusion

In this chapter answer was given to the research question; “How can Vlisco select the optimal inventory control policy parameter value for its spare parts?”. It was clarified how the inventory model operates and methods have been developed to determine the optimal inventory control policy parameters. The methods take the total relevant costs and the service constraint (maximum machine waiting time) into account.
7. Simulation model
Simulation modelling is the process of creating and analysing a mathematical model of a physical system (i.e. Vlisco’s spare part inventory control) to predict its performance in the real world. The mathematical model was described in the previous chapter. In this chapter it is explained how the simulation model is used to determine the optimal inventory control parameter values. First the general explanation of the simulation model is given and the simulation model settings (i.e. initial values and the simulation run length) are discussed. Thereafter the validation and verification of the simulation model is described. Finally it is explained how the optimal s level is determined.

7.1. The simulation model: introduction
With simulation based on the historical demand data and the input variables the real-world is imitated. Demand is generated over a time horizon (i.e. simulation run length) and the state of the inventory is tracked each time an event occurs (i.e. discrete event simulation). This demand is based on the historical demand of Vlisco (this has been discussed in paragraph 6.2). Every time demand occurs, it is subtracted from the spare part inventory. An inventory control policy, in this case the \((R, s, S)\) policy is used to control the inventory height. Because the parameter values for \(R\) and \(S\) are given (i.e. \(R\) is equal to 14 days and \(S\) is based on the EOQ formula in paragraph 6.4.1), the simulation model checks for each run which \(s\) value meets the service constraint. However, higher levels for \(s\) could be more cost efficient, therefore, the simulation model checks again if it can improve on total relevant costs by increasing the reorder level \(s\).

With the introduction of the simulation model given, initial values and the simulation run length are discussed in the paragraphs below.

7.1.1. Starting the simulation – initial values
Before the optimal inventory control policy parameter values for a part can be determined, the initial values for the input parameters are required. These are;

- Current inventory on hand
- Current back-orders
- Service measure
- Number of simulation runs
- Spare-part costs
- Review period
- Delivery lead time
- Replenishment costs
- Holding costs
- Simulation Run length
- Downtime specifics
  (Shutdown time, Mean Time To Repair, Setup Time, Non-consequential downtime, Costs Rate)

All parameter values, with the exception of the simulation run length and number of runs, can be determined by the maintenance engineers and have been elaborated upon in the previous chapter. However before the length of a simulation run and the number of runs are determined, the model needs to be assessed as valid.

7.1.2. Determining the simulation length
The simulation run length (also called simulation horizon) is the length of time that the simulation model will simulate demand. The length of a run depends on the expected time that part will be used by Vlisco. For example, part x is expected to be used for 30 more years until the machine it is located in, will be substituted. As a consequence, the simulation run time should be equal to 30 years. Since the location of parts are not known in the beginning the expected use of a part family will be used initially, afterwards the exact time of a part can be used.
7.2. Verification and validation

Before the simulation results can be used, the simulation model needs to be verified and validated. Verification is required to check if the simulation model performs the required calculations in the right manner. Thereafter, because the model represents the real world, validation is required to determine whether the representation.

7.2.1. Verification

The simulation model is built up into modules, namely;
- demand generation
- inventory policy logic
- calculation of order up to level (S)
- calculation of waiting time probability
- calculation of reorder level (s)
- calculation of costs

This gives the opportunity to check whether all output is correct for each module separately. Afterwards the entire model has been run with test input data and verified if the outputs are reasonable. Especially extremes show if the model works as expected. The cases below were used and resulted into a positive outcome.
- Demand occurrences with demand size of zero, resulted that the initial inventory on hand was maintained when this was higher than the reorder level (s), else it was once replenished up to the order up to level (S).
- An unrealistic high order up to level, reorder level and initial inventory on hand (IOH) lead to a service level of 100% with a zero waiting time (no backorders).
- An unrealistic high unavailability costs leads to a service level of 100% with a zero waiting time (no backorders).
- Risk period (delivery time + review period) is made equal to the maximum machine waiting time and NCDT, which results that the reorder level drops to 0.

In the following cases an input variable was increased and the effect was analysed and resulted into a positive outcome.
- Increase of the following input variables resulted into increase of the reorder level (s)
  - Service level
  - Review period
  - Delivery time
- Increase of the replenishment costs resulted in a higher order up to level (S)
- Increase of the holding costs resulted in a decrease of the order up to level (S)
- Increasing the demand sizes resulted that the reorder level (s) and order up to level (S) increase
- Increasing the arrival period of the demand resulted that the reorder level (s) and the order up to level (S) decrease

For the above cases the decrease of the input variable was also analysed and resulted in an opposite effect as described above, which was expected.

With the simulation model verified, in the next section, the validation will be discussed.

7.2.2. Validation

Validation is to check whether the model is a good representation of the reality. In the ideal situation the control policy is used in the past and the performance (i.e. service level and costs) is measured. The simulation results can then be compared with the historical data. Since the inventory control policy used in the models is not yet used in practice, it is not possible to compare the model output with real output. Therefore the following steps are taken:
The generated demand seeds are validated by a maintenance engineer. Validation meetings were performed in 05.2016. There, the maintenance engineer determined whether a demand seed may represent an actual demand pattern for Vlisco. Here, the maintenance engineer determined that the generated demand seeds were valid.

Created demand seeds are checked with the source data. A statistical test is used to check if the source data (i.e. historical demand data of Vlisco) and the proposed future demand by the model, originate from the same distribution.

The model was used for 5 spare parts and the behaviour of the model (e.g. when a replenishment order is placed, the arrival of the replenishment order, demand that is backordered) was discussed. Based on the events the maintenance engineer concluded that it behaves as it would in reality.

Now is concluded that the model is valid, the simulation run length and number of runs will be discussed in the following sections.

7.3. Determining the optimal s level
Within this paragraph is explained how the optimal s level is determined based on several runs and why several runs are used.

7.3.1. Determining the number of runs
Via a simulation run the optimal reorder value (s) is determined. A simulation run generates demand from a demand distribution which is determined based on the historical demand of Vlisco. The generated demand (called demand seed) is, however, unique. For a second run the demand occurrences occur at different moments with difference demand sizes, but to according the same demand distribution as the first run. Therefore, a second run provides a new and independent value for s. Conclusively, a run can be seen a scenario of demand occurrences which is simulated to determine the optimal re-order level s. This continues until a total of n runs all of which are identically distributed with a value for s are collected. The question arises then; how many runs should the simulation create to determine the optimal re-order level s?

Depending on the differences in the demand seeds (e.g. length of 0 demand or high demand instances) different runs test the robustness of re-order levels s. For example, if for a certain spare-part a re-order level of 5 is optimal for 99 out of 100 runs, it could be concluded that s = 5 is robust. However, whether 100 runs are sufficient to draw this conclusion depends the degree to which each run different from another.

The degree to which each run differs from another depends on the variance in the independent demand seeds which is caused by variance in the demand distribution. Variance in the demand distribution is caused by the demand size and the arrival of the demand, resulting into 4 different demand patterns: demand categories; smooth, erratic, intermittent and lumpy (as discussed in chapter 4.3).
To determine the required number of runs extreme values of the 4 demand patterns are used (e.g. highly lumpy demand). This to ensure the model is robust in the most extreme cases. For each of these 4 patterns, simulations consisting of 50 to 500 runs were executed. Each simulation is compared to each other by comparing the distribution of the optimal re-order level \( s \). See for example Figure 21 where simulations of 10 runs and 200 runs were executed for a spare-part with an erratic demand history.

![Distribution of optimal s levels](image)

Figure 21 Example of optimal re-order level s distribution for simulation with different amounts of runs

Figure 21 shows that the distributions of the optimal s levels differ. 10 runs does not cover all possible scenarios for a spare part with a lumpy demand. To determine when this difference is too big, a statistical test is used called the Pearson’s Chi-Square test. The chi-square test operates according to the following hypothesis:

\[
H_0: \text{Data sets A and B are identical distributed} \\
H_1: \text{Data sets A and B not identical distributed}
\]

Whenever the test is significant, \( H_0 \) is rejected and thus the two distributions are not the same. The cut-off value to determine when to reject \( H_0 \) is called the p-value for which is chosen a value of .9, i.e. whenever test results in a p-value <0.9, the compared distribution do not match. With a cut off value of .9 (i.e. 90%), there is a probability of 10% of obtaining a deviation at least as extreme shown by the compared data sets. For an extensive explanation of the Pearson’s Chi-Square test see Appendix F. With the test the minimum number of runs have been determined for all types of demand (an extensive explanation is given in Appendix N). The results are shown in Table 6.

Table 6 Required number of runs for each demand category

<table>
<thead>
<tr>
<th>Demand</th>
<th>Number of runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>300</td>
</tr>
<tr>
<td>Erratic</td>
<td>500</td>
</tr>
<tr>
<td>Intermittent</td>
<td>300</td>
</tr>
<tr>
<td>Lumpy</td>
<td>500</td>
</tr>
</tbody>
</table>
7.3.2. Selecting the optimal $s$ level

With the number of runs determined, the optimal re-order level $s$ can be selected. As already shown in the previous section, a simulation which consist out of a number of runs will report multiple optimal $s$ levels. In Table 7, the results for a spare part with smooth demand are shown (part 51.50696).

<table>
<thead>
<tr>
<th>$s$</th>
<th># runs</th>
<th>Cumulative # runs</th>
<th>Share of runs service constraint met</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.00</td>
<td>1</td>
<td>1</td>
<td>0.002</td>
</tr>
<tr>
<td>3.00</td>
<td>42</td>
<td>43</td>
<td>0.086</td>
</tr>
<tr>
<td>4.00</td>
<td>164</td>
<td>207</td>
<td>0.414</td>
</tr>
<tr>
<td>5.00</td>
<td>173</td>
<td>380</td>
<td>0.76</td>
</tr>
<tr>
<td>6.00</td>
<td>87</td>
<td>467</td>
<td>0.934</td>
</tr>
<tr>
<td>7.00</td>
<td>23</td>
<td>490</td>
<td>0.98</td>
</tr>
<tr>
<td>8.00</td>
<td>7</td>
<td>497</td>
<td>0.994</td>
</tr>
<tr>
<td>9.00</td>
<td>2</td>
<td>499</td>
<td>0.998</td>
</tr>
<tr>
<td>10.00</td>
<td>1</td>
<td>500</td>
<td>1</td>
</tr>
</tbody>
</table>

From the table can be seen that a reorder level of 7 is optimal in 23 runs. Selecting a $s$ level of 7 would be successful 98% of the runs in terms of abiding the service constraint. Which $s$ levels to select, based on this information depends on the risk Vlisco wants to take. As can be seen from the table, the higher the $s$ level, the higher the probability that the service constraint can be met. Comparing $s$ levels 7 up to 10 can be interesting, since there can possibly be a saving in the total relevant costs. Calculating the total relevant costs for each of the 500 demand seeds used to determine the optimal $s$ level shown in Table 7 gives insight in the expected total relevant costs over 500 scenarios. For $s$ level 7 up to 10 the costs per year are shown in Table 8.

<table>
<thead>
<tr>
<th>$s$</th>
<th>HC</th>
<th>RC</th>
<th>BC</th>
<th>TRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>€ 435,70</td>
<td>€ 114,59</td>
<td>€ 2.323,20</td>
<td>€ 2.873,49</td>
</tr>
<tr>
<td>8</td>
<td>€ 477,30</td>
<td>€ 114,79</td>
<td>€ 739,20</td>
<td>€ 1.331,29</td>
</tr>
<tr>
<td>9</td>
<td>€ 519,07</td>
<td>€ 115,03</td>
<td>€ 49,03</td>
<td>€ 683,12</td>
</tr>
<tr>
<td>10</td>
<td>€ 560,98</td>
<td>€ 115,32</td>
<td>-</td>
<td>€ 676,30</td>
</tr>
</tbody>
</table>

It can be concluded that the increase of $s$ level 7 to 10 is beneficial due to the lower total relevant cost. The difference is caused by the backordering costs which are lower for the 500 runs with re-order level 10.

7.4. Chapter conclusion

In this chapter the required extra input variables for a simulation model were determined. It was concluded that the model was valid. Further was determined that the required number of simulations runs to give a stable result was determined to be 500 runs and a method was developed to select the optimal reorder level from these 500 runs.
8. Classification

This chapter gives answer to the research question “How can the method of Vlisco for classifying its spare parts be improved and is it necessary?” In the following paragraphs classification at Vlisco is described, the criteria for classification according to literature are and how these should be applied at Vlisco.

8.1. Current classification at Vlisco

Vlisco differentiates its spare parts in different classes and manage its stocks based on these classes. Vlisco acknowledges three spare part classes;

- floor stocks; can be picked without individually scanning the items one by one (e.g. bolts, nuts, seals)
- repairables; parts that are technically and economically repairable (Fortuin and Martin, 1999)
- non-repairables or consumables; parts that are discarded after replacement (Fortuin and Martin, 1999)

The inventory of the floor stocks is each week replenished by a supplier, which is also responsible for the determination of the level of the inventory. Maintenance engineers are responsible for the inventory of repairable and consumables.

8.2. Spare part classification criteria

Classification of the spare parts should need to be executed on the characteristics of the spare parts that have an effect on the design of the inventory control system of these parts, hence the control characteristics (Huiskonen, 2001). According to Huiskonen (2001) the control characteristics are:

(i) **Criticality**: defined by the consequences caused by the failure of a part on the process in case a replacement is not readily available
(ii) **Demand pattern**: describes the arrival time and the volume of the demand of a spare part
(iii) **The value of a part**: its acquisition price.

To align the different combinations of characteristics with the different policies (and models), homogenous groups need to be created, hence classification (Macchi et al., 2011). This way classes are created for which a specific inventory control policy and model can be applied.

8.3. Classification not needed at Vlisco

The question that arises is thus whether one of these characteristics has an effect on the design of the inventory control system of spare parts at Vlisco and whether there is a need for homogenous groups. In chapter 4.3 is described that Vlisco has different demand patterns (smooth, erratic, intermittent, lumpy) and concluded that no cyclic and trend pattern exists. Since one inventory control policy and model will be used to cope with these demand patterns, there is no need for classification. Criticality is similar as the unavailability costs (defined in chapter 4.2.1 and the value of a part is used to determine the holding cost, these characteristics are thus taken into account and therefore do not affect the design of the inventory control system.

With these premises can be concluded that within the current design there is no need for a classification that results into homogenous groups with different policies and models. The current classification is thus also not necessary for the objective the inventory control system is developed, namely determine optimal parameter values. Nevertheless when parts are treated differently for a different purpose the classification should be maintained.
However if in the future, demand is encountered with cyclic and/or trend pattern, the current inventory control system needs to be adjusted since it is not able to cope with these patterns. Additionally, if in the coming years is decided to incorporate a delay time for intermittent and lumpy demand, a new policy should be created. Both changes could result in the need for classification and should be considered in due time.

8.4. Chapter conclusion
In this chapter answer has been given to research question 4. Classification is deemed unnecessary for Vlisco. The inventory control policy and (calculation) model covers the current variability in spare part characteristics/classes.
9. Order of analysis

Vlisco has a large number of spare-parts (circa 6000) currently on stock with a net worth of €6 million and an unknown amount of spare parts not on stock that could imply a risk in terms of high downtimes, however time and economic resources are insufficient to analyse them all within a short time-span (e.g. < 1 year). Hence the order of analysis is key to be as efficient as possible; in terms of reduced risks and costs savings. In this chapter the research question: “How can spare parts be selected for analysis and what are the risks?” is therefore answered. First the criteria to determine the order of analysis are clarified and finally how the order of analysis is determined at Vlisco is explained.

9.1. Criteria for order of analysis

To be as efficient as possible, the efforts and resources need to be directed to the parts that result to the highest results. The objective is to minimize total relevant costs given the service constraint (maximum machine waiting time). Results are therefore measured in reduced costs, increased service where the required service is not met and also reduced risk of downtime (costs) for parts that are not on stock or have insufficient inventory. Selecting a part should thus lead to the highest effect on the element just mentioned. Possible criteria to determine an order of analysis are:

- Deviation from the current performance of the inventory compared with the required service level
- Caused downtime (costs) of parts; since downtime is costly it very likely that a higher inventory will result to reduced total relevant costs.

In the next paragraph is explained how these criteria can be used at Vlisco to determine the order of analysis of the spare parts.

9.2. Order of analysis for Vlisco

Important for the use of these criteria is the availability of data. Unfortunately Vlisco does not register the performance of the inventory of each part or the downtime caused by not having a part on stock. Consequence is that none of these criteria can be used to determine the order of analysis and there is no most efficient way to analyse the parts. Nevertheless when the analysis of the machines is started, the highest downtime cost of the parts will become available one by one. The order this information becomes available in phase 2 of determining the downtime costs will thus dictate the order of analysis.

9.3. Chapter conclusion

In this chapter is concluded that with the available information at Vlisco, there is no opportunity to execute the order of analysing the spare parts as efficient as possible. However when the machines are analysed in phase 2 of determining the downtime costs the order of analysis is dictated by the order the highest downtime costs become available.
10. Inventory policy reconsideration trigger

The inventory control system has to be reconsidered as the environment wherein it operates is subjected to change (e.g. holding cost increase, lead times become longer, a new machine is bought). Further a reconsideration of control parameters is required when service targets are not met. This chapter answers the research question; “When should the inventory controls system of Vlisco be reconsidered?” To determine the triggers that are subjected to change a sensitivity analysis is executed. Varying the input parameters (e.g. holding cost, replenishment costs, downtime costs, lead times) will show the subsequent effect and thus gives insight in the most influential parameters of the inventory control system. The most influential parameters can thus be used as to determine the trigger to reconsider the inventory control system. Only one variable is varied at the time to determine its effect.

10.1. Service level

Within this paragraph the influence of the change in service level is discussed. For this sensitivity analysis spare part 51.10006 is used as example, the input values are shown in Table 9.

<table>
<thead>
<tr>
<th>Service measure</th>
<th>Replenishment costs</th>
<th>Holding costs</th>
<th>Backorder costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum waiting time (Wmax)</td>
<td>Fixed price per order (A)</td>
<td>€ 59.12</td>
<td></td>
</tr>
<tr>
<td>Min probability (Pmin)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delivery</td>
<td>Spare part price (v)</td>
<td>€ 18.79</td>
<td></td>
</tr>
<tr>
<td>Delivery lead time (LT)</td>
<td>Carrying charge (h)</td>
<td>0.000815 €/€/day</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>Backorder costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length run</td>
<td>Shutdown time (SDT)</td>
</tr>
<tr>
<td>Initial inventor on hand (IOH)</td>
<td>Mean Time to Repair (MTTR)</td>
</tr>
<tr>
<td></td>
<td>Setup time (ST)</td>
</tr>
<tr>
<td></td>
<td>Non-consequential downtime (NCDT)</td>
</tr>
<tr>
<td></td>
<td>Cost rate (C)</td>
</tr>
</tbody>
</table>

Since the service measure is influenced by the maximum machine waiting time and the probability the order is delivered within this time window the influences of changing both variables is analysed. In both cases an intermittent part is used and other variables are kept constant. The order up to level is determined by s+Q and Q is not dependent on the service level, therefore only the reorder level is discussed.

10.1.1. Minimum probability

Figure 22 shows that increasing the minimum probability of the waiting time results into an increase of the reorder level (s). This outcome itself is not shocking, but it gives insight in that if Vlisco wants to protect itself against the extremes (exceptional high demand during the risk period) the reorder level is increased rapidly. To cover the last 5% (from .95 to 1) the reorder level increases from 3 to 8 parts. When unavailability costs are high, as in the case of Vlisco, having high inventory levels could be justified as once not being able to fulfil a machine order will result to high costs.
10.1.2. Machine waiting time
In Figure 23 is shown that increasing the maximum machine waiting time from 0 days to 4 days will lower the reorder level (s) with 3 parts. The effect of changing the machine waiting time is thus not as severe as the required probability. However when the machine waiting time is equal to the risk period, which is in this example 10 days ($R = 7$ and $LT = 3$ days), the reorder level drops to 0 parts. This happens, because during the risk period, inventory should protect against variability of the demand, since the maximum machine waiting time is equal to this period no safety inventory is needed.

10.2. Risk period
This paragraph investigates the impact of changing the risk period. Since the risk period consist out of the review period and the delivery lead time, the impact of both is considered. The order op to level is determined by $s+Q$ and $Q$ is not dependent on the risk period, therefore only the reorder level is discussed.

10.2.1. Review period
Vlisco uses at the moment a review period of 7 days, therefore the impact of a bigger and smaller review period is determined. In Figure 24 Influence of the review period (R) Figure 24 is shown that increasing the review period will result in a higher reorder level. The impact is not severe; once the period is increased to 9 days the reorder level increases to 11 parts, which remains 11 parts when the review period is increased to 11 and 13 days. Decreasing the review period does not even result lower reorder level.
10.2.2. Delivery lead time influence
The impact of changing the delivery lead time is demonstrated in this paragraph. The part used has a delivery time of 3 days. Figure 25 shows that changing the delivery lead time will cause the reorder level to shift.

10.3. Costs influence
The impact of each element of the total relevant costs is discussed in this paragraph.

10.3.1. Holding costs
Holding costs exists out of carrying charge and the spare pare price, both are considered. Varying the carrying charge (holding costs) has a big impact on the control parameter values, which is shown in Table 10. It can be concluded that increasing the carrying charge will result into a decrease of the order op to level but an increase in the reorder level. The effect of decreasing the carrying charge is vice versa.

<table>
<thead>
<tr>
<th>$h$</th>
<th>$s$</th>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>30%</td>
<td>8</td>
<td>22</td>
</tr>
<tr>
<td>50%</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>70%</td>
<td>10</td>
<td>19</td>
</tr>
</tbody>
</table>
10.3.2. Replenishment costs
Changing the fixed order costs results that control parameter values shift, which is visible in Table 11. Increasing the fixed order cost has as effect that the order up to level increases, however the effect on the reorder level is marginal. When the costs are decreased, the order up to level is decreased as well.

Table 11 Influence of fixed order costs

<table>
<thead>
<tr>
<th>Change</th>
<th>( A )</th>
<th>( s )</th>
<th>( S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50%</td>
<td>€ 29.56</td>
<td>9</td>
<td>19</td>
</tr>
<tr>
<td>-25%</td>
<td>€ 44.34</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>0%</td>
<td>€ 59.12</td>
<td>8</td>
<td>22</td>
</tr>
<tr>
<td>25%</td>
<td>€ 73.90</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>50%</td>
<td>€ 88.68</td>
<td>9</td>
<td>26</td>
</tr>
</tbody>
</table>

10.3.3. Unavailability costs
The influence of unavailability costs is of great interest, since in chapter 4.2.1 and 5 a time consuming method is explained how to compute these costs. In this chapter is shown that it is beneficial to determine these costs with the explained method rather than with a rough estimation. As a reminder; unavailability costs are in the case of Vlisco downtime costs, which consist out of the following elements:
- Non-consequential downtime (NCDT)
- Cost rate (\( C \))
- Total failure effect (TFE)
- Time elements
  - Setup time (ST)
  - Shutdown time (STD)
  - Delivery lead time (LT)
  - Mean Time To Repair (MTTR)

Each of these elements will be discussed below. Total failure effect is similar as reducing the cost rate with the same percentage, thus these effects are tested simultaneously. A part is chosen that resembles the average part at Vlisco, in means of demand pattern and delivery time (92.6% is intermittent and 40% has delivery time <5 days). The price of the part is altered such that several scenarios are tested, since price influences the holding costs. In the table below the details of the part are shown.

Table 12 Input parameters part 5110006

<table>
<thead>
<tr>
<th>Service measure</th>
<th>Replenishment costs</th>
<th>Holding costs</th>
<th>Backorder costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum waiting time (Wmax)</td>
<td>Fixed price per order (( A ))</td>
<td>Spare part price (( v ))</td>
<td>Shutdown time (SDT)</td>
</tr>
<tr>
<td>Min probability (Pmin)</td>
<td>€ 59.12</td>
<td>€ 18.79</td>
<td>12 hours</td>
</tr>
<tr>
<td>Delivery</td>
<td></td>
<td>Carrying charge (( h ))</td>
<td>Mean Time to Repair (MTTR)</td>
</tr>
<tr>
<td>Delivery lead time (LT)</td>
<td></td>
<td>0.000815 €/€/day</td>
<td>6 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Setup time (ST)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non-consequential downtime (NCDT)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cost rate (( C ))</td>
</tr>
<tr>
<td>Simulation parameters</td>
<td></td>
<td></td>
<td>€ 11,000 per hour</td>
</tr>
<tr>
<td>Length run</td>
<td>35 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial inventory on hand (IOH)</td>
<td>8 units</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
10.3.3.1. Non-consequential downtime

It was explained that the non-consequential downtime is the time before the downtime of a part and machine will cause costs. The cost rate \((C)\) at Vlisco varies from €600 up to €11000 per hour, these big differences can influence the selection of the parameter values and therefore 3 values are used to create scenarios. The different scenarios that are used to test the sensitivity are shown in Table 13.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Price ((v))</th>
<th>Cost rate ((C))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>€11,000</td>
<td>€95.11</td>
</tr>
<tr>
<td>2</td>
<td>€11,000</td>
<td>€1,000</td>
</tr>
<tr>
<td>3</td>
<td>€11,000</td>
<td>€5,000</td>
</tr>
<tr>
<td>4</td>
<td>€6,100</td>
<td>€95.11</td>
</tr>
<tr>
<td>5</td>
<td>€6,100</td>
<td>€1,000</td>
</tr>
<tr>
<td>6</td>
<td>€6,100</td>
<td>€5,000</td>
</tr>
<tr>
<td>7</td>
<td>€1,200</td>
<td>€95.11</td>
</tr>
<tr>
<td>8</td>
<td>€1,200</td>
<td>€1,000</td>
</tr>
<tr>
<td>9</td>
<td>€1,200</td>
<td>€5,000</td>
</tr>
</tbody>
</table>

The assumption is taken that initially no non-consequential downtime is determined and the NCDT and the maximum machine waiting time are set to 0. For each scenario therefore the NCDT (and maximum machine waiting time) is increased until a deviation takes place in the reorder level \((s)\), hence costs can be saved. In Table 14 the results are shown, the total relevant costs are given in euros per year and the capital on stock is the average inventory on stock in euros.

For example in scenario 1 where the price of the spare part is €95.11 and the cost rate is €11000 euros per hour he results show that not estimating or being too strict for the NCDT results into higher total relevant costs and more capital on stock. When the NCDT is actually 144 hours the total relevant costs are 13.8% too high and 23.7% too much capital is kept on stock since the wrong reorder level is selected. The other 2 scenarios show a similar result. Scenarios 4 up to 9 show also that when the NCDT is not correctly estimated a wrong reorder level is selected and , which results into that the total relevant costs are too high and there is too much capital kept on stock (Appendix O).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NCDT</th>
<th>TRC</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>€309.44</td>
<td>4.4%</td>
<td>€1,045.60</td>
<td>11.8%</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
<td>€295.83</td>
<td>13.8%</td>
<td>€797.92</td>
<td>23.7%</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>144</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>€3,101.37</td>
<td>2.3%</td>
<td>€8,310.64</td>
<td>15.6%</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>96</td>
<td>€2,053.44</td>
<td>27.8%</td>
<td>€5,716.93</td>
<td>31.2%</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>216</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>€8,520.09</td>
<td>4.4%</td>
<td>€31,582.51</td>
<td>11.8%</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>96</td>
<td></td>
<td></td>
<td></td>
<td>15.6%</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>216</td>
<td></td>
<td></td>
<td></td>
<td>31.2%</td>
<td>3</td>
</tr>
</tbody>
</table>
With these results can be concluded that independently of the spare part price and the cost rate not correctly estimating the NCDT will result into higher costs and unnecessary capital locked up in inventory. A NCDT of 144 hours seems unrealistic, however for example spreader rollers can be used for approximately 7 days (168 hours) without affecting production. Besides within these scenarios extreme values are used for the shutdown time, setup time and the MTTR.

10.3.3.2. Cost rate
The sensitivity of the cost rate is tested for 3 scenarios which are shown in Table 15.

Table 15 Scenarios to test sensitivity cost rate

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>€ 95,11</td>
</tr>
<tr>
<td>2</td>
<td>€ 1,000,00</td>
</tr>
<tr>
<td>3</td>
<td>€ 5,000,00</td>
</tr>
</tbody>
</table>

For these scenarios the cost rate is varied from €600 up to €11000. Table 16 shows the results for scenario 1. When initially a cost rate of €11000 per hour is used, there is no difference in the selected reorder level when the cost rate is in reality €6100 or €1200 per hour. In case the cost rate is in reality €600 per hour, the reorder level is estimated to high, with as consequence that the total relevant cost are 3.4% to high and there is 11.8% more capital on stock than necessary.

Table 16 Results influence cost rate (scenario 1)

<table>
<thead>
<tr>
<th>C</th>
<th>TRC</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>€ 11,000</td>
<td>€ 309.44</td>
<td>€ 806.77</td>
<td>0.0%</td>
<td>5</td>
</tr>
<tr>
<td>Optimal</td>
<td>€ 6,100</td>
<td>€ 309.44</td>
<td>0.0%</td>
<td>€ 806.77</td>
<td>0.0%</td>
</tr>
<tr>
<td>Optimal</td>
<td>€ 1,200</td>
<td>€ 309.44</td>
<td>0.0%</td>
<td>€ 806.77</td>
<td>0.0%</td>
</tr>
<tr>
<td>Optimal</td>
<td>€ 600</td>
<td>€ 298.76</td>
<td>-3.4%</td>
<td>€ 711.79</td>
<td>-11.8%</td>
</tr>
<tr>
<td>Wrong</td>
<td>€ 600</td>
<td>€ 309.44</td>
<td>3.4%</td>
<td>€ 806.77</td>
<td>11.8%</td>
</tr>
</tbody>
</table>

In scenario 2 (Table 17) the effects of using a wrong cost rate result into a higher total relevant costs and more capital on stock than necessary for each of the tested cost rate.

Table 17 Results influence cost rate (scenario 2)

<table>
<thead>
<tr>
<th>C</th>
<th>TRC</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>€ 11,000</td>
<td>€ 2,100.65</td>
<td>€ 6,409.88</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Optimal</td>
<td>€ 6,100</td>
<td>€ 2,071.79</td>
<td>-1.4%</td>
<td>€ 5,411.36</td>
<td>-15.6%</td>
</tr>
<tr>
<td>Wrong</td>
<td>€ 6,100</td>
<td>€ 2,100.65</td>
<td>1.4%</td>
<td>€ 6,409.88</td>
<td>15.6%</td>
</tr>
<tr>
<td>Optimal</td>
<td>€ 1,200</td>
<td>€ 1,856.19</td>
<td>-11.6%</td>
<td>€ 5,411.36</td>
<td>-15.6%</td>
</tr>
<tr>
<td>Wrong</td>
<td>€ 1,200</td>
<td>€ 2,100.65</td>
<td>11.6%</td>
<td>€ 6,409.88</td>
<td>15.6%</td>
</tr>
<tr>
<td>Optimal</td>
<td>€ 600</td>
<td>€ 1,814.76</td>
<td>-13.6%</td>
<td>€ 4,407.74</td>
<td>-31.2%</td>
</tr>
<tr>
<td>Wrong</td>
<td>€ 600</td>
<td>€ 2,100.65</td>
<td>13.6%</td>
<td>€ 6,409.88</td>
<td>31.2%</td>
</tr>
</tbody>
</table>
Scenario 3 shows similar results (Appendix O). Based on these results can be concluded that using a different cost rate than the real cost rate can result into higher costs and capital that is unnecessary locked up in inventory.

10.3.3.3. Time elements
The sensitivity of the time elements, shutdown time, mean time to repair and setup time is tested for 3 scenarios which are shown in Table 21.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>C</th>
<th>Price</th>
<th>95,11</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>€ 1200</td>
<td>€ 95,11</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>€ 6100</td>
<td>€ 95,11</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>€ 11000</td>
<td>€ 95,11</td>
<td></td>
</tr>
</tbody>
</table>

For these scenarios the sum of the shutdown time, MTTR and setup time is varied from 1 up to 30 hours. Table 19 shows the results for scenario 1. For example when initially the time is estimated to be 30 hours, but in reality the total time is only 1 hour the reorder level is 1 too high. The results are that the total relevant costs and capital on stock are respectively 2.8% and 11.9% too high. In the 2 other scenarios no effect is measured.

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Optimal</th>
<th>Initial</th>
<th>€ 309.44</th>
<th>€ 806.77</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD+MTTR+ST</td>
<td>TRC</td>
<td></td>
<td></td>
<td></td>
<td>2.8%</td>
<td>€ 711.04</td>
<td>-11.9%</td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Optimal</td>
<td>Initial</td>
<td>€ 309.44</td>
<td>€ 806.77</td>
<td>0.0%</td>
<td>€ 806.77</td>
<td>0.0%</td>
<td>4</td>
</tr>
</tbody>
</table>

The impact of the time elements is present, however the effect seems to only present with extreme cases (e.g. STD+MTTR+ST=30 vs 1).

10.4. Chapter conclusion
Various input variables have been tested for their effect on the selection of the control parameter values. It has been shown that changes in each variable could lead to a shift of at least one of the control parameter values and also a deviation of total relevant costs and capital on stock. However the results are not exhaustive, whether a shift of a parameter value will occur is determined by the combination of the different variables. The developed method therefore allows to check whether a change of an input variable results into a different parameter value. This chapter gives an insight what the impact is of using wrong data and emphasizes the fact that knowing the exact location and the failure behaviour of a part are required to determine the correct s and S level.
11. Results
In this chapter the results of applying the methods developed in this master thesis will be shown. First the optimal parameter values are selected, next a comparison is made with the current situation at Vlisco. Finally the policy of Vlisco to only keep inventory for corrective maintenance is reconsidered.

11.1. Determining the parameter values
In this section the optimal parameter values are selected based on the methods explained in chapter 6.4. 5 parts are selected with varying demand patterns, prices and delivery time. Since the locations of the spare parts within the machines are not known the maximum time a machine can wait for a part and the downtime costs are also unknown. The required service measure is therefore set on a maximum waiting time of 0 days with a probability of 0.95 and the most extreme downtime costs is used for each of these parts. These input parameters are shown in Table 20.

<table>
<thead>
<tr>
<th>Service measure</th>
<th>Backorder costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum waiting time (Wmax)</td>
<td>Shutdown time (SDT)</td>
</tr>
<tr>
<td>Min probability (Pmin)</td>
<td>Mean Time to Repair (MTTR)</td>
</tr>
<tr>
<td></td>
<td>Setup time (ST)</td>
</tr>
<tr>
<td>Simulation parameters</td>
<td>Non-consequential downtime (NCDT)</td>
</tr>
<tr>
<td></td>
<td>Cost rate (C)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-consequential downtime (NCDT)</th>
<th>Cost rate (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 hours</td>
<td>€ 11,000 per hour</td>
</tr>
</tbody>
</table>

Replenishment costs
Fixed price per order (A) € 59.12

Part specific variables; spare part price (\(v\)), delivery time (\(LT\)) and the inventory position (\(IP\)) are shown in Table 21.

<table>
<thead>
<tr>
<th>Part</th>
<th>Name</th>
<th>Demand pattern</th>
<th>Price ((v))</th>
<th>Delivery Time</th>
<th>(IP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>511006</td>
<td>GROEFOGELLAGER SMT SS 6004 ZZ</td>
<td>Intermittent</td>
<td>€ 18.79</td>
<td>3 days</td>
<td>15</td>
</tr>
<tr>
<td>5110955</td>
<td>KLIP VOOR SPR19</td>
<td>Intermittent</td>
<td>€ 12.00</td>
<td>7 days</td>
<td>37</td>
</tr>
<tr>
<td>5111385</td>
<td>BOOGWALS STOWE WOODW. 1535MM</td>
<td>Intermittent</td>
<td>€ 1,000.00</td>
<td>50 days</td>
<td>6</td>
</tr>
<tr>
<td>5111929</td>
<td>PAKKINGRING SIGRAFLEX DN25</td>
<td>Intermittent</td>
<td>€ 1.24</td>
<td>2 days</td>
<td>10</td>
</tr>
<tr>
<td>5150696</td>
<td>SPREIDER. ART.27701480</td>
<td>Smooth</td>
<td>€ 140.00</td>
<td>14 days</td>
<td>10</td>
</tr>
</tbody>
</table>

The results of the determination of the parameter values are shown in Table 22. The parameters to be determined are the reorder level (\(s\)), the order op to level (\(S\)). For every part the review period is determined by the situation at Vlisco which is 4 days (\(R = 4\)). The total relevant costs are given in euros per year and the capital on stock is the average inventory on stock in euros.
Table 22 Results of optimal parameter values

<table>
<thead>
<tr>
<th>Part</th>
<th>Name</th>
<th>s</th>
<th>S</th>
<th>(P(W \leq W_{\text{max}}))</th>
<th>TRC</th>
<th>Capital on stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>5110006</td>
<td>GROEFKOGELLAGER SMT SS 6004 ZZ</td>
<td>8</td>
<td>22</td>
<td>1</td>
<td>€122.45</td>
<td>€297.49</td>
</tr>
<tr>
<td>5110955</td>
<td>KLIP VOOR SPR19</td>
<td>8</td>
<td>22</td>
<td>1</td>
<td>€73.68</td>
<td>€218.24</td>
</tr>
<tr>
<td>5111385</td>
<td>BOOGSVALS STOWE WOODW. 1535MM-</td>
<td>6</td>
<td>8</td>
<td>1</td>
<td>€4,991.39</td>
<td>€16,379.42</td>
</tr>
<tr>
<td>5111929</td>
<td>PAKKINGRING SIGRAFLEX DN25</td>
<td>6</td>
<td>58</td>
<td>1</td>
<td>€22.10</td>
<td>€40.95</td>
</tr>
<tr>
<td>5150696</td>
<td>SPREIDER. ART.277014B0</td>
<td>10</td>
<td>17</td>
<td>1</td>
<td>€636.59</td>
<td>€1,748.29</td>
</tr>
</tbody>
</table>

\(P(W \leq w)\) = probability that waiting time is smaller or equal to the maximum machine waiting time

TRC = total relevant costs (€/year)

Capital on stock = average inventory on stock (€)

For example for part 5110006 (a bearing) the methods in chapter 6 and 7.1 suggest an economic order quantity \(Q\) of 14 units and an optimal \(s\) level of 8 units. The order up to level is given by \(S = s + Q\), resulting that \(S = 22\). Control parameters for part 5110006 are therefore \(R = 4\), \(s = 8\) and \(S = 22\) with an expected total relevant costs of €122.45 each year and on average for €297.49 of parts are on stock.

11.2. Comparison with current policy Vlisco

In the introduction was already mentioned that Vlisco does not use a structured method is to determine when to order and how much. In the system used by Vlisco a reorder level is entered and an order quantity, thus a \((R, s, Q)\) policy. When the inventory position is below or equal the reorder level, the system gives a replenishment suggestion. However, in practice this advice is almost never followed, different quantity is ordered or replenishments are initiated earlier. To still make a comparison possible, the entered reorder point and order quantity are used and compared with the suggested parameter values and results in the previous paragraph.

In Table 23 the results are shown. First the policy and suggested parameter values based on the methods described in chapter 6.4 are given with the related results. Next the policy and parameter values used by Vlisco are depicted with the related results. In green the policy is shown with the lowest total relevant costs. For example with spare part 5110955 using the new policy will result into a cost saving of 33% and a reduction of 43% of capital locked up on stock, while achieving the same performance (i.e. service measure). This is in correspondence with the goal of this research.

The other spare parts show a costs saving as well, however an increase of the inventory is needed. All cases show a discrepancy between the model used for the current policy of Vlisco and practice. The model shows backorder costs although in the introduction (paragraph 1.3.2) is clarified that Vlisco has no issues with downtime due to insufficient inventory. The causes of these discrepancies have been determined based on an interview with the maintenance manager at Vlisco. It became clear that the following events or deviations of the input variables explain the results:

1. The machine is still used although a part is defective (e.g. a spreader roller can be easily used for 6 days in a defective state)
2. An intermediate solution is used (e.g. a less well fitting packing is used temporary)
3. Demand data is not correctly booked by mechanics (e.g. preventive demand is booked as corrective demand)
4. A different part is used with the same function
5. Emergency shipments are used in extraordinary cases.

Point 1 and 2 have the effect that the non-consequential downtime becomes longer Sensitivity analysis showed that increasing the NCDT indeed will result into lower reorder
levels. Further point 3 has as result that demand is used for the determination of the parameter values, while in reality the demand has never been used for corrective maintenance. With as result a deviation of the required inventory level. During the sensitivity analysis is also clarified that using different values for the input variables than the reality will result into wrong conclusions. With point 4 and 5 Vlisco makes use of pooling effects, which has as result that less inventory is needed (The effect of pooling was explained in paragraph 3.1.). The relevance of each point depends on the specific spare part. Nevertheless each point has its influence on the results of the model, thus without knowing for example the NCDT the model is very strict and the inventory is higher than needed.

In brief; the developed framework optimizes the inventory based on the total relevant costs given a service constraint. Due to unavailability of data costs savings of only one part were determined which were equal to 33%. Vlisco should obtain the input data that corresponds with the actual situation such that the correct conclusions can be made.
Table 2: Comparison policy with policy Vlisco

<table>
<thead>
<tr>
<th>Part</th>
<th>Policy</th>
<th>HC</th>
<th>RC</th>
<th>BC</th>
<th>TRC</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5110955</td>
<td>(s=8,S=20)</td>
<td>1</td>
<td>€ 64.97</td>
<td>€ 8.71</td>
<td>-</td>
<td>€ 73.68</td>
<td>€ 218.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vlisco (s=10,Q=30)</td>
<td>1</td>
<td>€ 93.02</td>
<td>€ 4.71</td>
<td>-</td>
<td>€ 97.72</td>
<td>33% € 312.46</td>
<td>43%</td>
</tr>
<tr>
<td>5110006</td>
<td>(s=8,S=22)</td>
<td>1</td>
<td>€ 88.56</td>
<td>€ 33.88</td>
<td>-</td>
<td>€ 122.45</td>
<td>€ 297.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vlisco (s=2,Q=8)</td>
<td>0.971</td>
<td>€ 35.79</td>
<td>€ 60.35</td>
<td>€ 181,036.11</td>
<td>€ 181,132.26</td>
<td>1478% € 120.22</td>
<td>-60%</td>
</tr>
<tr>
<td>5150696</td>
<td>(s=10,S=17)</td>
<td>1</td>
<td>€ 520.46</td>
<td>€ 116.13</td>
<td>-</td>
<td>€ 636.59</td>
<td>€ 1,748.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vlisco (s=3,Q=2)</td>
<td>0.968</td>
<td>€ 188.02</td>
<td>€ 279.42</td>
<td>€ 2,601,844.46</td>
<td>€ 2,602,311.90</td>
<td>4086% € 631.58</td>
<td>-64%</td>
</tr>
<tr>
<td>5111929</td>
<td>(s=6,S=58)</td>
<td>1</td>
<td>€ 12.19</td>
<td>€ 9.92</td>
<td>-</td>
<td>€ 22.10</td>
<td>€ 40.95</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vlisco (s=5,Q=15)</td>
<td>0.998</td>
<td>€ 4.75</td>
<td>€ 32.01</td>
<td>€ 573.26</td>
<td>€ 610.01</td>
<td>2660% € 15.95</td>
<td>-61%</td>
</tr>
<tr>
<td>5111385</td>
<td>(s=6,S=8)</td>
<td>1</td>
<td>€ 4,876.15</td>
<td>€ 115.23</td>
<td>-</td>
<td>€ 4,991.39</td>
<td>€ 16,379.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vlisco (s=3,Q=6)</td>
<td>0.998</td>
<td>€ 1,763.71</td>
<td>€ 40.38</td>
<td>€ 33,369.60</td>
<td>€ 35,173.69</td>
<td>605% € 5,924.46</td>
<td>-64%</td>
</tr>
</tbody>
</table>
11.3. Keep inventory for preventive maintenance

Vlisco keeps only inventory for corrective maintenance and for preventive maintenance the parts are ordered as already was mentioned in the introduction (chapter 1.3.2). Since demand for both are registered by Vlisco the model gives the opportunity to compare if it is beneficial to also keep inventory for preventive demand. If inventory is kept for both demands the total relevant costs are determined based on the total demand. When only demand is kept for corrective demand, the total relevant cost is the sum of the total relevant cost of keeping inventory for corrective demand and the total relevant costs of the preventive demand which is only determined by the ordering costs (see equation 11.1).

\[
TRC_{\text{preventive}} = \text{expected number of orders} \times \text{fixed order costs} \quad (11.1)
\]

Thus when \( TRC_{\text{total}} > TRC_{\text{preventive}} + TRC_{\text{corrective}} \) inventory should be kept for both demands, otherwise demand should be kept only for corrective demand and preventive demand is ordered each time. The decision logic is shown in Figure 26.

For the all parts of the previous paragraph this decision logic is applied and the input parameters shown in Table 20 and Table 21 also apply to the total demand. The result of this comparison is shown in Table 24. When it is beneficial to keep inventory for the total demand the part is marked in green, else the part is marked in red. For example for part 51.10006 it is beneficial to keep inventory for the total demand since the costs are €224.83 per year versus €550.39 per year for keeping only inventory for corrective demand. This would mean a cost reduction of 144.80%. The capital on stock increases from €297.49 to €539.45. On the contrary for part 51.11385 it is not beneficial to keep inventory for the total demand, since the costs would increase with 60.43%. Vlisco should therefore always use the framework to compare the results of keeping inventory only for corrective demand or the total demand.
Table 24 Results determination inventory for only corrective demand or total demand

<table>
<thead>
<tr>
<th>Part</th>
<th>Demand</th>
<th>Policy (s,S)</th>
<th>TRC</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corrective</td>
<td>(8,22)</td>
<td>€ 122.45</td>
<td>€ 297.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preventive</td>
<td></td>
<td>€ 427.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5110006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€ 550.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total demand</td>
<td>(15,41)</td>
<td>€ 224.83</td>
<td>-144.80%</td>
<td>€ 539.45</td>
<td>44.85%</td>
</tr>
<tr>
<td></td>
<td>Corrective</td>
<td>(8,20)</td>
<td>€ 73.68</td>
<td>€ 218.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preventive</td>
<td></td>
<td>€ 82.88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5110955</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€ 156.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total demand</td>
<td>(18,38)</td>
<td>€ 134.65</td>
<td>-16.27%</td>
<td>€ 356.97</td>
<td>38.86%</td>
</tr>
<tr>
<td></td>
<td>Corrective</td>
<td>(6,8)</td>
<td>€ 4,991.39</td>
<td>€ 16,379.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preventive</td>
<td></td>
<td>€ 407.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5111385</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€ 5,398.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total demand</td>
<td>(19,22)</td>
<td>€ 13,643.37</td>
<td>60.43%</td>
<td>€ 45,210.94</td>
<td>63.77%</td>
</tr>
<tr>
<td></td>
<td>Corrective</td>
<td>(6,58)</td>
<td>€ 22.10</td>
<td>€ 40.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preventive</td>
<td></td>
<td>€ 524.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5111929</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€ 546.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total demand</td>
<td>(18,70)</td>
<td>€ 43.61</td>
<td>-1153.48%</td>
<td>€ 84.04</td>
<td>51.28%</td>
</tr>
<tr>
<td></td>
<td>Corrective</td>
<td>(10,17)</td>
<td>€ 636.59</td>
<td>€ 1,748.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Preventive</td>
<td></td>
<td>€ 98.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5150696</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€ 734.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total demand</td>
<td>(10,17)</td>
<td>€ 647.33</td>
<td>-13.53%</td>
<td>€ 1,737.20</td>
<td>-0.64%</td>
</tr>
</tbody>
</table>

11.4. Chapter conclusion

In this chapter the developed methods to determine the parameter values were applied. It was shown that for part 5110955 a cost saving can be achieved from 33% and a reduction of capital on stock of 43%. For other parts even higher cost savings can be made, because unavailability costs were prevented. Using the policy of Vlisco within the simulation model, unavailability costs would have been occurred. However in the introduction was explained that downtime of machines due to unavailability of parts does not or rarely occur at Vlisco. Discussion with the maintenance manager showed that this deviation is caused by the following events or wrongly entered input variables:

1. The machine is still used although a part is defective
2. An intermediate solution is used
3. A different part is used with the same function
4. Demand data is not correctly booked by mechanics
5. Emergency shipments

Conclusively, the developed framework optimizes the inventory based on the total relevant costs given a service constraint, however it is required that the correct input data is used. Further results showed that it is beneficial to consider keeping inventory for preventive and corrective demand, instead of only for corrective demand. The yearly cost due to keeping inventory for the combined demand can be reduced for 4 of the 5 parts, which resulted into a
reduction of total relevant costs varying from 13.53% up to 1153.48%. Vlisco should thus always use the framework to compare the costs.
12. Conclusions and recommendations
This last chapter is concluded how this research answers the research questions and whether the research objective is achieved. Further the recommendations and suggestions for further research for Vlisco are listed.

12.1. Answer to research objective
Three of the previous research questions contribute to realizing the research objective:

“Develop a framework determines the optimal policy parameter values such that total relevant costs are minimized given a service constraint”

A framework is developed that provides:
- methods to determine all total relevant costs
  - Holding costs
  - Replenishment costs
  - Unavailability costs (downtime costs)
- a service constraint in the form of a maximum machine waiting time
- tool that determines the optimal parameter values given the service constraint and minimizes the total relevant costs

Several parts were analysed. Since there is no insight at Vlisco how the current policy operates and exactly performs a comparison was troublesome. Nevertheless to make a comparison possible the policy entered within the ERP system (although rarely followed) is used for comparison. 1 part showed a cost saving of 33% and a reduction of inventory on capital of 43%. Other parts show a bigger cost saving but an increase of inventory to prevent unavailability costs, although in the introduction is mentioned that currently at Vlisco no costs are incurred due to insufficient inventory. This is in contraction with one and another. In discussion with the maintenance manager is concluded that this is caused because data is not available (e.g. NCDT) or unreliable data (wrongly registered demand).

On contrary a fair comparison between keeping inventory for corrective demand or corrective and preventive demand (total) is possible. The framework showed that the yearly cost can be reduced for 4 of the 5 parts by keeping inventory for the total demand instead of only for corrective demand. The cost reduction varied from 13.53% up to 1153.48%.

Given the premises can be concluded that the developed framework determines the optimal parameter values such that the total relevant costs are minimized and the service constraint is met. It is very important that all input variables correspond with the actual situation such that the correct conclusions can be made.

12.2. Answers to research questions
In this paragraph the answers to the research questions are given.

1) Which inventory control policies are realistic to be implemented at Vlisco?
   a) Which inventory control policies are available in literature?
   b) Which inventory control policies can be applied at Vlisco?
After analysing the literature and evaluating the several policies given the current situation at Vlisco, it was concluded that the \((R, s, S)\) policy was best to be implemented.

2) What is the context in which the inventory control policies must operate?
   a) With what service constraint should the spare part policy operate?
b) What are the relevant costs for spare parts management for Vlisco?

c) What demand patterns do the spare-parts at Vlisco exhibit?

Analysing the context wherein the inventory control policies of Vlisco it was concluded that a maximum machine waiting time is the best service measure for Vlisco. The total relevant costs consist of holding costs, replenishment costs and unavailability costs. Unavailability costs are not known at Vlisco and a method is developed to determine these costs in phases. Further it has been determined that the spare parts at Vlisco can be distinguished by 4 different demand patterns (i.e. smooth, erratic, intermittent and lumpy demand). With the premises the method how to determine the optimal policy parameter values can be determined.

3) How can Vlisco select the optimal inventory control policy parameter value for its spare parts?

a) What are the characteristics of the inventory system at Vlisco?

b) What methods exist in literature to determine the optimal inventory control policy parameter values that meet the characteristics of the inventory system at Vlisco?

After analysing the characteristics of the inventory system at Vlisco it was concluded that it was not yet mathematically solved in the literature. A simulation model was developed to determine the optimal inventory control policy parameter values based on the maximum machine waiting time and the total relevant costs (i.e. holding, replenishment and unavailability costs).

4) How can the method of Vlisco for classifying its spare parts be improved and is it necessary?

a) How does Vlisco currently classify its spare parts?

b) Which criteria are appropriate to classify spare parts according to literature?

The classification at Vlisco is evaluated based on the comparison with the criteria found by literature research. Classification is needed when different combinations of characteristics result into different policies (and models). It was concluded that no classification was needed, since the developed inventory model can cope with all characteristics that come with spare parts at Vlisco.

5) How can spare parts be selected for analysis?

Several criteria are considered to find an order of analysis, such that it is most efficient. It was concluded that due to data unavailability there was no possibility to make an efficient analysis. However, unavailability costs are determined based on phases as described in chapter 5. Within this method machines are analysed in a specific order such that the unavailability costs of a spare part becomes available as soon as it is encountered within a machine. Consequently the availability of these costs dictates the order of analysis of the spare parts.

6) When should the inventory controls system of Vlisco be reconsidered?

A sensitivity analysis showed that all input variables have a significant influence on the parameter values selection; i.e. a small alteration of the input value causes that at least one of the parameter values changes. All input variables are therefore considered as a trigger to update the control parameter values.

12.3. Academic relevance

In practice certain data is not always available. Within the literature downtime costs of spare parts are always given, however how these costs are determined is not clarified. This research provides a method how to determine the downtime costs for spare parts. To obtain all data in practice could take several years; therefore a separate method is developed to determine the downtime costs in several phases. With this the research makes the academic
inventory optimization methods accessible for users in practice. Further by applying these results into a framework that optimizes control parameters, academic knowledge is implemented in practice, which contributes to the body knowledge on this subject.

12.4. Recommendations for Vlisco

Based on the analysis and conclusions in the previous chapters recommendations are made. Some recommendations can only be applied after another recommendation is implemented, therefore this paragraph is separated into; recommendations restrained by the order of implementation and not restrained by the order of implementation.

12.4.1. Not restrained by the order of implementation

12.4.1.1. Change data registration

Scanners

In chapter 3.2.1 it was mentioned that the scanners in the warehouse used to monitor the inventory position are only updated at the end of the day, therefore is decided in chapter 6.1.1 decided to model the demand at daily level. The consequence is that only a maximum machine waiting time can be chosen in days not in hour, because the demand distribution is in days. Timely delivery is crucial, since downtime is very costly; a few hours can make the difference between high costs or no costs. Resulting that, for example when a machine has a non-consequential downtime of 12 hours a service level with maximum waiting time of 0 days will probably be used.

When the scanners register the exact timestamp of each machine order it becomes possible to define a maximum waiting time in hours. Resulting in a more accurate maximum waiting time can be used and thus the inventory can be further optimised. It is expected that the current scanners can do this after changing the update time in the system.

Pumps and rollers

Currently all pumps and rollers have a unique identification number. These numbers are assigned such that the history of a specific pump can be tracked, namely where was the part installed. However during the analysis it appeared that not every movement of a pump was registered or that the location of the pump was not correctly registered. Consequence is that it was impossible to determine the demand distribution of a specific type of pump or roller and thus no suggestion can be made for the inventory control parameters. Vlisco should stress its employees that it is important to correctly register all movements of these parts. Further a group code should be assigned to pumps and rollers or the same type, such that the demand pattern can be easily determined. By added a single field in the info chart of the parts, this recommendation can be implemented.

12.4.1.2. Make an unambiguous definition of preventive and corrective demand

During the analysis of the demand became clear that some maintenance employees have a different definition of preventive and corrective demand. Since Vlisco has the policy to maintain only inventory for corrective maintenance thus how the demand is identified can have a great effect on the demand pattern and therefore also on the inventory, this effect was identified with comparing the results in chapter 11.2. 2 situations this issue applies to:

1) When corrective maintenance is executed and a different part is encountered which is expected to fail in the near future and this part is replaced. This replacement can be seen as opportunistic preventive maintenance; however depending on the employee the demand is registered as corrective or as preventive demand.

2) When preventive maintenance is executed and a different part is encountered which is already failed or will fail in the near future, the replacement of these parts should
be marked as respectively corrective and opportunistic preventive demand. How the demand is marked depends on the maintenance employee.

In both situations a deviation is obtained in the demand pattern, resulting that the inventory is not correctly adjusted to the actual demand. During the research it appeared that this is a major problem for obtaining the correct parameter values (see paragraph 11.2.). For the future all demand described above should be registered as corrective demand, since the inventory of the corrective demand is used. The result would be the following definitions:

- Corrective maintenance; part is encountered and replaced because it failed or part is encountered during a not planned maintenance activity and replaced because it needs direct replacement because it will fail in the near future
- Preventive maintenance; part is replaced due to planned maintenance activity

This gives the opportunity to trace back the demand and determine which demand should be used to determine the control parameter values. Important is that revisions and modifications of machines (are parts of the machine) are not booked as corrective or preventive maintenance since these occur rarely and often have a high demand size. The consequence of booking revisions and modifications as preventive or corrective demand, is that the reorder level (s) will be higher to be able to protect also against these rarely planned activities.

12.4.1.3. Register elements of holding costs

For the holding costs was concluded that the elements; product deterioration and product damage are not registered at Vlisco, resulting that the holding costs used in this research is an estimation made by the maintenance and financial manager of Vlisco. The warehouse and maintenance employees should register when products are damaged and therefore discarded. Further should the effect of deterioration of products on the shortened life time and extra required labour to prevent this be analysed to determine the costs.

12.4.1.4. Start measuring the performance of the inventory control system

In the current situation the performance of the inventory control system is not tracked. Stock out occasions never occurred and in the rare occasions a temporary solution was created (source maintenance engineers). Since in the future the inventory levels of some parts will be adjusted downwards the importance of the performance of the selected control parameters becomes more important; whether the required performance is achieved with optimal parameters. The ERP system is not yet set up to register the performance of the inventory control parameter values of a spare part.
12.4.2. Restrained by the order of implementation

12.4.2.1. Use the phases to determine the unavailability costs
In chapter 5 is explained that the unavailability costs (i.e. downtime costs) are not know and a method is developed to determine these costs. In addition a tool is provided. The advice is to determine the downtime costs via the suggested phases, such that in each phase the inventory can be further optimized. The importance that these costs are distinguished is emphasized in chapter 10.3

12.4.2.2. Use developed framework

Use the developed inventory control model to determine the parameters values
The inventory model created in this research has been implemented in a tool in Microsoft Excel. With the tool Vlisco can determine what the optimal reorder level and order up to level is for a specific spare part. Additionally, the tool is able to calculate the parameter values based on the required service level without the use of unavailability costs, however it will not minimize the total relevant cost. In paragraph 12.2 it has been proven that using the tool will result into costs savings if all data (i.e. including unavailability costs) are entered correctly. A detailed manual of the tool can be found in Appendix P.

Consider to keep inventory for preventive and corrective demand
Vlisco has the policy to only keep inventory for corrective maintenance. In chapter 11.3 is shown that this policy not always results into minimal costs. For each part should therefore be evaluated if it is beneficial to have inventory only for corrective demand or inventory for preventive and corrective demand. The developed framework will show for which part this is beneficial.

12.4.2.3. Determine non-consequential downtime (NCDT)
A method to approximate the non-consequential downtime is developed within this research. In the sensitivity analysis (chapter 10) it was proven that a deviation in the NCDT can result into a shift of the optimal parameter values. The non-consequential downtime is currently set to 0, which results to high downtime costs. Sensitivity analysis also showed that changing the machine waiting time will result to a shift of the optimal parameter values. Since the non-consequential downtime can be considered as the maximum machine waiting time this gives opportunity to further optimize the inventory. Vlisco should therefore determine the non-consequential downtime based on the developed method (Appendix E).

12.4.2.4. Standardize the parts used in the machines
Once every phase of determining the unavailability costs (i.e. downtime costs) is completed, Vlisco knows for every part where it is situated. With this result it is possible to compare the different machines and standardize the number of used parts. Vlisco can determine which part will be used in the future for which functional requirement, such that upon replacement only one specific part will be used. For example; only bearing x of brand y will be used to give free rotation around a fixed axle of diameter z. Less different spare parts are than required and thus pooling is created. With pooling demand is bundled and therefore less inventory is needed. The result is that less parts have to be handled, so less time consuming and the inventory is further optimised. Besides now it is also known which parts are not situated in one of the machines, but are on stock and thus obsolete. These parts can be sold or discarded.

The impact of standardizing parts has been demonstrated for two bearings; 51.10006 and 51.10035, which cost respectively €18.79 and €20.60. Table 25 shows the unstandardized and standardized situations. Having two separate inventories will result to a TRC of €280.15 per year and an average inventory of 35.57 units, which results that €704.14 is locked up in
inventories. In the standardized situation the TRC, average inventory and capital on stock is respectively reduced to €159.63 per year, 19.67 units and €369.56. Which would mean a cost reduction of 43.0% and a reduction of capital on stock of 47.9%.

Table 25 Standardized and not standardized situation

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<tr>
<th>Situation</th>
<th>Parts (parameter values)</th>
<th>TRC</th>
<th>E[IOH]</th>
<th>Capital on stock</th>
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<tr>
<td>Not standardized</td>
<td>51.10006 (s=8, S=22)</td>
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<td></td>
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<td>35.57</td>
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<tr>
<td>Standardized</td>
<td>51.10006 (s=9,S=29)</td>
<td>€159.63</td>
<td>19.67</td>
<td>€369.56</td>
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</tbody>
</table>

12.5. The order of implementation

The suggested order of implementation of the recommendations restrained by the order of implementation is shown in Figure 27.

Figure 27 Order of implementation

Recommendation 12.4.2.1 to use the phases to determine the unavailability costs is leading for the order of implementation. In chapter 5 was explained that in each phase more detailed data becomes available and thus the inventory can be further optimized. Within each phase the developed framework (recommendation 12.4.2.2) should therefore be used again with the available information as shown in Figure 27. This ensures that the optimal inventory control parameter values are selected and for each spare part the correct policy is used (i.e. only inventory is kept for corrective demand or inventory is kept for the total demand).

To determine the unavailability costs of phase 2 it is required that the non-consequential (NCDT) downtimes of the different machines are known. As explained in chapter 5 the order of analysing the machines (to obtain the unavailability costs) is namely partly determined by the NCDT. Recommendation 13.4.2.3. to determine the NCDT is therefore a constraint that has to be executed before phase 2 can be started and the framework can be used again. Within phase 3 all gathered data in phase 2 is used to calculate the demand weighted
downtime costs of a part (i.e. unavailability costs). With these costs the framework can be used again to further optimize the inventory.

Standardization of parts is only possible when for all parts with the same functional requirement (i.e. part family) is known where these are located. After all Vlisco needs to select one part that is able to fulfil the requirements on all locations. For certain parts this is only known when all machines are analysed. On the contrary the required data could be earlier available for parts that are located in a few machines. The execution of recommendation 12.4.2.4 is therefore dependent on when the required data becomes available. In Figure 27 is shown that the recommendation to standardize parts is possible in each phase, but is dependent on the availability of the data.

12.6. Weaknesses and suggestions for future research
Based on the analysis and conclusions in the previous chapters weaknesses or suggestions for future research can be made. Suggestions differ from recommendations; recommendations can be implemented directly using this report and the delivered tools, while the suggestions require more research or further development of the tool. Similarly as the recommendations the suggestions are separated into; restrained by the order of implementation and not restrained by the order of implementation.

12.6.1. Not restrained by the order of implementation

12.6.1.1. Develop method to determine demand for parts with no or insufficient history
Vlisco has parts with only a few demand occurrences and even parts where no demand occurred during the past 4 to 5 years. The current model cannot cope with these parts, because there is no (reliable) demand distribution available. A solution to cope with these parts is to use expert opinion to determine the demand distribution. A method needs to be developed that makes non statistical experts capable to determine the failure probabilities of the parts such that a demand distribution can be created. With this demand distribution the model can be used and the inventory parameter values can be determined.

12.6.1.2. Delay time model
In this research there is no delay time applied to delay the replenishment. With the delay time the inter-arrival time of intermittent and lumpy demand is used to save on holding costs. The use of a delay time model requires understanding of the demand distribution of the inter-arrival time and how to determine the optimal delay time. Extensive research is required to determine the methods and develop a model and therefore was a delay time model considered out of scope. With future research this topic can be elaborated such that the inventory can be further optimized. For the more interested reader see (Moinzadeh, 2001).

12.6.1.3. Non-consequential downtime
During this research an approximation method has been developed to determine the non-consequential downtime. Since this developed method was not the core of this research the approximation can be improved by for example taking future developments into account and determine NCDT via simulation. This topic has been addressed and hereby the fundamentals have been depicted. With future research a better approximation can be made such that the inventory can be further optimized.

12.6.1.4. Use non-consequential downtime for priorities in maintenance
When the non-consequential downtime is determined via simulation as mentioned in the previous paragraph, this gives the opportunity to update the NCDT weekly or even daily.
With the NCDT a maximum duration of the downtime becomes available and can help in the decision process how a failure should be solved:

- The failure is only solved temporarily and the final solution can be executed during a preventive maintenance stop.
- There is sufficient time to execute a final solution

Further since Vlisco has several machines, the machines will have varying NCDT. The machine with the shortest NCDT will thus have the highest priority to be maintained in case of a failure. This ranking can thus be used to priorities maintenance. Currently each morning Vlisco has a so called “workflow meeting” to determine the priorities.

12.6.1.5. Emergency shipments

In the research was already indicated that in some rare cases Vlisco uses emergency shipments. Emergency shipments are more costly than standard replenishments. Nevertheless it could be beneficial to protect against extreme demand by the use of emergency shipments. Keeping a certain time a spare part on stock is in some cases more costly than an emergency shipment. Since emergency shipments are not included in the model, this could be implemented in the tool.

12.6.2. Restrained by the order of implementation

This suggestion can only be applied after the locations of all parts are known, thus after phase 2 in the order of implementation.

12.6.2.1. System approach and assembly to order system

Within this research no system approach or assembly to order system is applied. A system approach gives the opportunity to reduce stock on expensive parts and increase stock on cheaper parts, but maintaining the required system availability. With the assembly to order system no excessive inventory has to be kept, to ensure an entire order can always be delivered, or the risk of only being able to partially fulfil a demand is reduced. Literature (Kranenburg and Van Houtum, 2007; Lu and Song, 2005) has proven that these approaches perform better than item approaches. It is therefore advisable that Vlisco investigate if the system approach and the assembly to order system would realize costs savings as well.
13. List of variables

- $\lambda_{pi}$ = throughput of product p in machine i (yards/hour)
- $A$ = fixed cost per order (€/order)
- $BO_t$ = backorders outstanding at time t
- $C_i$ = demand weighted average cost associated with CDT of machine i (€/hour)
- $C_{pi}$ = cost associated with consequential downtime of product p in machine i (€/hour)
- $CDT_{kij}$ = non-consequential downtime of part k in machine i on location j (hours)
- $CLP$ = compensable loss of production by sales (%)
- $CM_{pi}$ = contribution margin of product p in machine i (€)
- $d_{kij}$ = demand of part k in machine i on position j
- $d_{pi}$ = demand of product p that flows over machine i (%)
- $DC_{kij}$ = downtime costs of part k in machine i on position j (€)
- $de$ = delay time: time period that order is delayed after the replenishment decision
- $DT_{kij}$ = downtime of part k in machine i on position j (hours)
- $DWDC_k$ = demand weighted average downtime costs of part k (€)
- $E[D_{DH}]$ = the expected demand during the demand horizon
- $F_{pi}$ = percentage fents of product p in machine i (%)
- $FDBSD_{kij}$ = boolean variable defining if a the failure of part k in machine i on position j is detected before shortage
- $FE_{z_{kij}}$ = failure effect of failure mode z of part k in machine i on position j
- $FF_{z_{kij}}$ = functional failure of failure mode z of part k in machine i on position j
- $FM_z$ = failure mode z
- $FP_{z_{kij}}$ = probability that a failure mode z of part k in machine i on position j occurs
- $FR_k$ = function requirement of part k
- $FS_k$ = function solver k (hence part)
- $FU_k$ = function of part k
- $h$ = holding cost (%/unit time)
- $h$ = carrying charge (€/€/t)
- $HC_{SH}$ = holding costs over the simulation horizon (€)
- $HC_t$ = holding cost at state t (€)
- $I_{OH_t}$ = inventory on hand at time t (physical inventory)
- $I_{OO_t}$ = inventory on order at time t
- $IP_t$ = inventory position at time t
- $LT_k$ = delivery time for part k (hours)
- $LT$ = delivery lead-time (days)
- $MOW_t$ = boolean variable defining if a machine order has to wait
- $MTTR_{kij}$ = mean time to repair required for part k in machine i on position j (hours)
- $NCDT_i$ = demand weighted average non-consequential downtime of machine i (hours)
- $NCDT_{pi}$ = non-consequential downtime of product p of machine i (hours)
- $NI_t$ = Net inventory at time t
- $NP_{pi}$ = nett production rate of product p in machine i (yards/hour)
- $O_t$ = boolean variable defining if a replenishment order is released
- $P_{00}$ = the probability of going from no demand to no demand
- $P_{01}$ = the probability of going from no demand to demand
- $P_{10}$ = the probability of going from demand to no demand
- $P_{11}$ = the probability of going from demand to demand

List of variables |
- $P_{nn}$ is the probability of going from demand to demand
- $p_{\text{min}} = \text{minimum probability}$
- $Q = \text{Order quantity: a fixed order quantity of spare parts.}$
- $R = \text{review period (days)}$
- $RC_{SH} = \text{replenishment costs over the simulation horizon (€)}$
- $s = \text{reorder level: order spare-parts when inventory position of spare-parts drops below level this level}$
- $S = \text{Order up to levels: a quantity of spare parts is ordered to raise the inventory position up to level S.}$
- $SC_{pi} = \text{percentage scrap of product } p \text{ in machine } i \text{ (％)}$
- $SDT_{kij} = \text{shutdown time required for part } k \text{ in machine } i \text{ on position } j \text{ (hours)}$
- $SH = \text{simulation horizon}$
- $ST_{kij} = \text{setup time required for part } k \text{ in machine } i \text{ on position } j \text{ (hours)}$
- $TFE_{kij} = \text{total failure effect of part } k \text{ in machine } i \text{ on location } j$
- $TRC_{SH} = \text{total relevant costs over the simulation horizon (€)}$
- $U = \text{random number that is uniformly distributed over (0,1)}$
- $v = \text{spare part price (€/unit)}$
- $w_{\text{max}} = \text{maximum waiting time (days)}$
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## Appendix A. Agreed service levels

### Appendix 1 Agreed service levels

<table>
<thead>
<tr>
<th>Machine code</th>
<th>Machine name</th>
<th>Service level</th>
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<td>BAK05</td>
<td>Bakoven 5</td>
<td>96,0%</td>
</tr>
<tr>
<td>BGR35/36/37/38</td>
<td>Breekgroep 03</td>
<td>92,0%</td>
</tr>
<tr>
<td>BLK00</td>
<td>Continu strengenbleek</td>
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<tr>
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<td>Balenpers 1</td>
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<tr>
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<tr>
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<td>Code</td>
<td>Beschrijving</td>
<td>Percentage</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>LDM06</td>
<td>Lijmdrukmachine 6</td>
<td>96,0%</td>
</tr>
<tr>
<td>LMM03</td>
<td>Lijmdrukmatteermachine 3</td>
<td>95,0%</td>
</tr>
<tr>
<td>LMM04</td>
<td>Lijmdrukmateermachine 4</td>
<td>95,0%</td>
</tr>
<tr>
<td>MCM06</td>
<td>Merceriseermachine 06</td>
<td>98,0%</td>
</tr>
<tr>
<td>OHS02</td>
<td>Ontharsstraat 2 (SPR19, SBW03, JBX01, PSM01, PSM02, TB07)</td>
<td>95,0%</td>
</tr>
<tr>
<td>OHS03</td>
<td>Ontharsstraat 3</td>
<td>95,0%</td>
</tr>
<tr>
<td>OMM03</td>
<td>Op Maak Machine 3</td>
<td>95,0%</td>
</tr>
<tr>
<td>RDK12</td>
<td>Rol Druk Machine 12</td>
<td>96,0%</td>
</tr>
<tr>
<td>SBV01</td>
<td>Speciaal Breekverfmachine 1</td>
<td>92,0%</td>
</tr>
<tr>
<td>SBW06</td>
<td>Streng Buis Wasmachine 6</td>
<td>95,0%</td>
</tr>
<tr>
<td>SLB02</td>
<td>Ribon Slijp Bank</td>
<td>95,0%</td>
</tr>
<tr>
<td>SPR20</td>
<td>Spanraam 20</td>
<td>96,0%</td>
</tr>
<tr>
<td>SPR21</td>
<td>Spanraam 21</td>
<td>96,0%</td>
</tr>
<tr>
<td>SPR22</td>
<td>Spanraam 22</td>
<td>98,0%</td>
</tr>
<tr>
<td>SPR23</td>
<td>Spanraam 23</td>
<td>95,0%</td>
</tr>
<tr>
<td>STO20</td>
<td>Stomer 20</td>
<td>95,0%</td>
</tr>
<tr>
<td>VSM02</td>
<td>Voorbreek Spoel machine 2</td>
<td>92,0%</td>
</tr>
<tr>
<td>WIM04</td>
<td>Waterglas Impregneer Machine 4</td>
<td>95,0%</td>
</tr>
<tr>
<td>WIM05</td>
<td>Waterglas Impregneer Machine 5</td>
<td>95,0%</td>
</tr>
<tr>
<td>WJM01</td>
<td>Wax jet machine 1</td>
<td>95,0%</td>
</tr>
<tr>
<td>WJM02</td>
<td>Wax jet machine 2</td>
<td>95,0%</td>
</tr>
<tr>
<td>ZNG01</td>
<td>Zengen</td>
<td>96,0%</td>
</tr>
<tr>
<td>ZST23</td>
<td>Zuur Stomer 23</td>
<td>95,0%</td>
</tr>
<tr>
<td>ZWF01</td>
<td>Zweefdroger 1</td>
<td>95,0%</td>
</tr>
<tr>
<td>ZWF03</td>
<td>Zweefdroger 3</td>
<td>95,0%</td>
</tr>
</tbody>
</table>
Appendix C. Holding costs

The holding costs have to be determined and because Vlisco does not know the holding costs for each specific spare-part, an approximation method is applied. In the method, a holding costs factor is determined; which is a percentage of the purchase price of a spare part per unit time.

Here, the holding costs are determined based on the yearly total inventory holding costs which consist out of several elements. The specific elements are based on a literature review (Azzi et. al. 2014) shown in Table 26. Each element represents costs which can be made during the year to hold inventory.

However, not all elements are relevant for Vlisco. Therefore, is with the maintenance manager and financial manager at Vlisco determined which elements are influential on the holding costs for spare parts at Vlisco.

Table 26 Elements holding costs

<table>
<thead>
<tr>
<th>Evident costs</th>
<th>Investment costs</th>
<th>Relevant for Vlisco?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Floor space</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Cleaning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Surveillance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Insurances</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Taxes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Material handling/storage equipment’s</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>8. WHMS equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Direct labour</td>
<td></td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Semi-evident costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Obsolescence</td>
</tr>
<tr>
<td>2. Product damage</td>
</tr>
<tr>
<td>3. Product depreciation</td>
</tr>
<tr>
<td>4. Product deterioration/expiration</td>
</tr>
<tr>
<td>5. Indirect labour and supervision</td>
</tr>
<tr>
<td>6. Stock list execution</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hidden costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Inspection and counting during the year</td>
</tr>
<tr>
<td>2. Remanufacturing</td>
</tr>
<tr>
<td>3. Repackaging and relabelling</td>
</tr>
<tr>
<td>4. Lost sales or backlog</td>
</tr>
<tr>
<td>5. Opportunity costs</td>
</tr>
</tbody>
</table>

*WHMS = Warehouse Management System Software

With the relevant costs factors of Vlisco listed, the spare-parts holding cost factor can be determined. However costs for product damage, depreciation and deterioration/expiration are not registered ant thus unknown. Besides according to the maintenance manager the current warehouse is not correctly set up to prevent deterioration of the parts (e.g. the axle of spare pumps are not revolved, no current is put on electrical parts).

Table 27 shows the total inventory costs of Vlisco in 2014 based on the known elements. With the relevant holding costs elements and their respective costs for 2014, the percentage of each element compared to the total inventory value can be determined. The sum of these percentages results into the holding cost factor, which would in the case of Vlisco would be 18.45%.

Table 27 Relevant Cost factors to determine holding cost factor
<table>
<thead>
<tr>
<th>Costs</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>€ 6,000,000,00</td>
<td></td>
</tr>
</tbody>
</table>

**Hold costs cost factors**

<table>
<thead>
<tr>
<th>Costs</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>€4,999,00</td>
<td>0,08%</td>
</tr>
<tr>
<td>€53,800,00</td>
<td>0,90%</td>
</tr>
<tr>
<td>€60,000,00</td>
<td>1,00%</td>
</tr>
<tr>
<td>n.k.</td>
<td>n.k.</td>
</tr>
<tr>
<td>n.k.</td>
<td>n.k.</td>
</tr>
<tr>
<td>n.k.</td>
<td>n.k.</td>
</tr>
<tr>
<td>16,50%</td>
<td></td>
</tr>
</tbody>
</table>

Holding costs Factor 18,48%

Since this factor is not correct, since some elements are missing is decided that for Vlisco an estimation by the maintenance and financial manager is used in this research, namely 29.77%.
Appendix D. Replenishment costs

Vlisco does not know what the replenishment costs are, therefore a method is developed to determine these costs. The replenishment costs are determined based on the principle of activity based costing. Activity based costing identifies which activities are needed to realize a product or service and assigns the costs of these activities by the actual consumption of each. In the context of replenishment costs this are all activities of realizing that a replenishment of the inventory. In this paragraph is first described what these activities are and finally is explained how these are used to determine the replenishment costs.

Activities required for replenishment of inventory

The activities leading to a replenishment of inventory are called the operational purchase process and shown below (Weele, 2014):

Operational purchase process
- Ordering
  - Generate order
  - Send order
- Logistical evaluation
  - Monitor delivery
  - Receive ordered parts
  - Check ordered parts (amount and state)
  - Lay parts in the warehouse
- Aftercare and evaluation
  - Register invoice
  - Check invoice with packing slip
  - Payment of invoice

Determine replenishment costs

To determine the costs of the activities described above the employees of the maintenance, purchase and warehouse department are asked how much time they spent on average on these activities. The result is the number of Full Time Employees (FTE) that is occupied with replenishment activities. Together with the costs of the fulltime employees and number of orders the cost per order can be determined with equation 15.1.

\[
\text{Cost per order} = \frac{\text{FTE's required (##) } \times \text{ Costs FTE (\€/time) }}{\text{Number of orders (##/time) }}
\] (0.1)

At Vlisco 2.85 FTE's are occupied with replenishment activities (shown in Table 28), which results into an order costs of €59.12 per order.

<table>
<thead>
<tr>
<th>Department</th>
<th>FTE's</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance</td>
<td>1.05</td>
</tr>
<tr>
<td>Purchase</td>
<td>0.50</td>
</tr>
<tr>
<td>Warehouse</td>
<td>1.30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.85</strong></td>
</tr>
</tbody>
</table>
Appendix E. Non-consequential downtime

The goal is to determine the non-consequential downtime (NCDT) as defined in chapter 4.2.1. Machines have a buffer to absorb downtime, namely: inventory, capacity and time buffers (Hopp and Spearman, 2001). The total buffer of a machine defines the NCDT. To determine the NCDT, detailed information about these buffers is required. This premise asks for understanding of the production and planning process of Vlisco. In this paragraph first the production and planning process is described, next the buffers at Vlisco are explained and finally the method to make an approximation of the NCDT.

E.1 Production and planning process

E.1.1. Production process

The production process of the textiles differs per kind of product and takes on average 25 steps. Production routing differs per product, which depends on:

(i) the colours used (type, amount and basis colour): certain colours require other machines or more cycles on a machine are needed
(ii) the way of colouring: there are two ways of colouring, the fabric is waxed and submerged into a paint-bath or the colours are printed on the textile. Resulting that other machines are used.
(iii) the way of finishing; the product gets a different type of protective layer, requiring different type of machines

However, the main process (see Figure 28) has similar steps for each product, namely:

First in pre-treatment the textile is suited for the chemical treatment it goes through. The textile is bleached, washed and all the threads in the textile are straightened. In the next step dependent on way of colouring the wax is printed on the textile or goes directly to the fitting step. The not waxed parts will be coloured in the fittings step. To finish the product it gets a treatment depending on the kind of product in the finishing step. In the subsequent step making-up, the textile is visually inspected for errors. Based on these errors a quality label is given to segments of the textile. If errors are too severe the segments are discarded. In the final step the textile is cut into standard lengths of 6 or 12 yards and folded, labelled and pressed into bales, ready for shipment.
E.1.2. Production planning

The planning of the production process (shown in Figure 28) is updated daily and works as follows (Figure 29): Initially a volume planning for the different types of products is released. Based on this planning customer orders can be planned into these available volumes. Once this is completed the planning on machine level can be made. Initially these are made based on the Just in Time principle; orders are planned on the machines such that they directly succeed each other as soon as production of an order is finished. However given the amount orders that have different routings and the limited capacity this is never feasible, therefore Vlisco uses buffers. Buffers are; time, capacity and inventory (work-in-progress) buffers, which results in a so called slack planning. The time required to produce the products with the use of these buffers is called the production lead time. In the following section, the buffers as part of the slack planning will be discussed.

E.2 Buffers

In the previous paragraph it was explained that a slack planning is used for the planning of demand on the machines at Vlisco and three buffers exists. These three buffers will be discussed subsequently in the following sub-paragraphs; (i) capacity buffer, (ii) inventory buffer and (iii) time buffer.

E.2.1. Capacity buffer

The capacity buffer is defined by the spare capacity a machine has during the production lead time. How a machine is utilized determines the spare capacity. Utilisation is the time the machine is in use divided by the available production time as defined in the equation below:

\[ U_i = \frac{\text{Machine i in use}}{\text{Available production time}} \]  

(0.2)

where

\[ U_i = \text{utilization machine } i \text{ (%)} \]

Working hours define the total available time, however not all these hours are available for production due to events such as preventive maintenance. To determine the available production hours for a machine, historical data will be used. The historical data includes the production time (i.e. time the machine generates output) as well as events which cause that the total time cannot be used for production. The events that are logged by the operating system of the machines at Vlisco and are defined as followed:

- Production time; time the machine is producing output
- downtime due to technical failures; time the machine is down due to a failed part
- downtime due to disturbances of goods flow; time the machine is down due to the unavailability of materials (e.g. dye), ancillary materials (e.g. cooling water) and means of transport (e.g. pallets).
- downtime due to change overs & production failures,
- available production time but no orders are planned
- preventive maintenance

Figure 30 shows a schematic composition of the time of these events.
Besides production time, the machine can be in use due to downtime of change overs and production failures. Because the machine is in use during such events; it is subtracted from the spare capacity of the machine. Aggregating downtime events to the time the machine has been in use has as benefit that the variation in the spare capacity due to these events is incorporated.

With the premise the capacity buffer in percentage is calculated by subtracting the utilisation of 100:

\[ CBP_i = 100 - U_i \]  \hspace{1cm} (0.3)

where

\( CBP_i \) = capacity buffer machine \( i \) in percentage (\%)

With the capacity buffer in percentage, the buffer in hours can be calculated:

\[ CBH_i = CBP_i \times PLT \]  \hspace{1cm} (0.4)

Where

\( PLT = production \ lead \ time \ (hours) \) and \( CBH_i = capacity \ buffer \ machine \ i \ (hours) \)

To determine the capacity buffer, the utilisation of the machines in the past will be used. Which period and what amount of data will be used, is the topic of discussion in paragraph E.3.3.

**E.2.2. Inventory buffer**

The inventory buffer is defined by the inventory for a specific product after a specific production step (e.g. machine \( i \)). The throughput of the succeeding machine (\( i+1 \)) determines how fast the inventory is consumed and thus what time it takes before the entire inventory is depleted. With equation 1.4 the inventory buffer in hours can be calculated.

\[ IB_{pi} = \frac{I_{pi}}{\lambda_{pi+1}} \]  \hspace{1cm} (0.5)

Where

\( IB_{pi} = inventory \ buffer \ of \ product \ p \ after \ machine \ i \ (hours) \)
\( I_{pi} = inventory \ of \ product \ p \ after \ machine \ i \ (yards) \)
\( \lambda_{pi} = throughput \ for \ product \ p \ on \ machine \ i \ (yards/hour) \)
\( i+1 = machine \ succeeding \ machine \ i \)
E.2.3. **Time buffer**
The time buffer is defined by the spare time available in the production process. For example when the production lead time is 12 hours and the production is started 24 hours before the delivery date, the time buffer is 12 hours. However time and capacity buffers are not mutually exclusive. Situations exists that an order is using a time buffer but the required machine is in production (i.e. waits until the machine is available). Since time buffers are only present on order level and the interest is on what time a machine can be down without consequences, time buffer is assumed to be always 0.

Where

\[ TB_i = \text{time buffer machine } i \text{ (hours)} \]

E.2.4. **Data for buffers**
In this paragraph is explained how the available historical data can be used to determine the different buffers. The systems at Vlisco record the capacity, time and inventory each day. Each day has thus a capacity inventory and time buffer, therefore the sum over the given production lead time \((l)\) results into the capacity, time of inventory buffer during the production lead time.

For example when the production lead time is 3 days and the capacity buffer of each day is given such as in Figure 32, the capacity buffer during the production lead time becomes:

\[ CBH_i = 5 + 7 + 4.5 = 16.5 \text{ hours} \]

![Figure 31 Machine capacity buffer during production lead time](image)

Each day a production can be started, therefore there are more production lead times within a certain time horizon. The different production lead times are shown in Figure 32.
The total number of production lead times within a time horizon is defined by:

\[ N = H - PL + 1 \]  \hspace{1cm} (0.6)

where

\( H \) = time horizon (days)
\( PL \) = length of production lead time (days)
\( N \) = number of production lead times within a time horizon

Now is clear how to obtain the capacity buffer during a production lead time and how to obtain all the production lead times within the available time horizon. To determine the inventory buffer during the production lead time, the same method can be applied. The premises results into a new notation of the buffers:

\[ CBH_{il} = \text{capacity buffer in hours of machine } i \text{ during production lead time } l \]
\[ IB_{pil} = \text{inventory buffer for product } p \text{ on machine } i \text{ during production lead time } l \]
\[ TB_{il} = \text{time buffer of machine } i \text{ during production lead time } l \]

**E.3 Method to determine non-consequential downtime**

With the capacity, inventory and time buffer the total buffer and thus the non-consequential downtime can be determined of a machine. A machine is an element of the manufacturing system, a network of interacting parts (Hopp and Spearman, 2001) and therefore the throughput of a machine can be blocked or starved. Blocking occurs when the throughput of a succeeding machine is lower, while starving occurs when the throughput of the proceeding machine is lower. A machine is blocked when its production (i.e. output) cannot be processed further e.g. because of lack of inventory space. A machine is starved when to cannot produce due lack of input of a preceding machine.

The total buffer of a machine is thus not the sum of the separate buffers; the effect on the system needs to be taken into account (Chang et al., 2006). In the remainder of this paragraph a method will be explained to take account the effect of the system of the buffers.

The method consist of three steps; (i) determine the product routings, (ii) determine the total buffer of the machine as part of a routing, while considering system effects for a specific route and (iii) determine the total buffer of machine considering all routings for a specific product. These steps are shown in Figure 33.
As explained in the previous paragraph different products have different routings, therefore for each routing the buffer of a machine is computed. Based on the buffers of each routing the definitive buffer, using the methods described in the previous paragraphs, is determined.

Figure 33 Steps to determine the buffer of a machine

E.3.1. Determine product routings

A routing ($r$) specifies the steps that are used to produce a product ($p$). In Figure 34 an example is given of 5 machines that are used to produce several products. Each product has its unique routing; in the example 4 products are produced, that results into the following routings:

$$r_1 = \{A \rightarrow B \rightarrow C\}$$
$$r_2 = \{A \rightarrow B \rightarrow C\}$$
$$r_3 = \{A \rightarrow B \rightarrow D\}$$
$$r_4 = \{A \rightarrow D\}$$

Where

$r_p = \text{routing of product } p$

Figure 34 Example of routings

E.3.2. Determine buffer for product while considering system effect

For each routing in the previous step, the buffer a machine can be determined. First, the buffer of the last machine of a product routing is analysed, thereafter the proceeding machine in the routing is analysed which is repeated until the first machine in the routing is reached. These steps are shown in Figure 35.
To determine the buffer of a machine for a specific product while considering the system effects, first, the buffer of the last machine is determined, thereafter, buffers of preceding machines can be determined such that the total buffer of a product can be calculated.

**Determine buffer last machine in routing**

When the last machine in a routing fails, there is no machine that will starve; only the delivery of the product to the customer is delayed. Therefore the buffer is only defined by the capacity, inventory and time buffer available during the production lead time of the last machine within a routing. The buffer of the last machine in the routing is determined the sum of the capacity, inventory and time buffer.

\[ NCDT_{p_{il}} = IB_{p_{il}} + CBH_{il} \]  

(0.7)

where

- \( NCDT_{p_{il}} \) = non
- consequential downtime of product \( p \) on machine \( i \) during production lead time \( l \) (hours)

**Determine buffer preceding machine in routing**

For the buffer of a specific product of the proceeding machine \((i - 1)\) in the routing, the buffer of the previously analysed machine needs to be considered to take into account the system effect. This is done in 5 steps;

1) **Determine capacity buffer in hours**

First the capacity buffer \((CBH_{il})\) of the machine is determined.

2) **Determine functional capacity buffer of machine**

With the capacity buffer of the machine determined in the previous step the buffer can be compared with the total buffer of the succeeding machine. A failed machine can namely cause that the succeeding machine \( i \) does not have enough time to catch up the lost production. For example when a machine has a capacity buffer \((CBH_{il})\) of 4 hours, but an identical succeeding machine \((i + 1)\) has a total buffer \((NCDT_{p_{(i+1)l}})\) of 2 hours. The succeeding machine will be starved after 2 hours after which the delivery to the customer will be delayed for every additional hour of downtime. Consequence is that the minimum of these two defines the possible capacity buffer of the machine.
However machines can differ in throughput. When the throughput of the succeeding machine \((i+1)\) lower than machine \(i\), the inventory increases after machine \(i\) and eventually machine \(i\) is blocked (e.g. due to lack of inventory space). Most important is when the succeeding machine is not able to catch up the lost hours if the downtime is too big.

With a capacity buffer of 2 hours just determined, the effect of difference in throughput on the NCDT can be calculated. For example; when the throughput of machine \(i\) and \(i + 1\) are respectively 1000 yards/hour and 600 yards/hour, in the 2 hour capacity buffer machine \(i\) has produced 2000 yards and machine \(i + 1\), 1200 yards (Figure 36). However, when machine \(i\) is down for two hours, machine \(i + 1\) is not able to finish the remaining 800 yards in 2 hours for the delivery to the customer. This is because the throughput of machine \(i + 1\) is lower than the throughput of machine \(i\). The capacity buffer is therefore affected by the machine with the lowest throughput in the chain.

\[
\min(\text{CBH}_{il}, \text{NCDT}_{p(i+1)l})
\]  

(0.8)

The maximum amount of time machine \(i\) can be down in the situation where the throughput of a preceding machine is higher than the succeeding machine (i.e. \(\lambda_{pi} > \lambda_{p(i+1)}\)) is thus defined by the amount that machine \(i + 1\) can produce in its NCDT (i.e. \(\text{NCDT}_{p(i+1)l}\)). This can be obtained by multiplying the throughput of machine \(i + 1\) with its NCDT and divide this with the throughput of the preceding machine, i.e. machine \(i\).

\[
\text{Max DT machine } i \ (\lambda_{pi} > \lambda_{p(i+1)}) = \frac{\lambda_{p(i+1)} \times \text{NCDT}_{p(i+1)l}}{\lambda_{pi}}
\]  

(0.9)

When a succeeding machine has a higher throughput than the preceding machine (i.e. \(\lambda_{pi} \leq \lambda_{p(i+1)}\)), the NCDT of machine will not change and the maximum amount of time machine \(i\) can be down is equal to the NCDT of the succeeding machine, i.e. \(\text{NCDT}_{i+1}\). Including the scenario of the previous equation (i.e. \(\lambda_{pi} > \lambda_{p(i+1)}\)), the buffer is defined by:

\[
\text{Max DT machine } i = \min \left( \text{NCDT}_{p(i+1)l}, \frac{\lambda_{p(i+1)} \times \text{NCDT}_{p(i+1)l}}{\lambda_{pi}} \right)
\]  

(0.10)

With the maximum downtime determined for differences in throughput, the capacity buffer of machine \(i\) that can actually be used is determined by the following equation. From now on this buffer is called the functional capacity buffer of machine \(i\):

\[
\text{CBHF}_{pi} = \min \left( \text{CBH}_{il}, \min \left( \text{NCDT}_{p(i+1)l}, \frac{\lambda_{p(i+1)} \times \text{NCDT}_{p(i+1)l}}{\lambda_{pi}} \right) \right)
\]  

(0.11)

where

\[
\text{CBHF}_{pi} = \text{functional capacity buffer of product } p \text{ on machine } i \text{ during production lead time } l \text{ (hours)}
\]
3) Calculate inventory buffer
Now the inventory buffer \((IB_{pi})\) of the machine is determined.

4) Calculate time buffer
Now the time buffer \((TB_{il})\) of the machine is determined.

5) Calculate total buffer
With all buffers determined, the total buffer a product on a machine during a production lead time (i.e. \(NCDT_{pil}\)) can be determined with the following equation;

\[
NCDT_{pil} = IB_{pil} + CBHF_{pil}
\]

In the next paragraph is explained how to aggregate the non-consequential downtime of the different production lead times and determine the non-consequential downtime of a specific machine.

**E.3.3. Determine weighted buffer**

With the buffer for a machine determined for each product for the different production lead times, the buffer of the machine can be determined. There are 2 approaches in doing so; (i) a demand weighted average buffer or (ii) a worst case can be determined.

**Demand weighted average buffer**
The demand weighted average buffer is determined using the non-consequential downtime of all products and all production lead times. Each non-consequential downtime is weighted based on the demand and the total number of production lead times. Consequently the relative share of a specific product that flows over a machine during a production lead time is taken into account.

The non-consequential downtime for a product during one product lead time \((l)\) was defined by \(NCDT_{tpi}\), as explained in the paragraphs above. To determine the average non-consequential downtime of product on a machine, equation 15.12 is used. The non-consequential downtime of a production lead time for a product on machine \(i\) is divided by the number of production lead times, which results in a fraction of the non-consequential downtime. The sum of all these fractions define the average non-consequential downtime of product \(p\) on machine \(i\).

\[
NCDT_{pi} = \sum_{l \in L} \frac{NCDT_{pil}}{N} \tag{0.12}
\]

Where

\(NCDT_{tpi} = \text{average non – consequential downtime of product } p \text{ on machine } i\)

To determine the demand weighted average non-consequential downtime, all products that flow over a machine have to be taken into account. The sum of all \(NCDT_{tpi}\) multiplied by its fraction of the demand compared to the total demand results into the demand weighted average:

\[
NCDT_{i} = \sum_{p \in P} \frac{d_{pi}}{\sum_{p \in P} d_{pi}} NCDT_{tpi} \tag{0.13}
\]

where

\(NCDT_{i} = \text{minimal non – consequential downtime of machine } i\)
\( d_{pi} = \text{demand of product } p \text{ that flows over machine } i \) (\%)

**Worst case buffer**

The worst case is the shortest non-consequential downtime of a machine. Since the shorter the non-consequential downtime the earlier there are costs associated with the downtime costs. To obtain the shortest non-consequential downtime the minimum of the non-consequential downtime needs to be determined, by the following equation:

\[
\text{NCDT}_i = \min_{p \in P} \left( \min_{l \in L} (\text{NCDT}_{pl}) \right)
\]  

\[ (0.14) \]
Appendix F. Selection inventory model
A model is required to calculate the relevant costs and achieved service level, to select the best performing control parameter values. Models differ from each other in their specific assumptions about reality. To select a model its assumptions must resemble the characteristics of the inventory system of Vlisco. Within this chapter first the characteristics are discussed and thereafter a model is selected based on these characteristics.

F.1 Characteristics inventory system Vlisco
In Table 29 the relevant inventory system characteristics are shown (Prasad, 1994; Silver et al., 1998) for the selection of the inventory model at Vlisco. First the characteristics are explained. Next the situation at Vlisco is described and finally is determined if an assumption is needed or the reality is used. These characteristics are determined based on interviews with maintenance engineers, maintenance manager, warehouse manager, purchase manager and analysis of the delivery lead time that is registered in the ERP system.

Table 29 Characteristics of spare part inventory system of Vlisco

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Explanation</th>
<th>Vlisco</th>
<th>Reality or assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of items grouped together for analysis</td>
<td>N.A.</td>
<td>Item approach</td>
<td></td>
</tr>
<tr>
<td>Number of stocking locations</td>
<td>Reflects the number of stocking locations</td>
<td>1 stocking location</td>
<td>1 stocking location</td>
</tr>
<tr>
<td>Out of stock policy</td>
<td>The policy followed when items on stock are less than the demand.</td>
<td></td>
<td>Backordering</td>
</tr>
<tr>
<td></td>
<td>• Backordering; In case of out of stock the demand is backordered and filled as soon as the replenishment arrives.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Lost sales: In case of out of stock the demand is lost; the customer goes to different supplier.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency shipment</td>
<td>Emergency shipment in case a requested part cannot be fulfilled from stock.</td>
<td>If emergency demand exits a carrier is used to speed up delivery, however no contracts exists that arranges emergency shipments.</td>
<td>No emergency shipments</td>
</tr>
<tr>
<td>Shelf life</td>
<td>Shelf life defines the time until a part becomes unfit for use. Obsolescence refers to items that lose their value through time because of changes of machines such as technological innovations, whereas perishability refers to the decay of products. The life of some products can be indefinite.</td>
<td>Spare parts become obsolete if there are modifications to machines. Parts exist that could perish if these are not maintained, for example a voltage has to be applied to electronic parts and pumps need to be used after a certain time not being used.</td>
<td>Indefinite. As is assumed that parts on stock are maintained and the modifications of machines are incidents.</td>
</tr>
<tr>
<td>Delivery lead time</td>
<td>Delivery lead time is not constant but has a mean and variance. However these are not always known.</td>
<td>The delivery lead time is registered on supplier and order level and not easily traceable back to a specific part, therefore there is no reliable data available</td>
<td>Constant lead time</td>
</tr>
<tr>
<td>Procurement structure</td>
<td>Refers to whether discounts are offered by the supplier. The cost per unit item remains constant or varies according to the quantities bought.</td>
<td>Vlisco receives discounts from wholesalers as the total purchase amount over all products exceeds a limit. No discounts are given for order</td>
<td>No discounts</td>
</tr>
</tbody>
</table>
Order size can be restricted by the supplier, such as a minimum order amount or the amount is based on the packing unit.

No products with order size restrictions

No order size restrictions

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### F.1.1. Configuration of the machine orders at Vlisco

Partial delivery of an order will result in that a machine is down as already explained in paragraph 4.1. The inventory model should thus only have complete fulfilment of orders and therefore the configuration of the orders is of great importance.

Orders for parts at Vlisco can consist out of:
- Different parts of one or multiple units; an example is when the bearings of a roller are replaced. On both sides of the roller, the bearings and the bearing sleeves that hold the bearing on its place are replaced.
- One part of one or multiple units; an example is when a pump is replaced or when laths of a lathed roller are replaced.

In both situations not being to fulfil the entire order results that a machine remains down. Therefore the inventory of each part function as an assemble-to-order system in which parts are withdrawn from inventory based on order specifications; insufficient stock of one item may cause delays in order fulfilment (Hausman et al., 1998). The system is shown in Figure 37, where $D_k$ is the demand size (number of units) of the order for part $k$.

An ATO system requires joint probabilities and optimization of non-separable functions (Karaarslan et al., 2013). Insight is thus needed in the possible order configurations, such that the joint probabilities and optimization functions can be determined. As already mentioned in 4.2.1 locations of all parts are not known, therefore the different configurations of the assemblies are also unknown. Further with many parts and thus configurations the problem becomes computationally demanding (if not intractable), which causes the problem cannot be solved exactly and approximations are required (Lu and Song, 2005).

Given the premises and the time constraint of the project, the situation where different parts of one or multiple units are demanded is out of scope. However to cope with this problem the following recommendations are made:

![Figure 37 Assembly to order system](attachment://figure37.png)
- Service level the same for assemble to order parts
- Service level on item level, thus in the case of Vlisco the situation where for one part one or multiple units are demanded.

**F.1.2. Impact machine orders on inventory policy**

Assumptions about the configuration of the orders have an impact on the results obtained by the model. Several models assume constant demand. In case of constant demand (i.e. machine orders always have the same quantity) the inventory position at the beginning of the replenishment lead time is always exactly equal to the reorder point. With random demand the consequence is that inventory position can be below the reorder point when a replenishment order is triggered. Since this is the case at Vlisco this difference has to be taken into account when the reorder point is determined. The difference between the reorder point and the inventory position at the moment of ordering is called the undershoot ($U$) (shown in Figure 38). The selected model should therefore take this into account such that there is no deviation between the realized results and the calculated results.

![Inventory level vs Time diagram](image)

*Figure 38 Undershoot*

**F.2 Models suggested by literature**

With the characteristics of the inventory system at Vlisco defined, a model can be selected. In paragraph 3.3.1.1 is concluded that the preferred policy is a $(R, s, S)$ policy and otherwise a $(R, s, Q)$ policy. Further is in paragraph 4.1 decided that the model should use a maximum machine waiting time as service constraint. In the remainder of this paragraph the possible models are discussed.

Several models with a machine waiting time are suggested by literature. Numerous authors developed approximations for a continuous inventory policy, such as Kruse (1981, 1980) derived a waiting time distribution for an $(S-1, S)$ and an $(s, S)$ policy. Wang et al. (2005) considers a time-window ready rate for a $(s, S)$ policy. However since the inventory position at Vlisco is monitored with a review period these are not relevant. Tempelmeier (1985) proposes an approximation of the waiting time distribution for a $(R = 1, s, Q)$ policy, where no partial delivery is allowed. Kiesmüller and de Kok (2006) developed a more versatile $(R, s, Q)$ policy where $R$ can be bigger than 1. In this model partial backordering is not allowed and the maximum waiting time is the replenishment lead time, further the undershoot mentioned above is not taken into account. Tempelmeier and Fischer (2010) suggest an approximation
for the \((R, s, Q)\) policy, that does take the undershoot into account. However partial delivery is allowed, resulting that the service measure will show a higher performance than actually is achieved.

The models suggest by literature are thus not appropriate for the situation at Vlisco, since the inventory position monitoring period does not correspond, the undershoot is not taken into account or partial delivery is allowed. An alternative is simulation; simulation is the imitation of the operation of a real-world process or system over time. Simulation gives the opportunity to do good approximation of the inventory parameter values.

**F.3 Chapter conclusion**

In this chapter the characteristics of the spare part system and the configuration of orders at Vlisco were discussed. It was concluded that orders are a combination of several and/or multiple parts which requires an assembly to order system. However due to the fact the configurations of the orders are not known and the time constraint of the project only inventory is determined based on information of a single part. For assemble to order parts is therefore suggested that the service level should be maintained equal, such that the risk of not having one of the parts on stock is reduced and the order can be fully fulfilled. A literature search showed that currently no model is available that includes; the undershoot, the machine waiting time as service measure and can deal with full order fulfilment. Concluded is therefore that simulation will be used to determine the control parameter values, which is discussed in the next chapter.
Appendix H. Demand data exploration

Collected demand data will be checked for outliers (i.e. extreme demand or demand lead time values which do not represent that day-to-day situation at Vlisco) and properties, such as trends or cyclic patterns of the demand, will be described. To describe the properties of the data, a check will be performed to determine whether the demand data is stationary or non-stationary (i.e. trend and seasonal or cyclic pattern). The data is considered stationary if it is not affected by change in time. Stationary implies a statistical stability, meaning a constant mean and variance (Montgomery et al., 2008). Whenever this is the case distributions can be determined, otherwise, adjustments are needed to adjust for the trend or cyclic pattern using forecasting techniques.

With 6000 spare parts on stock it is not possible to check within the time span of the project if there are spare parts with a trend or cyclic pattern. Therefore initially the maintenance engineers are asked if parts exists in their inventory which have; 1) a decreasing or increasing demand in time, or 2) has a higher or lower demand during a certain time span because of for example different humidity, temperature and patterns of use. Although engineers at Vlisco conclude that no such parts exist; however it still could be the case that parts exists for which demand shows any form of pattern now or in the future. Therefore, a method is developed to make it possible to check for these patterns, which is explained in below,

H.1 Trend pattern

Trend is recognized by a variation in a time series that exhibits steady upward growth or a downward decline (Chatfield, 2001), therefore trend can be loosely defined as "long-term change in the mean level. This long-term change can best be observed by a time plot. The change can be detected by the eye for constant demand (Figure 39c). For slow moving demand this is harder to identify, because the periods of no demand blur the pattern (Figure 39b). Therefore the time periods with zero demand are left out, now the trend in slow moving demand is easier identified (Figure 39c).
Moreover a trend could be observable on day, week, month and even yearly level and is visible dependent of the time period that is used. Therefore to be sure to observe a possible trend pattern, the time plot should be eyeballed on the entire available demand history. However if there exist a modification of the specific part in one or several machines, the time period should start from the modification date. Conclusively the method to check for a trend pattern is as follows:

1) Check for a existing modification that could effect the demand  
2) Determine the time period  
3) Create a time serie on day, week, month and yearly level,  
4) Remove all zero demand periods  
5) Plot a graph on each level  
6) Check for increasing or decreasing demand

H.2 Cyclic pattern

A cyclic pattern is recognized when similar patterns of variation are observed in a returning time interval (Chatfield, 2001). For example during the summer due to the high temperature certain parts wear out faster, which causes that the demand of these parts are higher during this period. Although it is possible to detect a cyclic pattern by eyeballing the preferred method is the autocorrelation function (Montgomery et al., 2008). To detect a cyclic pattern by eye this pattern needs to be real distinct. Eyeballing is therefore not sufficient and the correlation of two demands in time creates a better image. Correlation indicates the dependence of 2 variables. In a cyclic pattern demands that have a recurring structure (e.g. high demand) in each cycle will have a high correlation with demands with the same structure. For example if a part has every November a demand of 4 while the rest of the year the demand is 2, the periods with demand of 4 will have a high correlation.

With the autocorrelation function (ACF) the correlation can be determined. The ACF is a measure of the overall correlation between a demand at time t-k (X_{t-k}) and demand at time t (X_t), which is the direct and indirect pathway shown in Figure 40.
When significant autocorrelations are observed at lags in a recurring cycle structure there is evidence for a cyclic pattern. For example in Figure 41 at lag 6 and 12 the columns cross respectively the critical lower and upper limit (shown by the dotted line) which indicates significant time lags. A recurring pattern of 6 is recognised and which thus indicates a cyclic pattern of 6.

**Figure 41 Example ACF with time cyclic pattern of 6 periods**

When time lags do not give a clear recurring structure, for example no significant time lags or significant time lag at 4, 9 and 11, no cyclic pattern is present. Whether a cyclic pattern is detected, is just like the trend pattern dependent of the time period used and the level of analyse (i.e. day, week, month or yearly level). The method to check for a cyclic pattern is therefore as follows:

1. Check for a existing modification that could effect the demand
2. Determine the time period
3. Create a time serie on day, week, month and yearly level,
4. Calculate the autocorrelation for all time lags on each level
5. Plot a graph for each level
6. Check for a recurring pattern of significant time lags
Appendix I. Demand analyses

The demand categorization scheme suggested by Syntetos et al., (2005) will be used to determine the demand pattern. Categorization in this scheme is based on two variables;

(i) Average Demand Interval (ADI) (i.e. the average time between two consecutive orders of the same part)

\[
ADI = \frac{\text{Total number of periods}}{\text{Periods with a demand occurrence}}
\]  

(ii) Variation of the demand size (CV\(^2\)).

\[
CV^2 = \left(\frac{\sigma}{\mu}\right)^2
\]

The result is spare-parts that are divided into the following demand patterns; Smooth, Erratic, Lumpy and Intermittent demand (shown in Figure 42).

There are two methods to determine the breakpoints for the demand pattern (Boylan et al., 2008)

1. Defining demand patterns and then testing which estimation procedure performs best on each particular demand category.
2. (i) compare alternative estimation procedures, (ii) identify the regions of superior performance for each one of them and (iii) define the demand patterns based on the methods’ comparative performance.

Within this project the categorization of demand is not used to align a certain policy or method to a demand pattern. Given this approach it is not necessary to identify the regions of superior performance. Therefore the demand patterns are defined in advance based on the breakpoints suggested by Syntetos et al. (2005).
Appendix J. Methods to determine downtime costs of phase 1 and 2

J.1 Method to determine hypothetical highest downtime costs

In this paragraph a method is introduced to determine a hypothetical highest downtime costs for phase 1 of Figure 16. When analysing all the elements of downtime costs in chapter 5 it became clear that the influence on downtime is part, machine or location dependent. The division of these elements are shown in Table 30.

<table>
<thead>
<tr>
<th>Table 30 Dependency of elements of downtime costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part dependent</td>
</tr>
<tr>
<td>Delivery time ($L_{T_k}$)</td>
</tr>
<tr>
<td>Setup Time ($ST_{ki}$)</td>
</tr>
<tr>
<td>Mean time to repair ($MTTR_{kij}$)</td>
</tr>
<tr>
<td>Failure detected before shutdown ($FDBSD_{kij}$)</td>
</tr>
</tbody>
</table>

When no elements would be location dependent, it would be easy to obtain the highest downtime costs of a part without analysing a machine in detail. However this is not the case, therefore the question that arises is; which information is known without analysing all machines in detail?

Maintenance engineers and mechanics at Vlisco do know the extremes (i.e. maximum) of the shutdown and setup time within a specific machine. This results in, that, although not of all parts the shutdown and setup times are known, the maximum shutdown and setup time in each machine, shown in equation 0.17 and 0.18 are available.

\[ SDT_i = \max_{k \in K} \left( \max_{i \in J} (SDT_{kij}) \right) \]  \hspace{1cm} (0.17)

where

$SDT_i = \text{maximum shutdown time in machine } i \text{ (hours)}$

\[ ST_i = \max_{k \in K} \left( \max_{i \in J} (ST_{ki}) \right) \]  \hspace{1cm} (0.18)

where

$ST_i = \text{maximum setup time in machine } i \text{ (hours)}$

Unfortunately Vlisco does not know the maximum of $MTTR_{kij}$ within a specific machine. Thus again it is required to know exactly which parts are in which machine, it is thus not possible to determine the highest MTTR of a part within a machine. However mechanics and maintenance engineers have insight in which parts of a family are in each machine. (A part family is a group of parts that are considered to have the same function and is therefore distinguishable of other families; e.g. bearings have the function to give free rotation around a fixed axis, while chains have the function to transport power over a longer distance.) For example; for bearing x (part) it is not known in which machines this part is installed, but where bearings (part family) are situated is known. In the example of Figure 43 machine A is already analysed and is known which part is on each position, however machine B is not analysed yet and only the part family is known for each position.
MTTR is dependent of the location of a part in a machine and the part itself, therefore theoretically the MTTR can be divided into 2 elements; location and part dependent MTTR (Figure 44).

\[
MTTR_{fi} = \max_{j \in J}(MTTR_{fij})
\]

where

\( MTTR_{fi} = \text{maximum mean time to repair of part family } f \text{ in machine } i \)
With the $MTTR_{fi}$ determined, the hypothetical highest downtime costs can be determined. The hypothetic downtime represents the highest possible downtime costs of a part within a machine that has not been analysed yet. The downtime elements to determine the hypothetical highest downtime costs are then:

- Maximum shutdown time ($SDT_i$)
- Maximum setup time ($ST_i$)
- Maximum mean time to repair ($MTTR_{fi}$)
- $NCDT_i = \min_{p \in P}(NCDT_{pi})$
- $C_i = \max_{p \in P}(C_{pi})$
- Total failure effect is 100% ($TFE_{kij} = 1$)
- Failure is not detected before shutdown such that shutdown and delivery are in sequence ($FDBSD_{kij} = 0$)
- Delivery time is always incurred (in sequence with shutdown time) and the same for all locations ($LT_k$)

Conclusively the hypothetic downtime costs can thus be calculated with; $SDT_i$, $ST_i$, $TFE_{kij} = 1$, $FDBSD_{kij} = 0$, $MTTR_{fi}$ and $LT_k$, since all elements are available as shown in Table 31. The result is the highest possible downtime costs for part $k$ of part family $f$ in machine $i$.

Table 31 Available downtime costs elements

<table>
<thead>
<tr>
<th>Variable</th>
<th>Available</th>
<th>Variable</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_i$</td>
<td>Yes</td>
<td>$C_i$</td>
<td>Yes</td>
</tr>
<tr>
<td>$FDBSD_{kij}$</td>
<td></td>
<td>$FDBSD_{kij} = 0$</td>
<td>Yes</td>
</tr>
<tr>
<td>$LT_k$</td>
<td>Yes</td>
<td>$LT_k$</td>
<td>Yes</td>
</tr>
<tr>
<td>$MTTR_{kij}$</td>
<td></td>
<td>$MTTR_{fi}$</td>
<td>Yes</td>
</tr>
<tr>
<td>$NCDT_i$</td>
<td>Yes</td>
<td>$NCDT_i$</td>
<td>Yes</td>
</tr>
<tr>
<td>$SDT_{kij}$</td>
<td></td>
<td>$SDT_i$</td>
<td>Yes</td>
</tr>
<tr>
<td>$ST_{kij}$</td>
<td></td>
<td>$ST_i$</td>
<td>Yes</td>
</tr>
<tr>
<td>$TFE_{kij}$</td>
<td></td>
<td>$TFE_{kij} = 1$</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Current situation Hypothetical situation

Downtime, consequential downtime and downtime costs are given by respectively equation 0.20, 0.21 and 0.22.

$$DT_{kfi} = SDT_i + MTTR_{fi} + LT_k + ST_i$$  \hspace{1cm} (0.20)$$

Where $DT_{kfi}$ = hypothetical downtime of part $k$ of part family $f$ in machine $i$ (hours)

$$CDT_{kfi} = \max(0, DT_{kfi} - NCDT_i)$$  \hspace{1cm} (0.21)$$

Where $CDT_{kfi}$ = hypothetical consequential downtime of part $k$ of part family $f$ in machine $i$ (hours)

$$DC_{kfi} = CDT_{kfi} \times C_i$$  \hspace{1cm} (0.22)$$
Where
\[ DC_{kfi} = \text{hypothetical downtime costs of part k of part family f in machine i (€)} \]

In the hypothetical downtime costs calculation, \( TFE_{ki} \) is not included, because multiplying with 1 is redundant. With the hypothetical downtime costs of a part for all machines obtained the highest hypothetical downtime costs can be obtained (equation 0.23).

\[ DC_{kf} = \max_{i \in I} (DC_{kfi}) \]  \hspace{1cm} (0.23)

Where
\[ DC_{kf} = \text{maximum hypothetical downtime costs of part k of part family f (€)} \]

Conclusively, in this paragraph, a method to determine hypothetical downtime costs for parts, necessary for phase 1 of the inventory policy parameter values, has been determined. In the next paragraph a method to determine the (actual) highest downtime costs for parts for phase 2 is determined.

**J.2 Method to determine the highest downtime costs**

With the hypothetical highest downtime costs for parts determined, in phase 2, the actual highest downtime costs for parts needs to be determined. Therefore, machines are required to be analysed to obtain the detailed information of all parts. The goal is to do this in a certain order such that the actual highest downtime costs of a part are obtained in an efficient manner.

In the previous paragraph is explained that it is possible to obtain the hypothetical downtime costs, given that variables as shutdown time are the maximum. The result is that machine dependent variables are now:

- Shutdown time \((SDT_i)\)
- Setup Time \((ST_i)\)
- Non-consequential downtime \((NCDT_i)\)
- Cost associated with consequential downtime \((C_i)\)

With the four machine dependent elements of downtime (Shutdown time, Setup time, Non-consequential downtime, Cost associated with consequential downtime) the selection of machines can be made.

The idea behind the selection of a machine, using the machine dependent elements mentioned above, is that when a machine is selected with high downtime costs, the probability of finding a part with the highest downtime costs is larger. Cost associated with the consequential downtime is machine dependent and differ largely for each machine (from €1,200 to €11,000 per hour). Besides the shutdown time, setup time and non-consequential downtime are responsible for a large amount of the downtime and differ for each machine. MTTR takes for most locations not longer than 1.5 hour, and there are only few extreme cases of 6 or 8 hours, while shutdown and setup time of a machine can take 24 hours. The delivery time of a part is part dependent and therefore for each location the same.

The value of the machine dependent elements indicate thus for the greater part the downtime costs of a part on a specific location (i.e. machine and position). The premises results thus indeed that the probability of finding parts with the highest downtime costs becomes larger when a machine is selected with the highest downtime costs.
What the actual downtime costs is of a part on a specific location (i.e. machine and position) needs to be determined on part level. With a machine selected the assumptions can be dropped, because now the location and part dependent elements as shutdown time, MTTR, failure effect can be determined and the downtime costs can be calculated for a part on a specific location. With the downtime costs can be verified if a part encountered on a specific location indeed represents the highest downtime costs compared to the downtime costs of the same part on different locations (i.e. machine and position). From now on the highest downtime cost of a part refers to the highest possible downtime cost of a specific part. If there is no certainty about; whether the downtime costs are the highest, the part will be taken under consideration and later reviewed again.

Once the analysis of a machine is finished the downtime costs of the parts on every position are available, this information could lead to a new conclusion for parts in earlier analysed machines. Therefore is again verified whether a part represents the highest downtime costs or not. For example now can be concluded that a part that was under consideration indeed represents the highest downtime costs.

The developed method how to select a machine and afterwards verify if the parts within the machine represent the highest downtime costs is explained in this paragraph. The steps taken in this method are shown in Figure 45.

![Figure 45 Steps to determine the highest downtime costs of a part](image)

Each step of the method will be clarified with an example based on the information available at the time of the step (shown in a box with dotted borders). In Table 32 an example of the downtime costs and the related elements of the parts in each machine \((i)\) on every position.
(j) are shown. The highest downtime costs of each part are shown in bold. With this information in advance, it can be verified whether the method will result in the same highest downtime costs for parts.

J.2.1. Machine selection

The goal is to select a machine such that the probability of finding parts with the highest downtime costs is the highest. Taking the maximum ensures that most elements of the downtime costs are machine dependent such that part and location dependent elements are not required to be analysed (Table 33).

### Table 32 Example of actual situation

<table>
<thead>
<tr>
<th>Part</th>
<th>Part name</th>
<th>i</th>
<th>j</th>
<th>SdT&lt;sub&gt;ki&lt;/sub&gt;</th>
<th>ST&lt;sub&gt;ki&lt;/sub&gt;</th>
<th>TFE&lt;sub&gt;ki&lt;/sub&gt;</th>
<th>MTTR&lt;sub&gt;ki&lt;/sub&gt;</th>
<th>LT&lt;sub&gt;k&lt;/sub&gt;</th>
<th>FDBSD&lt;sub&gt;ki&lt;/sub&gt;</th>
<th>C&lt;sub&gt;i&lt;/sub&gt;</th>
<th>DC&lt;sub&gt;kij&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>A</td>
<td>1</td>
<td>12</td>
<td>12</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>€ 3,400</td>
<td>€ 146,200</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>A</td>
<td>2</td>
<td>12</td>
<td>12</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>€ 3,400</td>
<td>€ 139,400</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>A</td>
<td>3</td>
<td>12</td>
<td>12</td>
<td>2</td>
<td>24</td>
<td>1</td>
<td>€ 3,400</td>
<td>€ 102,000</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>B</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>€ 6,600</td>
<td>€ 118,800</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>C</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>€ 8,200</td>
<td>€ 106,600</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Bearing y</td>
<td>A</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>€ 3,400</td>
<td>€ 81,600</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sensor x</td>
<td>A</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>48</td>
<td>0</td>
<td>€ 3,400</td>
<td>€ 224,400</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sensor x</td>
<td>A</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>48</td>
<td>0</td>
<td>€ 3,400</td>
<td>€ 139,400</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sensor x</td>
<td>C</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>48</td>
<td>0</td>
<td>€ 8,200</td>
<td>€ 328,000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Pump x</td>
<td>B</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>€ 6,600</td>
<td>€ 59,400</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Pump x</td>
<td>C</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>€ 8,200</td>
<td>€ 106,600</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Pump x</td>
<td>D</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>€ 7,000</td>
<td>€ 140,000</td>
<td></td>
</tr>
</tbody>
</table>

### Table 33 Elements of downtime costs

<table>
<thead>
<tr>
<th>Part dependent</th>
<th>Location dependent</th>
<th>Machine dependent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery time (LT&lt;sub&gt;k&lt;/sub&gt;)</td>
<td>Mean time to repair (MTTR&lt;sub&gt;ki&lt;/sub&gt;)</td>
<td>Shutdown time (SDT&lt;sub&gt;i&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
<td>Setup Time (ST&lt;sub&gt;i&lt;/sub&gt;)</td>
<td>Non-consequential downtime (NCDT&lt;sub&gt;i&lt;/sub&gt;)</td>
</tr>
<tr>
<td></td>
<td>Cost associated with consequential downtime (C&lt;sub&gt;i&lt;/sub&gt;)</td>
<td></td>
</tr>
</tbody>
</table>

However, the part and location dependent elements of downtime, given by MTTR<sub>ki</sub> and LT<sub>k</sub>, are unknown before the parts are analysed; these differ for different parts and it is not know which parts are in which machine. The question that arises: how can a machine be selected without having parts specific information about the MTTR and delivery time? A solution is to replace the MTTR<sub>ki</sub> + LT<sub>k</sub> by a variable, T (for time), which represents a hypothetical value for MTTR<sub>ki</sub> + LT<sub>k</sub>. Substituting MTTR<sub>ki</sub> + LT<sub>k</sub> with T results in:

\[
DT_i(T) = T + SDT_i + ST_i
\]  

(0.24)

Because the real value for MTTR<sub>ki</sub> and LT<sub>k</sub> is unknown, T can be used to represent these as hypothetical values. As a result, the downtime for a machine can be determined, given a certain value for T is chosen. With the downtime for a machine known, the downtime costs for a machine can be determined, using equation 0.26.

\[
CDT_i(T) = \max(0, DT_i(T) - NCDT_i)
\]  

(0.25)
\[ DC_i(T) = CD_i(T) \times C_i \] (0.26)

Naturally, the downtime costs for machine will partially depend on the chosen value for \( T \) and as such, for one value for \( T \) a specific machine can have higher downtime costs than another machine (with the same value for \( T \)) than when using another value for \( T \). As a result, it can be determined for what values for \( T \) a specific machine has the highest downtime costs. Doing this for all machines results in knowing that, for a specific value of \( T \), a machine has the highest downtime costs. This allows answering the question which machine has the highest downtime costs given that the MTTR and delivery time are equal to a certain \( T \).

Conclusively, to find which machines has the highest downtime costs, equations 0.24, 0.25 and 0.26 require to be executed for machines for different values of \( T \). This allows comparison between downtime costs for all machines such that the machine with the highest downtime costs can be selected for analysis.

An example of finding the highest downtime costs for 4 machines shown in Table 34. The example will be used to explain how procedure just described will help to find the highest downtime costs.

<table>
<thead>
<tr>
<th>Machine</th>
<th>( NCDT_i )</th>
<th>( SDT_i )</th>
<th>( ST_i )</th>
<th>( C_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8</td>
<td>12</td>
<td>12</td>
<td>€ 3,400</td>
</tr>
<tr>
<td>B</td>
<td>24</td>
<td>8</td>
<td>8</td>
<td>€ 6,600</td>
</tr>
<tr>
<td>C</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>€ 8,200</td>
</tr>
<tr>
<td>D</td>
<td>20</td>
<td>4</td>
<td>4</td>
<td>€ 7,000</td>
</tr>
</tbody>
</table>

For example when \( T = 0 \) in machine A the downtime, consequential downtime and the downtime costs are respectively (using equation 0.24, 0.25 and 0.26);

\[
\begin{align*}
DT_A(0) &= 0 + 12 + 12 = 24 \text{ hours} \\
CDT_A(0) &= \max(0, 24 - 8) = 16 \text{ hours} \\
CDC_A(0) &= 16 \times 3400 = € 54,400
\end{align*}
\]

The result of varying \( T \) for the 4 machines in Table 34 is shown in Figure 46, where the downtime costs on the vertical axis represent the total downtime costs \( (DC_i) \) in euros and on the horizontal axis the value for \( T \) (in hours) is displayed.
With different consequential downtime costs at each point as shown in Figure 46, it is also possible to determine the highest downtime costs of each point in time. Equation 0.27 gives the maximum downtime costs over all machines for each point in time.

$$\max_{i \in I}(DC_i(T)), \quad \forall T$$ (0.27)

For example at $T = 0$, the maximum downtime costs of machine A, B, C and is; $\max_{i \in I}(DC_A = €54,400, DC_B = €0, DC_C = €0, DC_D = €0)$ and thus machine A, with $DC_A = €54,400$, has the highest downtime costs at $T = 0$. Determining the downtime costs for all four machines for more values for $T$ results that for certain intervals of $T$, a machine has the highest downtime costs. In the example in Figure 46 Machine A has the highest downtime costs (i.e. the highest line) on the interval 0 up to 31 hours, Machine C from 31 or more. The results are shown in Table 35 where the highest downtime costs are indicated in purple.

<table>
<thead>
<tr>
<th>Time</th>
<th>0</th>
<th>1</th>
<th>…</th>
<th>31</th>
<th>32</th>
<th>…</th>
<th>50</th>
<th>51</th>
<th>…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine A</td>
<td>€54,400</td>
<td>€57,800</td>
<td>…</td>
<td>€159,800</td>
<td>€163,200</td>
<td>…</td>
<td>€224,400</td>
<td>€227,800</td>
<td>…</td>
</tr>
<tr>
<td>Machine B</td>
<td>€0</td>
<td>€0</td>
<td>…</td>
<td>€151,800</td>
<td>€158,400</td>
<td>…</td>
<td>€277,200</td>
<td>€283,800</td>
<td>…</td>
</tr>
<tr>
<td>Machine C</td>
<td>€0</td>
<td>€0</td>
<td>…</td>
<td>€155,800</td>
<td>€164,000</td>
<td>…</td>
<td>€311,600</td>
<td>€319,800</td>
<td>…</td>
</tr>
<tr>
<td>Machine D</td>
<td>€0</td>
<td>€0</td>
<td>…</td>
<td>€133,000</td>
<td>€140,000</td>
<td>…</td>
<td>€266,000</td>
<td>€273,000</td>
<td>…</td>
</tr>
</tbody>
</table>

From these results can be concluded that analysis could best be started with machine A and C; for these machines determine the highest downtime costs for the values for $T = 0$ to infinity. Although $T$ is unknown before actually analysing the machines, with this method, it can be concluded that whatever these values are, machines A and C will always have the highest downtime costs compared to the other machines. The only thing that needs to be verified is whether a part is actually installed in the machine under analysis and whether the
values for T (i.e. \(MTTR_{kij}\) and \(LT_k\)) correspond with the value for the highest downtime costs. A method to investigate this is discussed in the next paragraph (i.e. paragraph xxx).

The highest line on a certain interval can thus be seen as a frontier \((FI_{zi} = \text{Frontier interval } z \text{ represented by machine } i)\); there is no machine with higher downtime costs on this interval. The combinations of machines that cover all intervals of T until \(T = \infty\), shape the entire frontier of machines with the highest downtime costs. In Figure 47 the frontier of the example is indicated with a red line.

![Figure 47 Frontier highest downtime costs](image)

It is thus possible to select a machine that has the highest downtime costs on an interval for values of \(T\).

The result of selecting a machine of the frontier and analysing all its parts is and if all assumptions are met; the highest downtime costs of specific parts can be found directly. However the assumptions do not represent the real world. Nonetheless, by selecting a frontier machine (i.e. machine with highest downtime costs on an interval) the probability of finding a part that has the highest downtime costs is larger.

The frontier determines which machines are first selected for analysis, because these are most likely to have parts with the highest downtime costs. When all parts within a selected machine are analysed, the machine can removed from the frontier and a new frontier is created such that a new machine can be selected for analysis. To determine the new frontier new maximums for values of \(T\) have to be determined using equation 3.19.
**J.2.2. Analyse parts within the machine**

With a selected machine of the previous step, the parts within the machine can be analysed. The method to determine if a part on a specific position has the highest downtime costs is explained in this paragraph.

The basic principle behind the selection of a machine is that the parts within the machine incur the maximum possible shutdown time, setup time. However as explained in 4.2.1 these elements are location dependent and differ thus per location. The question that arises is: how is known if a part contains the highest downtime costs? This question is answered in 4 steps shown in Figure 48. First in step 1 the downtime costs of all parts within the selected machine are determined. Because a part can be installed on more positions within a machine, in the next step, the maximum downtime costs of the parts within the machine are calculated. Subsequently a part with the maximum downtime costs is selected and further analysed, this part is called a part under analysis. The downtime costs of a part under analysis ($D_C u$) is compared with a hypothetical downtime costs for parts within not yet analysed machines. Lastly is $D_C u$ compared with the downtime costs of the part in already analysed machines.

An answer whether the downtime costs is the highest or not, is not immediately possible (not all information is available, since not all machines are analysed), therefore, it is determined if the $D_C u$ is the highest, not the highest or still under consideration. 3 subsets are used for this purpose:

- $HDC$ (highest downtime costs) = subset of parts $(k_{ij})$ that have the highest downtime costs
- $DCUC$ (Downtime costs under consideration) = subset of parts $(k_{ij})$ where the downtime costs are under consideration
- $NHDC$ (not the highest downtime costs) = subset of parts $(k_{ij})$ that do not have the highest downtime costs

When new machines are analysed more information becomes available and a final answer can be given whether a part belongs to the subset HDC or NHDC. How each step works in detail is described in the next paragraphs.
3.2.1. Select machine (m_i)

3.2.2. Analyse all parts within machine (m_i)

3.2.3. Verify if new information results to new classification

All machines (m_i) analysed?

Yes

End

No

1) Determine downtime costs of each part (k_i) in machine i

Yes

2) Determine maximum DC of each part (k_i) in machine i

Select a part with maximum DC of step 2

3) Determine maximum DC (u) vs hypothetic DC

4) Determine if DC is the highest, not the highest or under consideration

All parts (k_{ij}) with maximum DC analysed?

No

Yes

Figure 48 Steps of analysing parts within a machine
J.2.2.1. Step 1 Determine downtime costs of each part

First, for all parts within the machine the downtime elements ($SDT_{kij}$, $ST_{kij}$, $TFE_{kij}$, $FDBSD_{kij}$, $MTTR_{kij}$ and $LT_k$) are determined and their downtime costs is calculated ($DC_{kij}$).

### Iteration 1 (All parts of machine A)

With machine A selected in the previous step all the downtime elements and the downtime costs of all parts on all positions within the machine can be determined. The results are shown in Table 36.

<table>
<thead>
<tr>
<th>Part</th>
<th>Part name</th>
<th>i</th>
<th>j</th>
<th>$SDT_{kij}$</th>
<th>$ST_{kij}$</th>
<th>$TFE_{kij}$</th>
<th>$MTTR_{kij}$</th>
<th>$LT_k$</th>
<th>$FDBSD_{kij}$</th>
<th>$C_i$</th>
<th>$DC_{kij}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>A</td>
<td>1</td>
<td>12</td>
<td>12</td>
<td>1</td>
<td>3</td>
<td>24</td>
<td>0</td>
<td>$\€ 3,400$</td>
<td>€ 146,200</td>
</tr>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>A</td>
<td>2</td>
<td>12</td>
<td>12</td>
<td>1</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>$\€ 3,400$</td>
<td>€ 139,400</td>
</tr>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>A</td>
<td>3</td>
<td>12</td>
<td>12</td>
<td>1</td>
<td>2</td>
<td>24</td>
<td>1</td>
<td>$\€ 3,400$</td>
<td>€ 102,000</td>
</tr>
<tr>
<td>2</td>
<td>Bearing y</td>
<td>A</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>24</td>
<td>0</td>
<td>$\€ 3,400$</td>
<td>€ 81,600</td>
</tr>
<tr>
<td>3</td>
<td>Sensor x</td>
<td>A</td>
<td>1</td>
<td>12</td>
<td>12</td>
<td>1</td>
<td>2</td>
<td>48</td>
<td>0</td>
<td>$\€ 3,400$</td>
<td>€ 224,400</td>
</tr>
<tr>
<td>3</td>
<td>Sensor x</td>
<td>A</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>48</td>
<td>0</td>
<td>$\€ 3,400$</td>
<td>€ 139,400</td>
</tr>
</tbody>
</table>

J.2.2.2. Step 2 Determine maximum downtime costs of each part within machine i

As soon as all parts are analysed, for each part the maximum downtime costs determined based on the equation below. When $DC_{kij}$ is not a maximum, the part is added to the subset NHDC, else the analysis can continue to step 3.

$$\text{If } DC_{kij} = \max_{j \in J}(DC_{kij})$$

then continue to step 3

$$\text{else } DC_{kij} \in NHDC$$

For convenience from now $\max_{j \in J}(DC_{kij})$ is called $DC_u$
J.2.2.3. Step 3 Determine maximum $DC_u$ vs hypothetic downtime costs

In the ideal situation the downtime costs of a part would be compared with the downtime costs on all locations, however because Vlisco does not know exactly which parts are in which machine this information is not available until all machines are analysed. The question that arises is; how is it possible to make a conclusion on whether the highest downtime costs for a part has been found, without having to analyse all parts within every machine? A possible solution is to use the hypothetic downtime costs of phase 1. The hypothetic downtime cost represents the highest possible downtime costs of a part within a machine that has not been analysed yet. This hypothetic downtime costs makes it feasible to compare $DC_u$ with parts in machines that are not yet analysed.

Thus when $DC_u$ is higher than the hypothetic downtime costs, there is no possibility there exist a higher downtime costs within the not yet analysed machine for this part. In addition to the premise; when the $DC_u$ is the maximum of all hypothetic downtime cost of this part it is certain that $DC_u$ is the highest downtime costs compared with not yet analysed machines. The sub-steps of step 3 are shown in Figure 49 and described below.
**Figure 49 Steps to determine maximum DC_u vs hypothetic DC**

**Sub-step 3a Determine part family and remove hypothetical downtime costs of machine under analysis**

For the part under analysis of step 2 the part family \( f \) is determined. Now the hypothetical downtime costs for all parts of this part family changed to 0 (such that these are not considered anymore). The actual downtime costs of all parts within this machine are after all known.

Replace \( DC_{kfi} \) by \( DC_{kfi} = 0 \) for \( \forall k \) of part family \( f \) of machine \( i \)

\[(0.29)\]
**Sub-step 3b  Verify if $DC_{kf}$ is available**

With the equation below can be verified if there already exists a value for $DC_{kf}$ for part family $f$ with downtime costs of not yet analysed machines. If the $c$ does not exist (i.e. $DC_{kf}$ is not equal to a real value), e.g. because this part was not analysed before in phase 1, there is no opportunity to compare $DC_{k}$ with the hypothetical downtime costs $DC_{kf}$. To create $DC_{kf}$ the method continues to step c. However whenever the $DC_{kf}$ does exist ($DC_{kf}$ is equal to a real value), the downtime costs $DC_{kf}$ can be compared to hypothetical downtime costs $DC_{kfi}$ and there is continued to step d.

\[
\text{If } DC_{kf} = \mathbb{R} \\
\quad \text{then continue to step d} \\
\text{else continue to step c (0.30)}
\]

where

$DC_{kf} = \text{maximum hypothetical downtime costs of part } k \text{ of part family } f$

$DC_{kfi} = \text{hypothetical downtime costs of part } k \text{ of part family } f \text{ in machine } i$

---

**Iteration 1 (Part 1 out of machine A on position 1)**

A part is selected for which in step 2 was concluded that it has the highest downtime costs in machine A. $DC_{1A}$ is the highest downtime costs of part 1 (bearing x) in machine A. Now the part family is determined: “Part 1” is a bearing and therefore its part family is “Bearings”

**Table 38 Example part family**

<table>
<thead>
<tr>
<th>Name</th>
<th>1 Bearing</th>
</tr>
</thead>
</table>

Now all hypothetical downtime costs ($DC_{kfi}$) known from phase 1 for parts of part family bearings can be changed to 0. Which results into the following hypothetical downtime costs:

**Table 39 Hypothetical downtime costs of parts of part family bearings**

<table>
<thead>
<tr>
<th>$k$</th>
<th>$f$</th>
<th>Family name</th>
<th>$i$</th>
<th>MTTR$_{fi}$</th>
<th>$DC_{kfi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Bearing A</td>
<td>4</td>
<td>€</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Bearing B</td>
<td>2</td>
<td>€</td>
<td>118,800</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Bearing B</td>
<td>2</td>
<td>€</td>
<td>118,800</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Bearing C</td>
<td>1</td>
<td>€</td>
<td>106,600</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Bearing C</td>
<td>1</td>
<td>€</td>
<td>106,600</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Bearing D</td>
<td>n.a.</td>
<td>€</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Bearing D</td>
<td>n.a.</td>
<td>€</td>
<td>0</td>
</tr>
</tbody>
</table>

---

**Iteration 1 (Part 1 out of machine A on position 1)**

In step 3a was concluded that “Part 1” is part of the part family “Bearings”. For part 1 hypothetical downtime costs are available, thus $DC_{kfi} = \mathbb{R}$ and there is continued to step d.
Sub-step 3c  Create $DC_{kf}$
Determine $MTTR_{fi}$ and calculate $DC_{kf,i}$ for all machines not yet analysed to determine $DC_{kf} = \max_{i \in I}(DC_{kf,i})$. When a part family is not installed in a machine, the $DC_{kf,i}$ is set to 0.

It is only possible to arrive in step 3c when the part is not analysed in phase 1. To demonstrate this step there is therefore a jump taken into the number of iterations. There is assumed that part 3 of part family sensors is never analysed.

Iteration 3 (Part 3 out of machine A on position 1)
Machine B, C and D are not yet analysed. The $MTTR_{fi}$ and $DC_{fi}$ are determined for the part family “Sensors”. The results are shown in the table below.

<table>
<thead>
<tr>
<th>$f$</th>
<th>Family name</th>
<th>$i$</th>
<th>$MTTR_{fi}$</th>
<th>$DC_{kf,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sensors</td>
<td>B</td>
<td>n.a.</td>
<td>€ 0</td>
</tr>
<tr>
<td>1</td>
<td>Sensors</td>
<td>C</td>
<td>4</td>
<td>€ 328,000</td>
</tr>
<tr>
<td>1</td>
<td>Sensors</td>
<td>D</td>
<td>n.a.</td>
<td>€ 0</td>
</tr>
</tbody>
</table>

Since there are no sensors installed in machine B and D, the $DC_{kf,i}$ is set to 0. The result is: $DC_{kf} = € 328,000$.

Sub-step 3d  Determine if $DC_u$ is the maximum
In this step is verified if the part under analysis has the highest downtime costs compared to the hypothetical downtimes. In both cases the result can be compared with the downtime costs of parts in machines that are already analysed.

If $DC_u \geq DC_{kf}$
then continue to step 4a
else continue to step 4d

(0.31)

Iteration 1 (Part 1 out of machine A on position 1)
In the step 3c the subset of hypothetical downtime costs was created. Now the downtime costs of the part under analysis can be compared with these hypothetical downtime costs:

$DC_u = € 146,200$
$DC_{kf} = € 118,8000$

thus
$DC_u > DC_{kf}$

$DC_u$ is bigger than $DC_{kf}$ therefore there is continued with step 4a.

J.2.2.4.  Step 4 Determine if $DC_u$ is the highest, not the highest or under consideration.
Once is determined if the $DC_u$ is higher or lower than maximum of the hypothetical downtime costs, it can be determined in step 4 whether the downtime costs of a part is the highest, not the highest or still under consideration. How this process works is described below and the main structure is shown in Figure 50.
The conclusion in step 3 determines which decision tree is taken, namely when is concluded that the $DC_u$ is bigger or equal than the $DC_{kf}$ the analysis continues at sub-step 4a and else in sub-step 4d.

**Sub-step 4a Verify if part is an element of HDC**

In step 3 is concluded that the $DC_u$ are higher than the hypothetic downtime costs in all machines that still have to be analysed. Now is verified (with the equation below) if the part is earlier encountered in a machine that is already analysed and was identified as the highest. When the part is an element of the subset highest downtime costs $DC_u$ is not the highest, else can be continued to step b.

$$\text{If } k \in HDC \quad \text{then } DC_u \in NHDC \quad (0.32)$$

**Iteration 1 (Part 1 out of machine A on position 1)**

Part 1 is the first part that is analysed therefore the part is not earlier encountered and the subset HDC is empty: $HDC = \emptyset$. $K$ is thus not an element of HDC and therefore there is continued with step 4b.
Sub-step 4b Verify if part is an element of DCUC
Step a verified that the part is not encountered as the highest downtime costs in previously analysed machines. In this step is checked if the part is an element of the subset where the downtime costs is under consideration. When this is the case these need to be compared in step c, else $DC_u$ the highest (since $DC_u$ is the maximum of parts in not yet analysed machines and is not encountered in already analysed machines).

\[
\text{If } k \in DCUC \\
\text{then continue to step c} \\
\text{else } DC_u \in HDC
\]  

\[ (0.33) \]

Iteration 1 (Part 1 out of machine A on position 1)

Part 1 ($k$) is the first part that is analysed therefore the part is not earlier encountered and the subset DCUC is empty: $DCUC = \emptyset$. $K$ is thus not an element of DCUC and therefore $DC_u$ is an element of HDC. Consequently, the analysis of part 1 in machine A is finished and a new iteration can be started.

$$HDC = \{DC_{1A1} = €146,200\}$$

Sub-step 4c Compare $DC_u$ with $DC_{DCUC}$
If in step b is concluded that the part is an element of the subset where downtime costs are under consideration, then in this step is determined if $DC_u$ is higher than $DC_{DCUC_u}$. When $DC_u$ is higher than the parts within the machines that still have to be analysed, thus when $DC_u$ higher than the downtime costs under consideration ($DC_{DCUC_u}$), $DC_u$ is the highest possible. However when $DC_u$ is smaller than $DC_{DCUC_u}$, $DC_{DCUC_u}$ is the highest possible.

\[
\text{If } DC_u > DC_{DCUC_u} \\
\text{then } DC_u \in HDC \text{ and } DC_{DCUC} \in NHDC \\
\text{else } DC_{DCUC_u} \in HDC \text{ and } DC_u \in NHDC
\]

\[ (0.34) \]

where
$DC_{DCUC_u} =$ downtime costs of the part under analysis in subset DCUC (€)
Following the decision tree for when $DC_u$ is bigger or equal than the $DC_{kf}$ resulted in a highest downtime costs for part $k$. Next sub-steps are related to the decision tree for when $DC_u$ was smaller than the $DC_{kf}$.

**Sub-step 4d Verify if part is an element of HDC**

Step 4d is reached if in step 3 is concluded that the $DC_u$ is smaller than the hypothetic downtime costs in all machines that still have to be analysed. Now is verified (with the equation below) if the part is earlier encountered in a machine that is already analysed and was identified as the highest. When the part is indeed earlier encountered as the highest and thus an element of the subset highest downtime costs, $DC_u$ is not the highest, else can be continued to step e.

If $k \in HDC \quad (0.35)$

---

$HDC = \{DC_{1A1} = €146.200\}$
$DCUC = \{DC_{2A1} = €81.600, DC_{3A1} = €224.400\}$

**Iteration 5 (Part 3 out of machine C on position 1)**

When the analysis of machine A was finished, the machine was removed from the frontier and a new frontier is originated (as explained in the machine selection step). The next machine that is analysed is machine C, because it is an element of the new frontier. The result of step 1 and 2 for machine C is shown in Table 40.

**Table 40 Maximum downtime costs of parts in machine C**

<table>
<thead>
<tr>
<th>Part</th>
<th>Part name</th>
<th>i</th>
<th>j</th>
<th>$\max(DC_{kJ})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>C</td>
<td>1</td>
<td>€106,600</td>
</tr>
<tr>
<td>3</td>
<td>Sensor x</td>
<td>C</td>
<td>1</td>
<td>€328,000</td>
</tr>
<tr>
<td>4</td>
<td>Pump x</td>
<td>C</td>
<td>1</td>
<td>€106,600</td>
</tr>
</tbody>
</table>

The part that is analysed in iteration 5 is part 3. In step 3 is concluded that part 3 is bigger than the hypothetical downtime costs, such that it via step 4a and c ends up in this step (4c). Now the DCUC of part 3 can be compared with the downtime costs of part 3 in machine C:

$DC_u = €328,000$
$DC_{DCUCu} = €224,400$

thus

$DC_u > DC_{DCUCu}$

$DC_u$ is bigger than $DC_{DCUCu}$ therefore there is concluded that $DC_{3C1}$ is an element of the subset $HDC$ and $DC_{3A1}$ of subset $NHDC$. The summary of the results is:

$HDC = \{DC_{1A1} = €146.200, DC_{3C1} = €328.000\}$
$DCUC = \{DC_{2A1} = €81.600\}$
then $DC_u \in NHDC$
else continue to step e

Iteration 6 (Part 4 out of machine C on position 1)

In step 3 is concluded that part 4 is smaller than the maximum hypothetical downtime costs, therefore there could be parts in other machine that have a higher downtime costs. Since the part is not earlier encountered as an element of the subset HDC the subset HDC is empty: $HDC = \emptyset$. $k = 3$ is thus not an element of HDC and therefore there is continued with step 4e.

Sub-step 4e Verify if part is an element of DCUC
Step d verified that the part is not encountered as the highest downtime costs in previously analysed machines. In this step is checked if the part is an element of the subset where the downtime costs is under consideration. When this is the case the downtime costs need to be compared in step f, else $DC_u$ is an element of the subset downtime costs under consideration. Since $DC_u$ is not the maximum of parts in not yet analysed machines and there could thus exist a part with higher downtime costs.

$$\text{If } k \in DCUC$$
then continue to step f
else $DC_u \in DCUC$  

Sub-step 4f Compare $DC_u$ with $DC_{DCUC_u}$
Step e showed that the part is an element of the subset where downtime costs are under consideration, therefore is now determined if $DC_u$ or $DC_{DCUC}$ is higher. When $DC_u$ is higher than the downtime costs under consideration ($DC_{DCUC}$), $DC_u$ is the added to the subset DCUC and $DC_{DCUC_u}$ is moved to the subset NHDC. However when $DC_u$ is smaller than $DC_{DCUC_u}$, the result is the other way around.

$$\text{If } DC_u > DC_{DCUC_u}$$
then $DC_u \in DCUC$ and $DC_{DCUC_u} \in NHDC$  
else $DC_{DCUC_u} \in DCUC$ and $DC_u \in NHDC$
It is only possible to arrive in step 4f when a new machine is analysed and in an earlier analysed machine the part is added to the subset DCUC. To demonstrate this step is therefore a jump taken into the number of iterations and first a summary is given of the results of earlier iterations:

\[ HDC = \{ DC_{1A1} = € 146.200, DC_{3C1} = € 328.000 \} \]
\[ DCUC = \{ DC_{2A1} = € 81.600, DC_{4C1} = € 123.000 \} \]

**Iteration 9 (Part 4 out of machine B on position 1)**

When the analysis of machine C was finished, the machine was removed from the frontier and a new frontier is originated (as explained in the machine selection step). The next machine that is analysed is machine B, because it is an element of the new frontier. The result of step 1 and 2 for machine B is shown in Table 41.

<table>
<thead>
<tr>
<th>Part</th>
<th>Part name</th>
<th></th>
<th>j</th>
<th>( \max_{j&lt;3} (DC_{kj}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bearing x</td>
<td>B</td>
<td>1</td>
<td>€ 118,800</td>
</tr>
<tr>
<td>4</td>
<td>Pump x</td>
<td>B</td>
<td>1</td>
<td>€ 59,400</td>
</tr>
</tbody>
</table>

The part that is analysed in iteration 9 is part 4. In step 3 is concluded that part 4 is smaller than the hypothetical downtime costs, such that it via step 4d and e ends up in this step (4f). Now the DCUC of part 4 can be compared with the downtime costs of part 4 in machine B:

\[ DC_u = € 59.400 \]
\[ DC_{DCUC_u} = € 123.000 \]

thus
\[ DC_u < DC_{DCUC_u} \]

Therefore there is concluded that \( DC_{4B1} \) is an element of the subset NHDC and \( DC_{4C1} \) remains an element of subset DCUC. The summary of the results is:

\[ HDC = \{ DC_{1A1} = € 146.200, DC_{3C1} = € 328.000 \} \]
\[ DCUC = \{ DC_{2A1} = € 81.600, DC_{4C1} = € 123.000 \} \]
J.2.3. Verify if new information results to new classification

J.2.3.1. Verify if part becomes an element of HDC

Once all parts in a machine are analysed, the hypothetical downtime costs of all parts \( (DC_{kfi}) \) that were created for this machine are changed into 0 in step 3a. Parts that were not encountered in this machine, but earlier added to the subset \( DCUC \), because the hypothetical downtime costs were bigger could now be the highest. All parts in the subset \( DCUC \) should therefore be checked again, to verify if the downtime costs are now higher than the remaining hypothetical downtime costs. The downtime costs of the parts in the subset \( DCUC \) are compared with the maximum hypothetical downtime costs via the equation below:

\[
\text{If } DC_{DCUC_u} \geq DC_{kf} \text{ then } DC_{DCUC_u} \in HDC \\
\text{else } DC_{DCUC_u} \in DCUC \quad (0.38)
\]
All parts of machine B are now analysed. $DC_{k_f B}$ is changed into 0 in step 3a for parts of all product families of machine B. The downtime costs of parts in subset DCUC could now be the highest, because the only restriction the downtime costs were not the highest, could be the hypothetical downtime costs of machine B. Therefore is verified in iteration 10 if parts that were added to the subset DCUC have the highest downtime costs.

Iteration 10 (Part 2 out of machine A on position 1)

The downtime costs that is analysed in iteration 10 is of part 2 in machine A on position 1; $DC_{2A1}$.

$DC_{DCUC_u} = € 81,600$

$DC_{k_f} = € 0$

thus

$DC_{DCUC_u} \geq DC_{k_f}$

$DC_u$ is bigger than $DC_{DCUC_u}$ therefore there is concluded that $DC_{2A1}$ is an element of the subset HDC. The summary of the results is:

$HDC = \{DC_{2A1} = € 146,200, DC_{2A1} = € 81,600, DC_{3C1} = € 328,000\}$

$DCUC = \{DC_{4C1} = € 123,000\}$
Appendix L. Selection demand distribution

L.1 Approach
There are 2 approaches to determine a demand distribution (Syntetos et al., 2012):

(i) Parametric approaches that assumes a demand distribution that estimates the mean and variance using available demand (e.g. forecasting procedures, goodness of fit)

(ii) Non-parametric (empirical) approaches that re-construct the demand distribution (e.g. frequency distributions, bootstrapping)

The parametric approach is an exploratory method, as it makes assumptions and thus a statement about unknown data. Whether this is possible, demands on how much data is unknown. The non-parametric approach only takes known data into account. The number of demand occurrences over the total available demand history (2009-2015) of Vlisco is analysed of which the results are shown Figure 51. From it can be concluded that 69% of the parts have only 4 demand occurrences or less. With 13 or less demand occurrences already 90% of the parts are included. The conclusion is thus that the majority of the parts have not enough data from which the demand distribution can be assumed using a parametric approach.

Using a parametric method would thus result in making conclusions on a large amount of unknown data for at least 69% of the parts. Additionally, a parametric approach increases in complexity when more types of demand data exists. Vlisco has smooth, erratic, intermittent and lumpy demand. Each demand category has its own characteristics and for a parametric approach this would incur different distributions to be assumed for the data. A parametric approach implies thus understanding of many distributions. With an empirical approach the only assumption made is that the demand seen in the past will also occur in the future. Additional, just 1 method is needed to be able to cope with the different demand characteristics. An empirical approach is therefore more robust. Concluding, the preferable approach is an empirical approach due to stationarity of the data, the small sample sizes and the required assumptions.

L.2 Data Validation
With a part of the spare parts having low amount of occurrences, it needs to be determine whether these data points are reliable enough to be used to fit an empirical distribution to. For some parts, low occurrences resemble the actual demand pattern but for other parts, it might not. Data validation is therefore done by the maintenance engineers of Vlisco in which they decide if the demand data is valid for parts.

Appendix M. Fit statistic
The data acquired through the simulation is grouped (i.e. optimal s levels on integers). An eligible goodness of fit tests for this specific kind of data is the Chi-Square test (i.e. Pearson ratio test). With grouped data, variables fall into k+1 intervals of \[ I_j = [a_{j-1}, a_j), \quad j = 1, ..., k + 1 \]  

The upper limit of the s level is equal to \( a_{k+1} \). Let \( d_j \) be the number runs of the in total \( n \) runs for s level \( I_j \). With \( p_j \) is equal to the probability that a s level lies in the interval of \( I_j \); \[ p_j = \frac{d_j}{n} = \text{Probability} (\text{Lifetime} \in I_j), \text{where} \sum p_j = 1 \]

The chi-square test provides insight concerning whether there is a difference between two sets of optimal s levels generated by the different number of runs (i.e. using a simulation of 100 runs and comparing it with a simulation of 200 runs). Using the hypothesis, the Chi-square test statistic can be used to determine when there is a difference between the data sets. The null hypothesis \( (h_0) \) is the following: ‘data set A comes from the same distributions as data set B’ whereas the alternative hypothesis \( (h_1) \) is ‘Data set A and data set B come from different distributions’, this equals; 

\[ h_0: p_j = p_j(\theta_1, \theta_2) \text{ for } j = 1, ..., k + 1 \]  
\[ h_1: p_j \neq p_j(\theta_1, \theta_2) \text{ for } j = 1, ..., k + 1 \]

The hypothesized statistical distribution selected for the estimated data is the two parameter Weibull function, its parameters (Shape and Scale) are denoted by \( \theta_1 \) and \( \theta_2 \).

To conclude whether there is a difference between the data sets, first, the \( \chi^2 \) test statistic needs to be calculated, which is equal to;

\[ \chi_0^2 = \sum_{j=1}^{k+1} \frac{(p_j - p_j(\theta_1, \theta_2))^2}{p_j(\theta_1, \theta_2)} \]  

Then the, \( \chi_0^2 \) test statistic is compared to the \( \chi^2 \) reference statistic which determines the critical region. Whenever the test statistic is bigger than the critical region, the null hypothesis is rejected. This is because high \( \chi_0^2 \) test statistic values mean higher deviations between the estimated and the fitted data. The reference statistic follows a chi-square distribution which is equal to;

\[ \text{Critical Region} = \chi_{p-value, degrees of freedom}^2 \]

Therefore, the null hypothesis is rejected whenever the following holds;

\[ \chi^2 > \text{Critical Region} \]

The degrees of freedom of the reference statistic are equal to the number of rows minus 1 multiplied with the number of columns minus 1;

\[ \text{Critical Region} = \chi_{p-value,(r-1)*(c-1)}^2 \]

The p-value can be seen as a cut-off value and which can be set; it determines under which likelihood the null hypothesis must be tested e.g. how likely is it that data set A and data set B originate from the same distribution. With higher p-values used for the critical region, the test will be strict on reject the null hypothesis upon detecting smaller differences. Because
the data sets always differ, the p-value determines when this difference is too big to be seen as an acceptable deviation. Ultimately, a p-value of for example 0.75 means that it is 75% likely that data set A is the same as data set B. High p-value means that the test is going to reject the null-hypothesis quicker and thus accepts less deviation between the two data sets.

An example will show this procedure. First, a $\chi^2$ test statistic is calculated, using the formula above. Using t) shown in table X, the $\chi^2$ test statistic is calculated and equal to 16.2.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Data set A (runs)</th>
<th>Data set B (runs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

With 6 rows and 2 columns, the degrees of freedom required to determine the critical region is equal to 5. Depending on the p-value, the test statistic will either be larger or smaller than the critical region.

<table>
<thead>
<tr>
<th>P-value</th>
<th>Critical Region using 5 degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>24,8</td>
</tr>
<tr>
<td>0.2</td>
<td>20,5</td>
</tr>
<tr>
<td>0.4</td>
<td>16,3</td>
</tr>
<tr>
<td>0.8</td>
<td>12,8</td>
</tr>
</tbody>
</table>

It can be concluded that with higher p-values, the null hypothesis is more likely to be rejected, resulting in the conclusion that the data sets are not the same. This also shown in figures Figure 0-52 and Figure 0-53.

---

1 In technical terms, a P value is the probability of obtaining an effect at least as extreme as the one in your sample data, assuming the truth of the null hypothesis.
Figure 0-52 Critical Region vs P-value 0.1

Figure 0-53 Critical Region vs P-value 0.5
Appendix N. Explanation and example how the number of runs are determined

The number of runs are obtained as follows; first is verified from what amount of runs the s level seems to stabilizes via eyeballing a graph, subsequently the number of runs are tested via the Chi-square test. Finally the model is executed several times with the same amount of runs (called a try) and again verified if each try is identical distributed. An example for erratic demand is shown below.

Example: erratic demand

In Figure 54 is visible that the demand is clearly not identical distributed thus more runs are required. From 400 runs the s level seems to stabilize which can be seen in Figure 55 and therefore a test statistic is executed to confirm the results. The p-value of 500 runs compared to 400 runs is 0.948453, thus the test also indicates that the set of 400 and 500 runs are identical distributed.
In this extreme case there is no need do have more than 400 runs, however to be extra robust there is chosen for 500 runs such that the program works always as desired. 3 times the model is used with 500 runs and based on eyeballing the results shown in Figure 56 can be concluded that the runs are identical distributed.
When all tries are compared with each other via the chi-square test (Table 42) it can be concluded that with 500 runs the model is robust for erratic demand.

<table>
<thead>
<tr>
<th>Comparison (tries)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 vs 2</td>
<td>0.99999916</td>
</tr>
<tr>
<td>1 vs 3</td>
<td>0.99999012</td>
</tr>
<tr>
<td>2 vs 3</td>
<td>0.99999864</td>
</tr>
</tbody>
</table>
Appendix O. Sensitivity

O.1 Non consequential downtime

Table 43 Results sensitivity NCDT (scenario 7-9)

<table>
<thead>
<tr>
<th>NCDT</th>
<th>TRC</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>€ 281.07</td>
<td>0.2%</td>
<td>€ 922.34</td>
<td>13.6%</td>
<td>3</td>
</tr>
<tr>
<td>96</td>
<td>€ 280.45</td>
<td>11.5%</td>
<td>€ 668.95</td>
<td>27.5%</td>
<td>2</td>
</tr>
</tbody>
</table>

scenario 4

<table>
<thead>
<tr>
<th>NCDT</th>
<th>TRC optimal</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>€ 1,856.91</td>
<td>4.0%</td>
<td>€ 7,016.51</td>
<td>18.5%</td>
<td>3</td>
</tr>
<tr>
<td>72</td>
<td>€ 1,781.92</td>
<td>17.2%</td>
<td>€ 5,716.93</td>
<td>25.4%</td>
<td>2</td>
</tr>
</tbody>
</table>

scenario 5

<table>
<thead>
<tr>
<th>NCDT</th>
<th>TRC optimal</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>€ 7,120.25</td>
<td>17.2%</td>
<td>€ 25,113.37</td>
<td>25.4%</td>
<td>2</td>
</tr>
<tr>
<td>72</td>
<td>€ 5,892.36</td>
<td>13.6%</td>
<td>€ 18,724.16</td>
<td>20.5%</td>
<td>4</td>
</tr>
</tbody>
</table>

scenario 6

O.2 Cost rate

Table 44 Results influence cost rate (scenario 3)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>TRC</th>
<th>Deviation</th>
<th>Capital on stock</th>
<th>Deviation</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>€ 11,000</td>
<td>€ 8,579.63</td>
<td></td>
<td>€ 24,368.99</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Optimal</td>
<td>€ 6,100</td>
<td>€ 8,148.43</td>
<td>-5.0%</td>
<td>€ 24,368.99</td>
<td>0.0%</td>
<td>4</td>
</tr>
<tr>
<td>Optimal</td>
<td>€ 1,200</td>
<td>€ 7,717.23</td>
<td>-10.1%</td>
<td>€ 24,368.99</td>
<td>0.0%</td>
<td>4</td>
</tr>
</tbody>
</table>

Optimal | € 600   | € 6,621.05 | -22.8%    | € 19,377.03     | -20.5%    | 3 |
| Wrong  | € 600   | € 7,664.43 | 13.6%     | € 24,368.99     | 20.5%     | 4 |

Appendix P. Manual for the tool to determine the inventory control parameter values

This manual explains how the tool to determine the optimal parameter values should be used.

When opening the file, select the sheet “Input variables” (shown in Figure 57). First enter in column A and B respectively the date and the quantity of the demand of the part under consideration. The export date in cell D3 defines the date the demand data is exported into an excel file and should be entered as well. Further in column H all remaining input variables should be entered. The reorder level (s) and reorder quantity (Q) are optional.
After all data is entered the model can be executed, by clicking on the button “Run”, the screen shown in Figure 58 pops up.

The tool gives the opportunity to generate results based on manually entered values of the reorder level (s) and reorder quantity (q) or search for the optimal values. The optimal value for the reorder level can be searched based on only the service constraint (i.e. maximum machine waiting time) or the search can be executed also based on the costs. The tool is executed by clicking on the button “execute”. It takes 30-45 minutes before the results are generated with a Core i7 2670QM processor. The results are shown in sheet “Results” which is shown in Figure 59.
In column A - D the optimal reorder level (s) is shown for each separate run. Column F-K shows in green the optimal reorder level based on all demand seeds (500 runs) and in column M and N the summary of the optimal parameter values are given.

| A | s | From | Cumulative runs | Share of runs service constraint met | B | C | D | E | F | G | H | I | J | K | L | M | N | O |
|---|---|------|-----------------|-------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 0 | 0 | 0 | 0 | 7 | € 420.70 | € 224.50 | € 887.49 | € 1,073.49 | € 1,483.53 | 4 |
| 3 | 1 | 0 | 0 | 0 | 8 | € 470.30 | € 116.70 | € 776.30 | € 1,013.29 | € 1,625.29 | 10 |
| 4 | 2 | 1 | 1 | 0.002 | 9 | € 529.07 | € 115.09 | € 49.03 | € 683.12 | € 1,745.00 | 5 |
| 5 | 3 | 43 | 0.004 | 10 | € 589.90 | € 113.52 | € 876.70 | € 1,844.30 | |
| 6 | 4 | 164 | 0.414 | | | | | | | |
| 7 | 5 | 173 | 0.74 | | | | | | | |
| 8 | 6 | 477 | 0.574 | | | | | | | |
| 9 | 7 | 490 | 0.93 | | | | | | | |
| 10 | 8 | 497 | 0.994 | | | | | | | |
| 11 | 9 | 499 | 0.998 | | | | | | | |
| 12 | 10 | 500 | 1 | | | | | | | |