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DEVELOPMENT OF A SPARE PART INVENTORY SYSTEM

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ABSTRACT

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61 pages, 21 figures, 10 tables and 0 appendices

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Spare part management is an important part of operations in a large scale of businesses. Spare parts are relevant in a manufacturing industry to everything with wear parts from manufacturing machinery, to for example forklifts used in logistics. Spare parts require different methods to their management compared to more commonly studied inventory control methods such as storages within manufacturing or for example in a convenience store. Challenges present in spare part inventory management are infrequent difficult to predict demand, the low demand of parts and the large costs in case of a stockout. The objective of this study is to implement different methods for calculating and controlling spare part inventory levels found from literature in the factory for the chosen manufacturing machinery. The purpose of the implementation of new practices is to improve the reliability of the manufacturing machinery and to reduce late deliveries. New methods for controlling the inventory levels via an excel based system were done. In addition, a clear workflow for the ordering of spare parts and updating of stock levels was determined and spare parts were organized on the factory floor according to Lean and 5S principles. It was noticed that by making investments to the spare parts that have the smallest price compared to their failure rate big advantages in the system availability rate can be achieved for a relatively small investment. Investments to spare parts are a suitable way to improve the reliability of manufacturing machinery.

TIIVISTELMÄ

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Olli Salonen

Varaosajärjestelmän kehitys

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61 sivua, 21 kuvaa, 10 taulukkoa ja 0 liitettä

Tarkastaja: Professori Juha Varis
TkT Mikael Ollikainen

Hakusanat: Varaosajärjestelmä, varaston hallinta

Varaosien hallinta on tärkeä osa useiden yritysten toimintaa. Varaosat ovat oleellisia kaikilla teollisuuden aloilla, joissa käytössä on koneita, joihin kuuluu kuluvia osia. Varaosien hallinta vaatii eri käytäntöjä verrattuna esimerkiksi ruokakaupan varastojen hallintaan johtuen niiden epäsäännöllisestä tai pienestä kysynnästä ja puutetilanteissa syntyvistä suurista kustannuksista. Tämän diplomityön tavoitteena on ollut löytää tapoja varaosavarstojen varastotasojen hallintaan ja soveltaa niitä tehdasympäristössä. Varaosien hallinnan kehittämisen tulisi parantaa valmistuslaitteiston luotettavuutta ja vähentää myöhästyneitä toimituksia. Varaosien hallintaa varten kehitettiin Excel perusteinen laskentamalli, sekä määritettiin vastuut varaosien hallinnoimisesta. Varaosat järjestettiin tehtaalla Lean- ja 5S-filosofioiden mukaisesti. Kun hankittiin varaosia, joiden hinta suhteessa niiden kysyntään huomattiin, että suhteellisen pienillä investoinneilla saavutettiin huomattavia hyötyjä laitteiston luotettavuudessa. Investoinnit varaosiin on sopiva tapa parantaa valmistuslaitteiston luotettavuutta.

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Olli Salonen

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LIST OF SYMBOLS AND ABBREVIATIONS

λ	Failure rate [1/a]
DT	Downtime costs [€/h]
H	Holding rate [%]
lc	Labor costs per product [€]
mc	Manufacturing costs per product [€]
p	Profit per product [€]
P	Difference in costs for a stocking decision [€]
PA	System availability rate [%]
PT	Payback time [a]
Q	Order quantity [1]
R	Order costs [€]
S_{AVG}	Average stock [1]
SS	Safety stock [1]
t	Lead time [a]
$t_{manufacturing}$	Manufacturing time of a product [s]
t_{repair}	Time needed for repairs [a]
$t_{stockout}$	Expected time of stockout [a]
V	Value [€]

1 INTRODUCTION

Maintenance is the process in which an item is maintained in a state or restored to a state by repairs or other actions so that it can perform its desired function. Maintenance affects all operations inside a company. The purpose of a maintenance organization is to ensure that an organization has the available tools to reach its function. For example, in manufacturing industry to convert raw materials and knowledge into final products. (Manzini et al. 2010, p. 65-66) Reliability means how likely it is that an item for example an manufacturing cell can perform its function without interruptions. (Birolini 2017, p. 2)

Spare part management is an important part of operations in a large scale of businesses. Spare parts are relevant in a manufacturing industry to everything with wear parts from manufacturing machinery, to for example forklifts used in logistics. Spare parts require different methods to their management compared to more commonly studied inventory control methods such as storages within manufacturing or for example in a convenience store. Challenges present in spare part inventory management are infrequent difficult to predict demand, the low demand of parts and the large costs in case of a stockout. With correctly implemented inventory control systems large savings can be made in inventory holding costs and in the reduction of downtime due to missing spares. An efficient spare part system has advantages to storages, customer satisfaction and production planning. (Propadalo et al. 2012)

Manufacturing downtime can be very costly. The downtime affects all operations of the company. The costs range from the lost production and lost work time to fewer tangible factors such as lost customer satisfaction. Exact numbers for costs related to downtime can be difficult to calculate due to the less tangible factors related, but good estimates can be made. The knowledge of what the incurred costs are helps to understand the workings of the company and justify investments to reduce it. A good system for spare part inventory management can reduce unplanned downtime greatly. (Fox et al. 2004)

This study is concentrated on the maintenance process regarding spare parts applied to manufacturing machinery. First background information on why this study has been conducted and what its goals are have been presented. A literature review is given to give the reader a good baseline of information to understand the topic. Methods by which the goals have been achieved are laid out. Results of the study are given and analyzed. Chapter 5 examines some of the risk related to the study, its reliability and some possible areas of future improvements. Conclusion and future considerations about the findings of this study are given.

1.1 Background

The company has three different machines that manufacture sheet metal parts and sheet metal assemblies. These machines have cutting, bending, screwing and assembly capabilities in different combinations. Two machines of machine type A and one machine of machine type B. All of the machines have different layouts of tools and material handlers. The machinery consists of equipment designed and/or supplied by the manufacturer itself and equipment designed and/or acquired by the company. The final products are manufactured to order with a buffer storage to compensate for changes in demand. Machines are run in three shifts five days a week.

The company conducting this project has noticed problems in the reliability of its machinery resulting in late deliveries. The company has noticed that the current way of handling spare parts poses risks to the reliability of the system. Certain spares that are critical to the function of the machinery and can have long lead times are not stored. In case of an unexpected breakdown this may mean long downtimes resulting in the worst-case scenario to major strains on the relationship with the customer. Unneeded spare parts are stored and are taking away valuable storage space from other inventory items. Currently no accurate system to manage the inventory levels of spare parts for manufacturing machinery exists in the company and there’s no knowledge of the amounts and the exact types of spare parts stored at the factory. Spare parts have been stored in an unorganized fashion making maintenance work more challenging and time consuming. Background data for spare part inventory management has not been collected systematically. The company wants to improve its reliability on all areas and to achieve new industrial standards to provide even better service to its customers and to attract more potential customers. Investments to spare parts are thought to be a good investment to achieve said goals.

1.2 Objective of the study

The objective of this study is to implement different methods for calculating and controlling spare part inventory levels found from literature in the factory for the chosen manufacturing machinery. The purpose of the implementation of new practices is to improve the reliability of the manufacturing machinery and to reduce late deliveries.

1.3 Research problem and questions

As described in chapter 1.1 it has been noticed that the current way of handling spare parts is not optimal and poses risks on the reliability of the machinery. Some of the reasons for this are the lack of knowledge what are the spare parts that have the biggest risk of breaking down, the lack of knowledge regarding the current inventory levels of spare parts and the unorganized spare part storage on the shop floor. The research problem of this study is defined as “the lack of implemented cohesive ways to analyze and control spare part inventories is creating risks to the reliability of the machinery.”. The main research questions derived from the problem are “how to determine what spare parts should be kept in storage”, “how to determine inventory levels for stored spare parts” and “how to organize the spare part inventory on the shop floor”.

1.4 Scope

The scope of the spare parts included in this thesis are all mechanical and electrical components except for tool parts. These tool parts include such items such as cutting and bending elements. The service for tools and tool design are part of the core business of the company and an accurate system for the inventory management and service for those components already exists.

1.5 Literature review

Plenty of scientific literature regarding maintenance and spare parts management exists. In this chapter literature findings related to the area of this study are presented.

1.5.1 Maintenance & reliability

According to the definition by Manzini et al. 2010 maintenance “is the function that monitors and keeps plant, equipment, and facilities working. It must design, organize, carry out, and check the work to guarantee nominal functioning of the item during working times “Ti” (uptimes) and to minimize stopping intervals (downtimes) caused by breakdowns or by the resulting repairs." Reliability is defined by (Birolini 2017, p. 2) as "a characteristic of the item, expressed by the probability that it will perform its required function under given conditions for a stated time interval.". The definition can be assigned either to a single component, a machine or a system of machines. The purpose of maintenance efforts is to improve the reliability of the inspected function.

The maintenance organization is not an isolated organization inside a company. It is an integral part of a company's operations to ensure that the company can perform its desired function. The maintenance organization should listen to other stake holders such as the machinery operators when planning their functions. Kelly 2006b, p. 68-82)

The maintenance process should aim into creating a situation where ration between resources spent on maintenance and the advantages gained from increased reliability is optimal. In addition to just financial attributes the ratio should take into consideration even more qualitative viewpoints from different stakeholders such as the operators and the customer. The effectiveness of the maintenance organization can be measured by using multiple different measures such as plant downtime or availability. (Kelly 2006b, p.68-82)

Maintenance operations are often designed based on two different base philosophies. The philosophies are corrective maintenance and preventive maintenance. Corrective maintenance means that maintenance operations are conducted after the need for them arises. Usually this means that a machine breaks down and cannot perform its desired function. Corrective maintenance measures are difficult to plan in advance due to the random nature of breakdowns and usually unnecessary downtime is caused from the time spent reacting to the breakdown to the eventual repair. Unexpected downtime causes difficulties in for example production planning. With preventive maintenance measures will be performed before the need for them arises. This means for example that the condition of a machine is monitored and when an oncoming breakdown can be predicted time for maintenance will be reserved in a way where it has the least effect on the operations. With preventive maintenance the time spent on repairs and downtime can be reduced compared to corrective maintenance. Preventive maintenance can require investments compared to corrective maintenance and those investments depending on the machinery and their use may not be always viable. The used philosophy has to be decided on a case to case basis. (Kelly 2006b, p. 85-118)

TPM is short for Total Productive Maintenance. TPM is a philosophy where responsibilities regarding maintenance are given to the workers involved with a certain function such as operators of manufacturing machinery. The objective of TPM is improve the reliability of the machinery by making all personnel more invested in the maintenance process. These maintenance procedures could be very simple such as checking the oil levels of the machinery regularly. (Manzini et al. 2010, p. 73-83 ; Kelly 2006a, p. 248-267)

1.5.2 Demand analysis

The demand for spare parts can be difficult to estimate. The systems in which spare parts exist are very rarely isolated and outside factors affect the wear of the components.] (Propadalo et al. 2012) Outside factors could be poor operating on the machinery, faulty installations, sudden excessive loading causes caused by malfunction of other components etc.

The probability of a failure during a products lifetime can be presented with a bathtub curve. The curve has three distinct parts that represent different periods in the product lifetime. These three parts are infant mortality period, normal life and end of life wear out period. Infant mortality period consists of issues that happen close to the products installation. This can mean that a product has been defective before installation, an yet be identified design flaw exists that causes the product to fail prematurely or a mistake has been made during the products installation which causes it to break. Normal life is a period where the failure rate of products is very close to constant. Defects noticed during the infant mortality period have been solved. Products are susceptible to gradual wear and outside interference such as poor operation that can cause failures. Wear out period is a period close to the end of a products designed lifetime where products are more susceptible to breakdowns due to their age and wear. An important thing to know is that a bathtub curve uses the probabilities for a large number of products to display the tendencies of breadowns. It can’t be used to display the lifetime of a single product. The actual time intervals for different products can vary greatly and no universal values can be assigned. A portrayal of the bathtub curve is presented in figure 1. (Wilkins 2002)

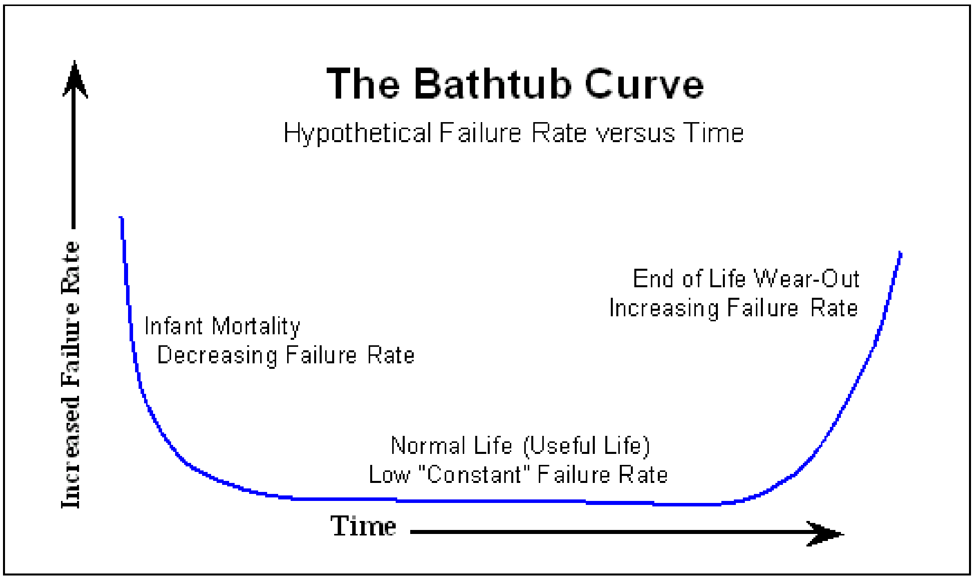

Figure 1. Bathtub curve (Wilkins 2002)

Normal distribution is commonly used to portray demand. It is most suitable for regularly moving items with a known demand such as those in sales inventories. Normal distribution can give values from -∞ to ∞. (Birolini 2017, p. 462) When studying demand demands with a negative value are not possible in reality so the use of normal distributions may give errors in the calculations. According to (Propadalo et al. 2012) this comes especially apparent with slow moving items with irregular demands, which means that the normal distribution is not suitable for the analysis of all spare parts and its wider use in calculations poses unnecessary risks. A normal distribution is with is presented in figure 2.

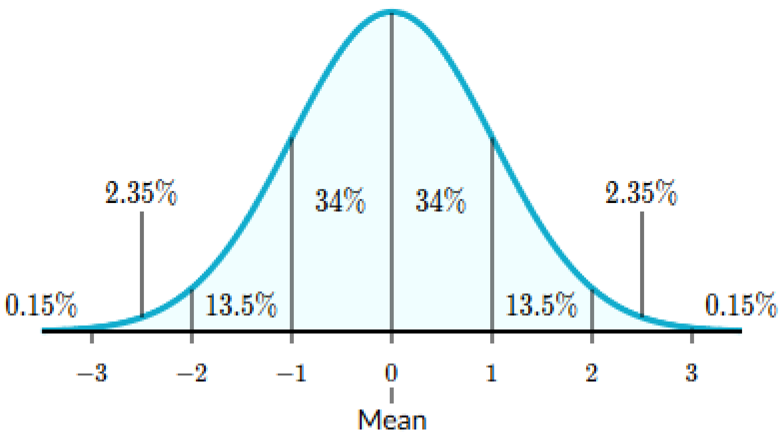

Figure 2. A normal distribution (Khan Academy 2019)

In scientific literature Poisson distribution is the most commonly used method used for estimating the demand of spare parts. Poisson distribution portrays situations with a known average time between events. The events happen independently from each other at random intervals. (Propadalo et al. 2012) A visual presentation of Poisson distributions is presented in figure 3. For the Poisson process to be suitable for spare parts some assumptions have to generally be made. According to (Koehrsen W. 2019) these three assumptions are:

1. The failure rate of a single product is a constant
2. Failures are not dependent on each other
3. Items are not repairable

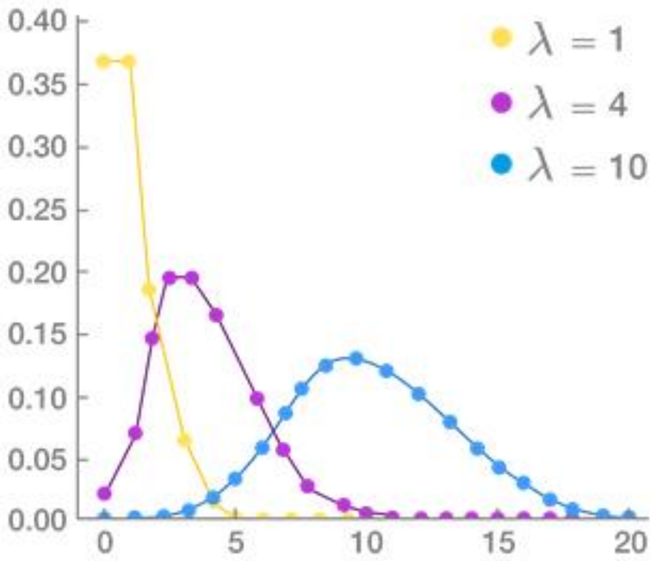

Figure 3. A Poisson distribution for different failure rates (Brilliant.org 2019)

Poisson process can be used to calculate the probability of a certain number of events happening during a certain period of time. In spare parts management the Poisson process can be used to calculate the probability of a stockout by calculating the probability of a certain number of spare changes during the ordering lead time. In the case of stored spare parts, the probability of a stock out is the probability that the amount of failures during the products ordering lead time is larger than the safety stock. (Koehrsen 2019) The cumulative Poisson process is presented in equation 1.

$$P(X=x) = (A^{X}*e^{-A})/X! \quad (1)$$

Two common measures of reliability used in industry are MTTF (mean time to failure) and MTBF (mean time between failure). The equation for calculating MTBF where λ is the failure rate of a single component is presented as equation 2. MTTF should be used for spare parts that are not repairable and MTBF for those that are repairable. The relationship of MTTF and MTBF is shown on equation 3. There MTTR (Mean time to repair) gives out the time that is reserved for the repair of the component. Equation 3 can also be used for non-repairable components by replacing the MTTR with the lead time of the delivery of the component and the time spent on replacing the faulty component with the spare part. This equation is presented as equation 5 where t stands for the lead time and t_{repair} for the replacement time. The MTTF of a system with multiple components can be calculated as the inverse of the sum of each individual components MTTF value. The equation for calculating the MTTF of a system is presented as equation 4. (Stanley 2019)

$$MTBF = 1/(\lambda_1+\lambda_1+\ldots+\lambda_N) \quad (2)$$

$$MTBF = MTTF + MTTR \quad (3)$$

$$MTTF_{tot}=MTTF_1+\ldots+MTTF_n \quad (4)$$

$$MTBF = MTTF + t + t_{repair} \quad (5)$$

Failure rate describes the occurrence of failures per a unit of time. Failure rate is the inverse of MTTF or MTBF. The equation is presented in equation 6 where λ is the failure rate of a component with a MTTF value. (Stanley 2019)

$$\lambda = 1/MTTF \quad (6)$$

Gamma distribution is a form of Poisson distribution where the probability of an occurrence depends on the time of the previous occurrence. The gamma distribution is useful when for example looking into the failure rate of a single spare part. If the spare parts are thought to be worn gradually assumptions can be made that the probability of a failure is the smallest after the component has been replaced. (Propadalo et al. 2012) Gamma distribution is shown in figure 4. The use of gamma distributions requires identified data or reliable estimation of a single components wear during its lifetime to work.

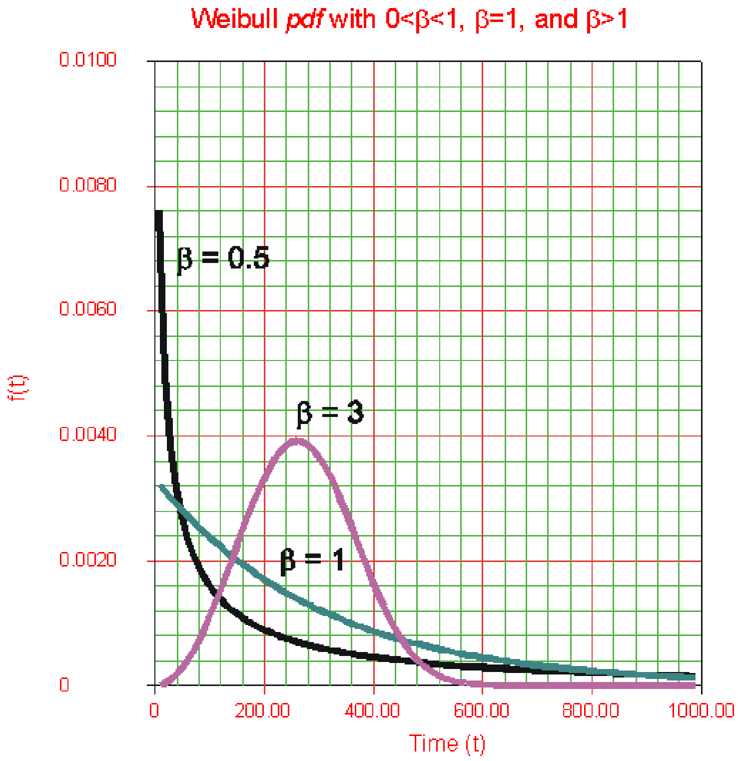

Figure 4. Gamma distribution (Reliability Hotwire 2019)

1.5.3 Machine downtime

Studies have shown that a big part of manufactures are not knowledgeable about the true costs that machine downtime can have on their operation. In addition, manufacturers often only concentrate on a few basic cost categories of downtime and fail to realize the effect it can have on a larger scale. (Fox et al. 2004; Fitchett et al. 2019)

The downtime costs realized from a breakdown scenario can be divided into multiple segments from which the biggest driver of downtime costs is the lost production during the period in which the machinery is not running. (Fox et al. 2004)

Unless workers can be allocated to other productive activities during the downtime period the salaries are incurred as unneeded costs. Meeting crucial production goals may require overtime to be done which results in extra unneeded labor costs. In addition to the workers working directly with the machinery downtime requires action from multiple other members of maintenance personnel and management. Management must spend time extra time on production scheduling, contacts with the customer and organizing new deliveries to name a few examples. This extra time is not very productive and could be better spend on developing the operations of the plant. Unexpected delays cause stress for the workers and management which can lead to lower job satisfaction, loss of productivity and quality issues. (Fox et al. 2004)

Delayed deliveries caused by unplanned downtime may cause major strains on the relationship with customer that might in the worst-case result in the loss of sales. Depending on the contracts the supplier has agreed with the customer, in case of delays the supplier may be required to pay reimbursements on the time the customer has had to spend waiting for deliveries. (Fox et al. 2004)

The incurred downtime costs don’t always begin to accumulate immediately after a breakdown. Cases like these may however require extra actions from workers and management that result in costs even though the delayed production can be achieved without major disturbances. (Fitchett et al. 2019)

1.5.4 Spare classification

Manufacturing machinery can consist of thousands of different parts. Considering the need for spares for all these parts separately is not wise due to time constraints. Good results can be achieved by grouping spare parts with similar characteristics together. That is why different classification systems have been introduced. By applying inventory management policies to larger groups of spare parts together simplifies the whole process and frees resources to other activities. (Bošnjaković 2010)

Perhaps the most important criteria when classifying spare parts is the criticality of the items. Criticality is defined as the impact the missing of that single spare part would cause. Often spare parts are organized into three different categories as presented in SOURCE. These three categories are crucial, desirable and unneeded. Crucial spare parts are something that without which the machinery cannot function at all or it poses safety risks to the workers or environment. Desirable spare parts don’t cause the operation of the machinery to stop completely but may cause some minor disturbances to the production. Unneeded spare parts do not cause any functional problems to the machinery while missing. For example, cosmetic parts don’t require storage. (Bošnjaković 2010)

Another important classification criterion is lead time and availability. Very seldomly used spare parts may have long lead times. For older constructions new spare parts may not be available at all. Price is a factor that affects to inventory policy decisions of a spare part. For expensive parts more justification is needed for their requirements.

One factor affecting the stocking and inventory management decision is the perishability of spares. Certain spare parts might become redundant if the construction of the machine is modified or the machines are taken out of operation completely. In these cases, the inventory might have to be scrapped causing losses to the company. In addition, certain types of spears for example ones with rubber elements such as rubber seals might perish during storage and lose their sealing properties.

Spare parts inventories can either be handled by optimizing the inventories of single items or by applying common inventory control methods to larger groups of items. These methods are referred to in literature as single- and multi-item control methods. (Van Houtum et al. 2015, p. 6-7)

ABC-analysis is a way of categorizing inventory from which the most profitable areas of inventory can be identified. (Bošnjaković 2010; Martin 2006) A visual representation showing how items could be divided is shown in figure 5. Pareto principle is often called the 80/20 rule. The basis of pareto principle is that about 20 percent of actions can cause about 80 percent of results. This can be applied into inventory control, where for example a small amount of inventory creates most of the profit. The principle works well with ABC-analysis. (Kruse 2016) The pareto principle could be applied into spare part inventory control.

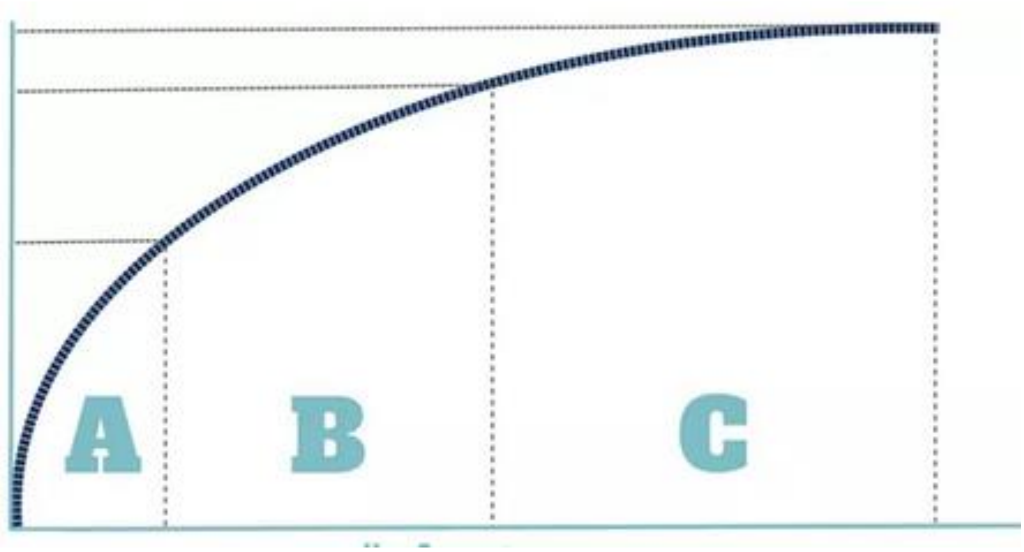

Figure 5. Inventory divided into categories by using ABC-analysis (Martin 2006)

1.5.5 Inventory management

Spare inventory management differs from the more studied inventory methods related to manufacturing and sales inventories. This is due to the special features of spare parts, which are the difficult to determine and low demand and large costs caused by stockout situations. However commonly known inventory management methods can be used with spare part inventory management with slight modifications. (Trimp et al. 2004)

The decision of to stock and not to stock is dependent on the criticality, availability and price of the parts, as described in chapter 1.4.3. If the part is critical enough to halt the whole production, then the decision of stocking the item can be by comparing the expected costs of downtime during a year with the incurred holding costs during a year. If the incurred downtime costs are bigger than the holding costs keeping items in stock is justified. The equation is presented as equation 7. (Trimp et al. 2004)

$$H*V < V*DT*\lambda \qquad (7)$$

EOQ stands for economic order quantity. It is used to calculate the optimal order quantity that minimizes the incurred order costs and holding costs of the stored inventory. The EOQ model works on the assumption that the demand is a constant. Inventories with heavy variations in demand the model does not work as the relation between holding costs and ordering costs is constantly changing. The traditional EOQ-model is presented on equation 8. (Kenton 2019) The traditional EOQ-model was introduced already in 1913. After that the knowledge of inventory control has advanced and the tradition EOQ-model has been developed overtime to consider the new knowledge. The normal EOQ-model is however still used quite widely as it is relatively simple and easy to understand. One modified EOQ model is according to (Rodrigues et al. 2012) is presented in equation 9. The modified model considers the incurred costs in case a stock out scenario occurs. The modified model produces larger order quantities than the normal model. An alternative ordering method to EOQ is the order up to method where orders are always placed so that the target base stock level is reached

$$Q = SQRT((2 * \lambda * R)/(H * V)) \quad (8)$$

$$Q = SQRT((2 * \lambda * R * (H+DT))/(H * V * DT)) \quad (9)$$

Stock levels can be monitored either continuously or periodically. In continuous review the inventory data is changed every time that a demand situation occurs. Orders are also made immediately after the order point has been reached. With periodic review inventory levels are monitored at certain pre-determined intervals for example once a week. (Sherman 2019)

Stock levels change with time as demand situations occurs. As demand can occur at a random point in time the accurate stock level at a point in time cannot be accurately predicted. The average stock level can be used to approximate stock level in random point in time to be used for financial calculations. The equation to calculate the average stock level is presented as equation 10. (Trimp et al. 2004)

$$S_{AVG} = SS+(Q/2)-(t * \lambda) \quad (10)$$

Holding onto inventory is never free. The exact amount of inventory holding costs is difficult to define. Often the holding costs are thought to be about 20 percent of the total inventory value per year. Holding costs should include items such as capital cost, the insurance of stock, the space reserved for stock and the time workers and management spend organizing the stock. The expected holding costs are defined as the average stock multiplied by the holding cost rate. Capital cost means the cost of the capital investment tied to the inventory. Capital tied to spare parts does not provide any profits. The capital tied to unused spare parts could be better spent on investments to other operations. An often-used metric for capital costs is at which rate would a bank lend money to the company which is something that a company could expect to get back from a relatively risk-free investment. The insurance rate depends on the field of business the company is in, the total value of the inventory and the insurance contracts in place. The handling costs include everything that is done to the inventory. This includes actions such as when the inventory is moved from one place to another or the pieces of inventory are registered to the company system. The cost tied to the storage space depends on the company situation. The costs incurred from storage space are higher where space is limited. (Durlinger 2012)

Service level is defined as the probability of a stockout when demand occurs. Determining the target service level requires managerial decisions. The target service level for a spare part inventory can be derived by the service level decided upon in the contracts with the customer. In spare part management the service level is defined as the probability of a stockout during the products lead time. In other terms it is the probability that a demand of more than the assigned safety stock occurs during the lead time. Using the Poisson process the probability of x failures during the lead time A for an item with a demand of l is shown in equation 11. (Dreyfuss et al. 2017)

$$P(X=x) = (A^{X} * e^{-A})/X! \qquad (11)$$

Expected time of stockout in case a spare part is not kept in cost can calculated as the probability of demand times the downtime period caused by a failure. The downtime is the lead time of the needed spare plus the time required for the repair of said part. This equation is presented as equation 12. (Dreyfuss et al. 2017)

$$T_s = \lambda * (t + t_{repair}) \qquad (12)$$

System availability is a measure that describes how much of operation time can the system be expected to be functional. It is given as a percentage of total time. System availability percentage PA for stocked parts where the equipment is functional expect for the time it is being repaired or waiting for spare parts are presented in equation 13. (Birolini 2004. p. 9)

$$PA = MTTF/(MTTF+MTTR) \qquad (13)$$

1.5.6 Supply contracts

Spare part supply networks differ depending on for example the scale of the system or the locations of the supplied machinery. (Van Houtum et al. 2015, p 1-7) Depending on the field of business the customer is in some spare parts may be manufactured locally without having contact with suppliers. Repairs can also be made either locally or in suppliers' facilities. Need for spare parts stocks is not eliminated in case of locally repaired or manufactured parts. The same probability calculations can be used for both repairable and manufactured parts by replacing the supplier lead time with the expected manufacturing or repair lead time. In instances with unreliable delivery methods or in places where deliveries are not at all possible for example aboard of cargo ships, spare parts have to be stored locally. Suppliers can offer services where spare parts are reserved for the customer at the suppliers' warehouse. The advantages of this arrangement for the customer are that they do not have to spend the initial investment to the spare parts and that they don't have to spend their own resources and space for storage. A fixed time from which after an order the parts are delivered to the customer can be agreed on. This arrangement is favorable to the supplier since their capital tied to inventory and storage are smaller than they would be at a single factory location thanks to bigger volumes. The storage contract does not however work if quick delivery to the factory location is not possible. (Bihler 2019) It should also be noted that even a lead time of 24 hours can be too costly for the company to wait on and local storage despite the increased cost is favorable. In urgent cases emergency shipments may be required. Emergency shipments generally are more expensive than normal shipments. Close partnerships with the supplier can be beneficial. Clear target levels for example for service level and availability can be given. Real time data of the company's inventories can be sent straight to the suppliers and no separate order process is required saving valuable time from the operators and management.

1.5.7 Lean & 5S principles

The effectiveness of maintenance can be improved by implementing common operating measures used in industry. Both can be implemented into storage and usage of spare parts. Lean and 6S principles are commonly used for organizing factory operations and storage. The basic principle of Lean manufacturing philosophy is to reduce waste. Waste can for example mean unnecessary work. (lean5-sanomat 2019) In spare part management waste can be eliminated for example by reducing the time spent on looking for spare parts and reducing the time waiting for spare parts to be delivered.

2 METHODS

Throughout this study constant scientific methodology has been used. In this chapter the used methodology is discussed. Quantitative methodologies used for this study are the different calculations used for both the inventory calculations and the calculations regarding the advantages and results of this study. Qualitative methods used are in the case of this study discussions with the operators and management that have been used to identify the starting scenario regarding issues where no calculated data exists and evaluating the feasibility of putting the created system into use and evaluating whether or not the achieved results and advantages are realistic.

2.1 Literature review

The main sources used in the literature study are scientific articles, conference papers and online articles. Literature has been searched systematically from online sources such as ResearchGate, ScienceDirect and Google. The results of the literature review were presented in chapter 1.6.

2.2 Interviews and discussions

Discussions were had with company personnel throughout the project. Discussion regarding the components and the technical aspects were discussed with design personnel responsible for tool and machine design. Operation of the machinery was discussed with the machine operators and production management. Production schedules and financial aspects were discussed with the management. The results were presented to all personnel involved with the project and were verified to be suitable for the company to put into use.

2.3 Data discovery & analysis

Spare part related data such as frequency and duration of spare changes or orders of spare parts had not been collected systematically. The data had to be located by consulting different personnel in the factory and by looking into different file directories with the company’s hard drives.

The part lists for the considered equipment have been collected from multiple sources. The part lists have been built by studying manufacturer given material such as instruction manuals and spare part listings. and purchase order confirmations considering pieces of equipment. The required data in these part lists are the model numbers and purchase codes for each assembly or item. The final list of assemblies has been confirmed by reading item numbers from the machinery itself. Separate lists were made for equipment manufactured by the manufacturer of the machinery and other suppliers. Assembly listings were made by listing the main assemblies inside the machines. These main assemblies were then used with the help of the suppliers and company data to find the parts susceptible for wear and degradation.

Demand values for spare parts were based on the real demand in the factory from a time period of five years and from the data provided by the equipment manufacturers and suppliers. The real demand in the factory was observed by studying the purchase confirmations of the ordered items from the last five years. The purchase confirmations were acquired from factory personnel that have been responsible for the ordering of spare parts during the last few years. The demand data would be stored as the failure rate of components to suit the used inventory calculations. For spare parts with no known demand in the last five years or no manufacturer estimations of wear the demand of those items was zero. Some of the parts in the machinery had been discontinued by the suppliers. For these parts that were unavailable the suppliers were consulted about possible replacements.

The factory had no calculated value for the holding costs of inventory. For this application a holding cost of 20 percent of the parts value was chosen based on literature findings as presented in chapter 1.5.4.

2.4 Used equipment and resources

The main equipment used in this study was a computer with a windows operating system. The application used for all calculations and that was used to build the final inventory control program was Microsoft Excel. The Excel-workbook is functional with other versions of Microsoft Excel and should also be compatible with other sheet calculation programs. When the inventory control system was put into practice a storage facility such as a sheet metal cabinet and boxes was needed. A printer and laminating machine were used when the spare parts were marked in the storage facility. For the final application a computer is needed for the operators of the machinery as well as the management.

2.5 Spare classification

For this project a decision map for the classification of spare parts was defined. The decision map is shown in figure 6. More specific instructions on different junctions are defined in the following chapters.

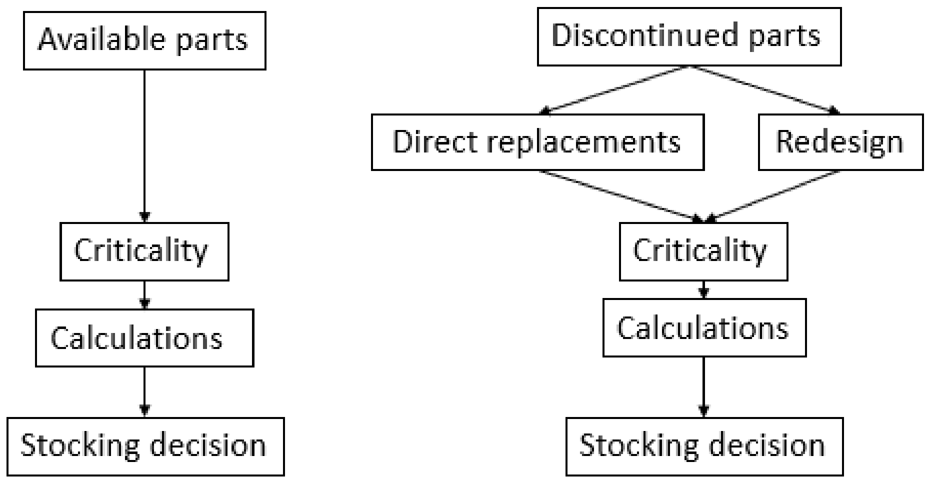

Figure 6. Decision map with the necessary steps for a stocking decision of spare parts

Items were firstly classified by their availability. Items were divided to items where spare parts are available and to items that have been discontinued by the supplier so that services are not offered anymore or will not be offered in the future. For those parts possible replacement options were considered. These could be refurbishing or complete replacements. Parts still available were divided by whether they are readily stocked by the suppliers and what are the lead times for those parts.

Spare parts were then divided to non-wear parts and wear parts. The stocking decision for these items is presented in chapter 2.6. Wear parts were identified from supplier recommendations and the realized demand in the factory. Additionally, all spare parts were then divided into critical and non-critical items as according to SOURCE which was presented in chapter 1.5.3.

2.6 Downtime

Downtime was calculated by using financial and operational data stored in the database of the ERP (Enterprise resource planning) system used by the company. The data required for calculations were the profit margins of each product, the manufacturing times of each product, the labor costs divided for each produced part and the amounts sold of each product. Data regarding manufacturing amounts and calculated profit margins was collected from the period of last year. The downtime costs were calculated for each of the three machines separately.

The labor costs from the workers were divided between the three machines. Discussions were had with the management to determine how much work must usually be spent by the managers to solve different downtime scenarios. An hourly rate for the extra work spent was calculated.

Multiple different products are manufactured on each machine. Lost production for each different product was calculated separately and then an average based on the order numbers of each part was calculated. The number of products lost per hour was based on the production time of a single component. The formula for the costs incurred from lost production during a downtime period of the length t is presented in equation 14 where t is the length of the downtime period, $t_{manufacturing}$ is the manufacturing time of a product and p is profit per product and DT is the downtime costs per one hour.

$$DT = (t/t_{manufacturing})*p \tag{14}$$

The total downtime for each machine is presented in equation 15 where lc is labor costs and mc is management costs.

$$DT_{TOT} = DT + (lc+mc)/3 \tag{15}$$

The production schedules and products have variations throughout the year. This means that the incurred downtime costs during a random downtime period can have multiple different values. As the current manufacturing situation during the downtime period cannot be known an average value was calculated. The calculations used for the average downtime value are presented on equation 16, where x_n is number of components in a certain machine x_{tot} is the total number components and DT_n is the corresponding downtime value for the machine n.

$$((X_1/X_{tot})*DT_1)+\ldots+((X_n/X_{tot})*DT_n) \qquad (16)$$

The hours per day that the machinery was running were defined. In this case the production was running in three shifts. Ideally the machinery should be running all the time minus product changes and scheduled services. The hours running were decided for with discussions with the operators and management based on their experience how much the utilization rate of the machinery is. Based on these discussions the daily downtime cost was decided to be 16 times the hourly rate.

2.7 Inventory calculations

The calculations were done under three assumptions as specified in chapter 1.5.4. These assumptions are that the failure rate of items is constant, items are not repairable, and two failures cannot happen simultaneously. Demand of spare parts was chosen to be presented with a Poisson distribution as according to (Koehrsen 2009)

Lead time was given by the suppliers. The response from the management at the factory and from the suppliers is not instantaneous so some time had to be reserved for ordering and receiving of the items on top of the lead time itself. In this case two days were reserved for the handling times. Lead times were calculated as workdays meaning weekends and national holidays were excluded.

The decision on whether it would be feasible to store a certain spare part was done by comparing the yearly inventory holding costs to the expected yearly downtime costs that would occur if the spare part was not stored. The comparison was done according to equation 7. Based on the literature review a yearly holding rate of 20% was used. Expected yearly downtime was calculated X times to daily downtime costs as specified in chapter 2.4 If the yearly holding cost was smaller than the yearly downtime costs the spare part was deemed to be financially viable for storage.

A base stock level for spare parts deemed for storage was calculated. The base stock level was selected so that the target service level was achieved. It was done that the safety stock is the smallest possible while achieving the target service level. The service level was calculated as the probability of a scenario where the demand during the lead time of an item is larger than the average stock levels. Poisson process as shown in equation 1 was used to calculate the probability and equation 10 was used to calculate the average stock level. EOQ values used in the average stock level calculations were calculated according to equation 8. The solver addon in Excel was used to find an optimal value for the base stock level so that the total inventory holding costs are minimized while achieving the service level targets of each spare part. This was done by first setting the base stock level as a variable. The target was to minimize the average inventory holding costs whilst keeping the service level above the target. The algorithm is presented on table 1. The optimal solution can also be found manually by trying different values of safety stock to see which is the lowest amount of stock that meets the target service level while adhering to the same rules as specified in table 1. Existing inventory levels were compared to the results of the inventory calculations and were used as the starting point of stock level calculations.

Table 1. Constraints and rules for the Excel solver

Minimize	Total inventory costs
Variable	Safety stock
Constraints	Safety stock = Integer Service level > Service level target

Service level was calculated for the whole system and for the spare part system consisting of items decided to be stored. The service level of the system was according to probability calculation rules the sum of the service levels of each separate item. The equation is presented as equation 17.

$$SL_{TOT}=SL_1+SL_2+\ldots+SL_n \tag{17}$$

Payback times for initial investments to spare part inventory were calculated. Payback were calculated according to (Kagan, 2019) as the initial investment divided by the estimated profit. The estimated profit of the stocking decision compared to a situation where the part is not stocked was the expected saved downtime costs subtracted by the holding costs. This equation is presented as equation 18. The payback time is presented on equation 19. (Kagan, 2019)

$$P = \lambda * lt - p * h \quad (18)$$

$$PT = V/P \quad (19)$$

A priority list of spare parts considered for investment was made. The spare parts were put in order by their payback time. This can be done by for example using the sorting feature of Excel. After the spare parts were put in order the cumulative sum of investments and demand occurrences solved by storing parts were calculated for further analysis. Cumulative sums for both measures were calculated in Excel and the plotted results can be seen in figure 19.

The expected rise in system availability percentage was calculated by calculating separate values for different scenarios of stored spare prats by using equation 20. These different scenarios were then compared to each other. The expected amount downtime saved was calculated based on the calculated MTTF-values and the average lead time of items. It was calculated that for each MTTF period a downtime of the average lead time of parts would be incurred. The equation for calculating the expected yearly downtime in hours is presented in equation 20. A value of 240 workdays per year was used.

$$t_{stockout} = (\lambda / MTBF) * h * MTTR \quad (20)$$

Spare parts that were found on more than one machine were not allocated to a single machine. Spares with multiple uses were pooled together from which they were drawn when demand occurs.

2.8 Supplier contacts

Suppliers were first mapped by the spare parts they had available. After that suppliers were contacted for quotations. Suppliers were contacted by e-mail. The same e-mail was used in the initial message. Request were made on a quotation with the prices and lead times for the desired items. The suppliers were also requested for estimates of failure rates of the components. This was done while understanding that the given failure rates differ from one production environment to the next. The values when given were still thought to be useful when comparing the real failure data taken from the real demand, to see if the production environment produced unexpectedly large wear on some components. First criteria for choosing suppliers was the availability of the desired spare parts. For the initial stocking of spare parts, the next criteria were the price of spare parts. Third criteria for suppliers was the lead times they could offer for the products. For the initial stocking decision, the lead time is not as crucial as it is for resupplying inventory.

2.9 Inventory management system

The formulas presented in chapter 2.5 were inserted to Excel in a suitable format. Five different sheets were built into the Excel file. On sheet was used to calculate the downtime data of the machines. One sheet was used for all of the calculations regarding spare parts such as for example the stocking decision calculations as presented in chapter 1.5.5. Two different sheets for the control of the spare part inventory and displaying information were built. One with more detailed info was made for management and a simpler sheet whit only the control of the inventory levels was done for operators to use. The data chosen to be displayed based on what the management needs to see to control the inventories, analyze how reliable the process is in terms of failures and what are the running costs of its implementation.

The inventory management system was designed to automatically recalculate the service level and the estimated average stock values for four different order intervals. The calculations were made in Excel by using IF variables to check what the chosen order interval is.

2.10 Storage

A plan for the storage of spare parts was done according to LEAN and 5S principles. The storage layout and the chosen responsibilities were heavily influenced by the comments of the operators and the management as they had the best knowledge regarding the daily operations of the factory. The responsibilities were chosen based on the knowledge of the machinery and already assigned duties regarding for example manufacturing. Instructions were written for both the operators and the management.

3 RESULTS

In this chapter the main results used for further analysis acquired from this study are presented. There were 162 different spare parts for which calculations were conducted.

3.1 Effects of machine downtime on operations

The scale of downtime by machine is presented in table 2. The downtime is shown as a percentage of the combined value all machinery.

Table 2. Downtime as percentage of the total sum of downtime hours

Machine	%
1	11
2	39
3	50

As described in chapter 2.6 a unique downtime value was calculated for each component depending on which machines it has been installed on. Downtime incurred by each spare part is presented in figure 7.

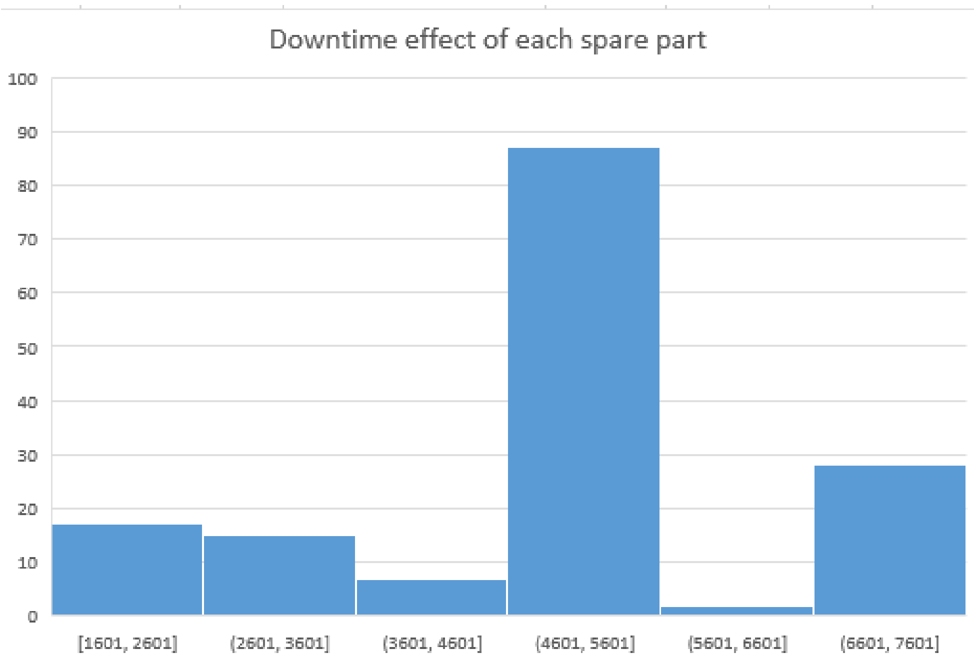

Figure 7. Distribution for downtime incurred for spare parts [pcs - €]

3.2 Spare classification

The distribution of failure rates for the investigated spare parts with available demand data are presented in figure 8.

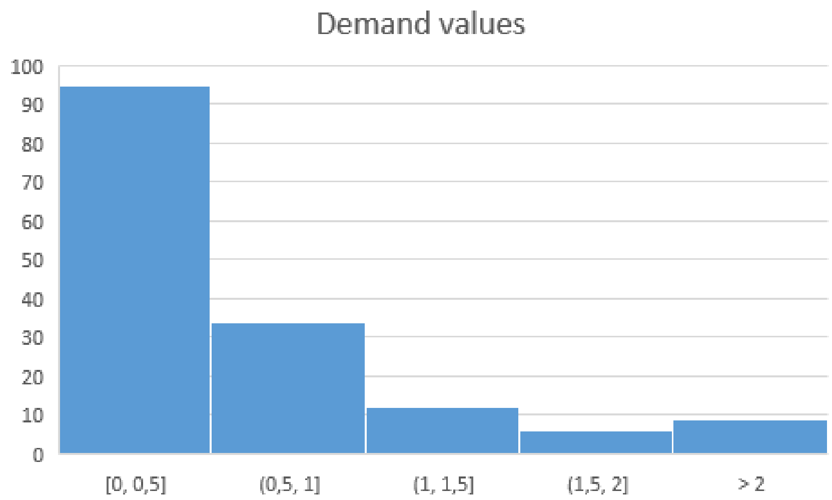

Figure 8. Distribution for the failure rates of spare parts [pcs – 1/a]

The division of spare part prices is presented in figure 9. Most regularly worn spare parts are valued for less than 50 €.

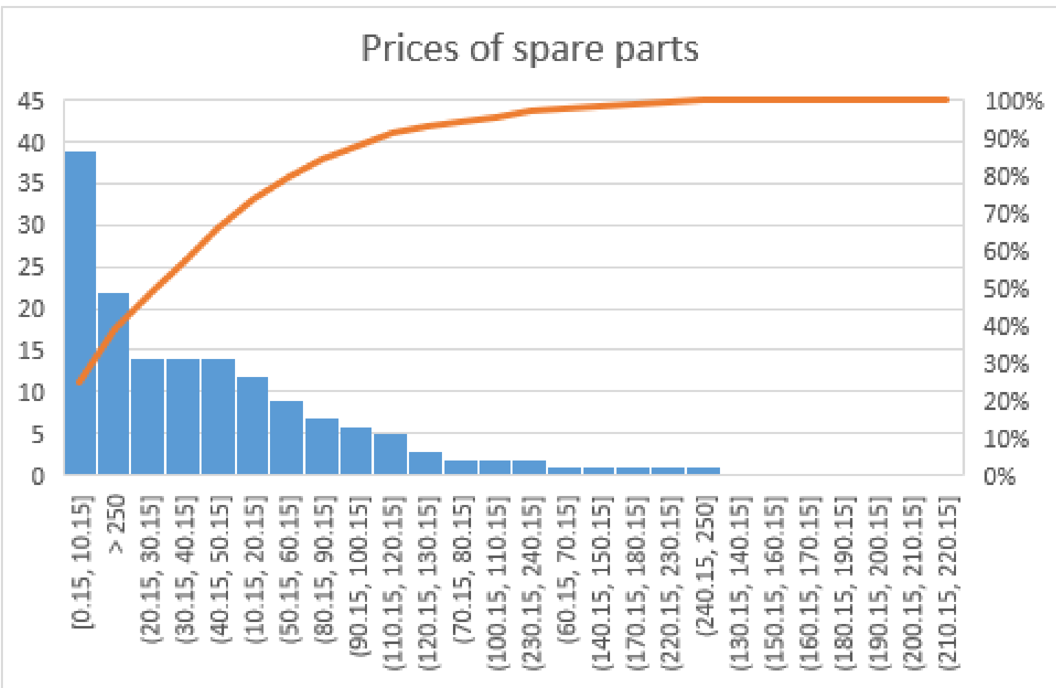

Figure 9. Distribution of prices of spare parts [pcs - €]

The division of calculated payback times used in prioritizing the spare parts as described in chapter 2.7 is presented in figure 10.

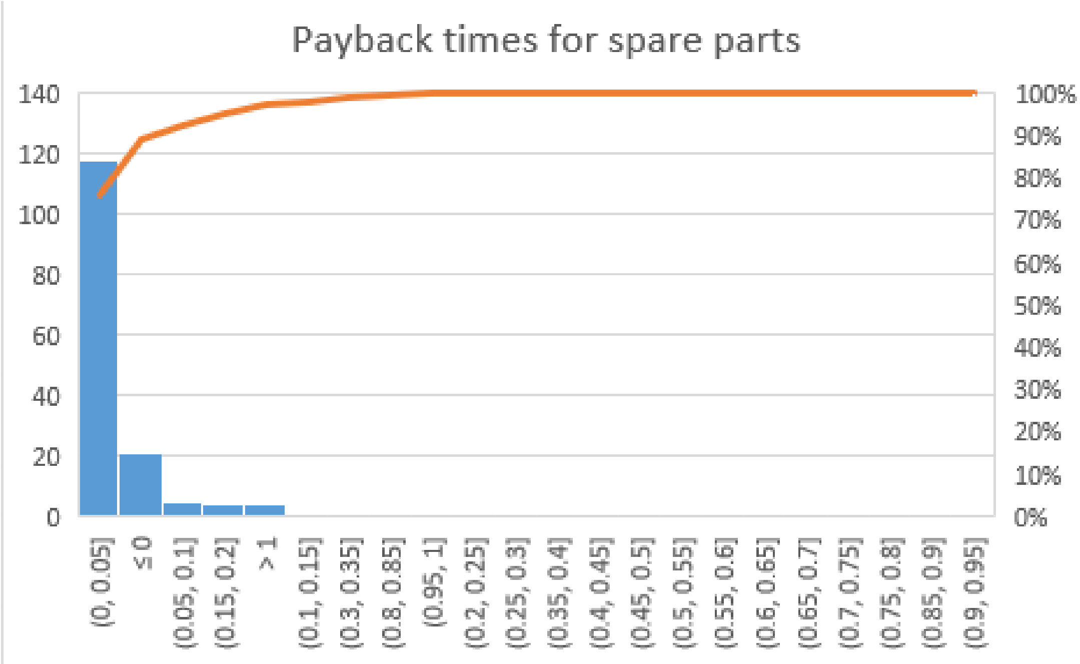

Figure 10. Distribution of payback times for each spare part [pcs - a]

3.3 Inventory calculations

Majority of the calculated re-order points were 0 or 1. The distribution of calculated re-order points is presented in figure 11.

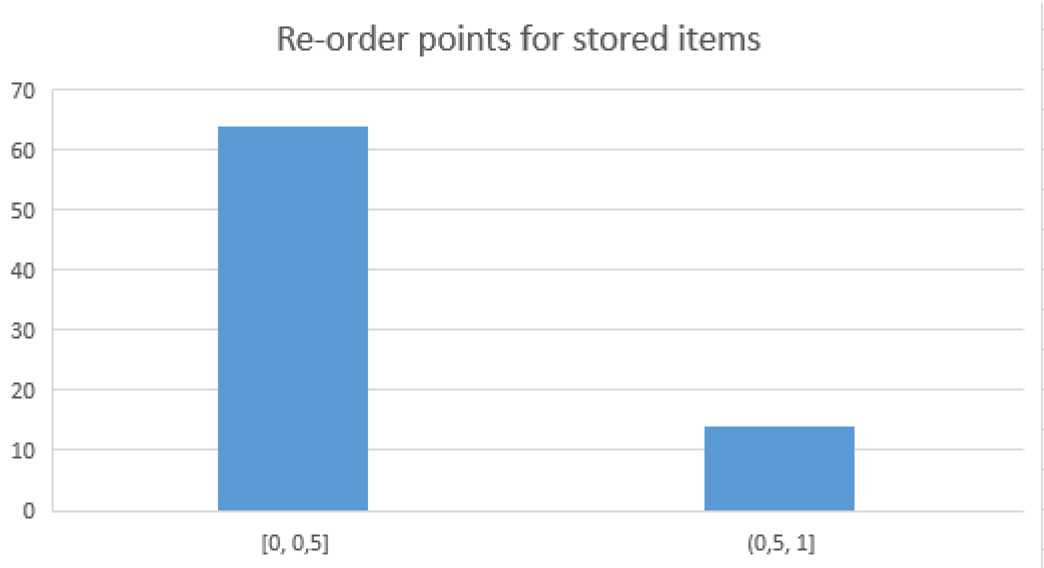

Figure 11. Re-order points for spare parts [pcs - pcs]

The amount of known demand situations solved by the spare part inventory for every machine are presented in figure 12.

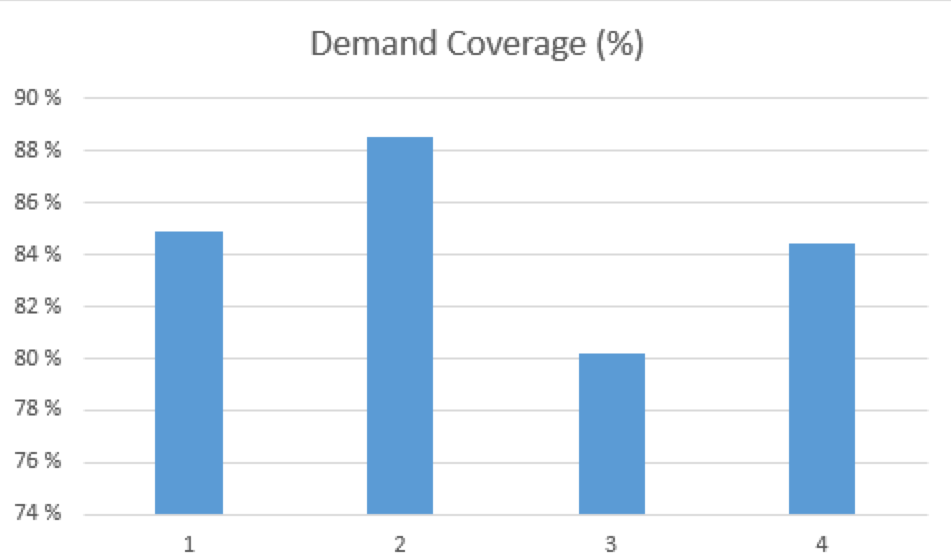

Figure 12. The percentage of demand situations solved for each machine [pcs - pcs]

Total inventory, inventory value per machine and the yearly holding costs for all of the investigated spare parts for storage are presented in table 3.

Table 3. Inventory value and holding costs for each machine

Machine	Inventory value (€)	Holding costs (€/a)
1	6200	1000
2	3200	500
3	7200	1300
Combined	13900	2800

The calculated MTTF values for the manufacturing machines are presented in table 4.

Table 4. MTTF values for each machine

Machine	MTTF (d)
1	6
2	10
3	8
Combined	3

The values for reduced downtime and saved downtime costs per machine are shown in table 5.

Table 5. Downtime reduced

Machine	Downtime reduced (d/a)
1	29
2	20
3	24
Combined	75

3.4 Suppliers & bidding

For this project altogether five different suppliers were chosen. Another 10 were shown have the same spare parts and were left as reserves in case of problems with the previous suppliers.

3.5 Storage & operations

The spare parts were chosen to be stored at sheet metal cabinet close to the machinery. The parts were laid to separated containers inside plastic boxes with labels showing for what subassembly the parts inside are used. The parts as laid out in the cabinet are presented in figure 13.

Figure 13. Spare parts as laid out in the cabinet on the factory floor

Laminated Kanban cards were printed for all spare parts. These cards contain the name and order code of the spare part, the subassemblies and machinery in which it is installed and in which box the spare part is stored. The laminated Kanban cards were put into the compartments were the corresponding spare part was stored. The laminated cards as inside the compartments can be seen in figure 14. Spare parts that had once been used in the machinery and taken out but were still deemed functional were stored at a different cabinet, where they were held as emergency backup parts. The stock of these part was decided not to be monitored in detail and the function of the maintenance operations should not be dependent on the storage of these parts.

Figure 14. Spare parts as laid out in their plastic boxes with laminated cards

The responsibilities of the control of inventory levels and the organization of the storage were decided. Every time a spare part is used the operator who takes the spare part out of storage moves a corresponding Kanban card into a separate compartment. From that compartment by looking at the Kanban cards it is easy to see what spare parts have been used. It was decided that the stock levels of spare parts would be updated once a week. The operators would update the stock levels by checking from the Kanban cards the spare parts used. After the stock levels have been updated to the Excel sheet the cards are then returned to the spare part storage. The information on spare parts used would move between the operators and management through the Excel worksheet. The management checks the storage levels monthly and places orders. Once the ordered spare parts arrive the management brings the spare parts to the operators who then put the parts to their correct places. At the same time as the parts are put into the cabinet a thorough cleaning of the cabinet is done to ensure that all parts are in their correct places and no extra items or used spare parts are stored. The operators confirm that the weekly inventory has been done by signing a sheet with their own name, so that the management can see easily whether or not the inventory levels are up to date. Clear instructions were printed and put next to the storage cabinet for the operators to see. The operators and management were instructed on the operations regarding the spare part inventory system before it was put to use. The responsibilities for the operators and management are presented in table 6. The instructions, the signing sheet and the place for used cards can be seen in figure 15. The system where operators are involved in the process for organizing and controlling spare part levels utilizes the TPM philosophy. The idea in this system is that when the operators are closely involved they are more likely to follow the instructions given when they can immediately see their work getting easier from the more organized working practices.

Table 6. Responsibilities regarding the upkeep of the spare part inventory

Personnel	Responsibilities
Operator & maintenance personnel	Keeping the spare part stock organized and clean Organizing newly ordered spare parts to the storage Use and installation of spare parts Updating of the spare part stocks Updating the management on activities
Production and Maintenance Management	Ordering of the spare parts Updating spare part data Monitoring of the financial data Monitoring of the technical data

Figure 15. The instructions, signing sheet and a place for the used Kanban cards

3.6 Inventory management system

An Excel based program for monitoring and controlling inventory levels and underlying parameters was developed. The control of inventory levels as seen on Excel is presented on figure 16 and the measures taken from the inventory model are seen on figure 18. The inventory level screen shows all the necessary information that is needed for daily controlling of the inventory levels. Current inventory can be seen and the amount that should be ordered from what supplier can be quickly found. Colors are used to highlight the stock levels that need attention. The measures are shown in a simple way where the most important values can be easily found. The inventory control system can also be used to change the inventory control parameters to apply to different resupply intervals. The control of resupply intervals with embedded instructions can be seen in figure 18. In addition, a simple sheet with only the names, location and stock levels of the spare parts was created. This is meant to be used by the operators as they update the stock levels weekly. The information from the control sheet is transferred automatically to the more detailed control sheet in which management can make decision such as ordering spare parts regarding the inventory system. Screenshots of the inventory control system are presented in figures 16, 17 and 18.

Huomioita	Kokoonpano	Osa	Koodi	Varastotaso	Tilauspiste	EOQ
	0	SPRING (TELLERFEDER)	900-20-0008.5	26	1	14
	0	SPRING	900-20-0018.5	26	1	9
	137-05-0833.1 TRIP LEVER 909-11-0297.5 PRESSURE SPRING 0,	PRESSURE SPRING	909-11-0297.5	1	0	5
	0	DISC (SCHEIBE)	100-31-2628.5	1	1	2
	0	RING	100-31-2592.5	1	0	1
	0	ZUMESSVENTIL	905-02-0019.5	1	1	1
	137-04-0262.1 GLEITSTEIN 909-11-0307.5 PRESSURE SPRING 0	PRESSURE SPRING	909-11-0307.5	1	0	4
	0	SLEEVE (HÜLSE)	100-31-0769.5	1	1	1

Figure 16. Inventory level monitoring in the inventory system

	Kysyntä	Hinta	Toimitusaika	Toimituskulut	Toimittaja	Edellisen Konerikon syy	Laatikko	Kattavuus (%)
4	6,25	0,25	3	22	Bihler			0,0459039
9	6,25	0,65	3	22	Bihler			0,0918078
5	2	0,45	3	15	Bihler			0,106497048
2	2	4,05	3	22	Bihler			0,121186296
1	5,25	47	3	22	Bihler			0,159745572
1	2,25	8,6	3	22	Bihler			0,176270976
4	1,5	0,65	3	15	Bihler			0,187287912
1	1,5	5,5	3	22	Bihler			0,198304848

Figure 17. Essential data regarding spare parts as seen in the inventory control system

Kone	MC42-1	MC42-2	MC82-1	YHT.		
Seisonta hinta (€/d)				4717	Tilausväli	4
Varaston arvo (€)	1776	796	1627	4198		
Pitokustannukset (€/a)	355	159	325	840		
Varaston kesk arvo (€)	1723	162	726	2612		
Palveluaste (%)				96 %		
MTTF (d)	6	11	9	3		
System availability (%)	94 %	97 %	95 %	90 %		
Kattavuus (%)	86 %	91 %	82 %	86 %		

Figure 18. The measures regarding the inventory control system

4 ANALYSIS

4.1 Downtime

As seen from table 2 it was noticed that the first machine had a significantly lower downtime costs compared to the other two machines. For the customer the production from the first machine is equally as important and production rates should be as high as from the rest of the machines so spare part acquisitions cannot be optimized in way where the investments to the reliability of the first machine are considerably lower than the rest. In addition, the first machine has the most moving parts from the machines, which means that investments for its spare parts tend to be naturally higher when using the methodology that is applied for this project. Most of the downtime values are slightly smaller than the average value from the three machines since the first machine has the most installed components in it.

4.2 Spare data

During the project it was noticed that most parts in the machinery were considered to be critical for the operations of the machinery. Noncritical spare parts were not considered for storage in this project as generally the lead times were low enough to justify minor inconveniences in the production versus expensive investments. The capital was better thought to be invested in critical parts. The company has knowledgeable staff to do repair work to further reduce the need for non-critical spare parts. It was noticed that for most spare parts the demand values are smaller than once per year which according to the literature studied in chapter 1 is very typical for spare parts.

Due to the large downtime costs in relation to the relatively small prices of certain spare parts most of the spare parts have a theoretical payback time of less than 0.1 years. The savings a realized when a downtime scenario occurs so it cannot be assumed that the investment is paid after the payback time has elapsed. The value of the payback is better used to work as a reference value by which to rank the spare parts in terms of their profitability as was done in this study. Items that were deemed not worth storing produced payback times indicated by a minus. These items were easily identifiable when ranking the spare parts in terms of profitability.

Majority of the calculated re-order points were 0 or 1. This is due to the fact that for the investigated wear parts delivery times were short and the probability of demand during that short period of only a few days is very small and the desired service level of 99 percent for each spare part can be achieved.

4.3 Inventory calculations

When comparing the prices of spare parts to the incurred downtime costs it was noticed that the prices for most spare parts were smaller than the daily downtime costs. This suggests that having a good inventory of spare parts on hand is useful and profitable. This statement was later confirmed by the calculations comparing the incurred holding costs and downtime costs.

The amount of spare parts and the value of spare parts was not evenly distributed between the different machines as can be seen from table 3. The amount of identified spare parts and the value tied to spare parts was concentrated mostly on the first machine and lastly for the second machine. This is since the first machine has the most components installed to it and has the most complicated assembly of the machinery whereas the second machine has the simplest assembly.

A small amount of spare parts causes a large part of demand. A small investment can solve majority of demand scenarios and improve the reliability of the machinery considerably. The observed situation works according the Pareto principle. The cumulative investment and demand scenarios are shown as plotted in Excel in figure 19 where the blue line shows the percentage of demand scenarios solved and the red line shows the amount of money invested in spare parts. The steep raises in investment value are single spare parts with high values.

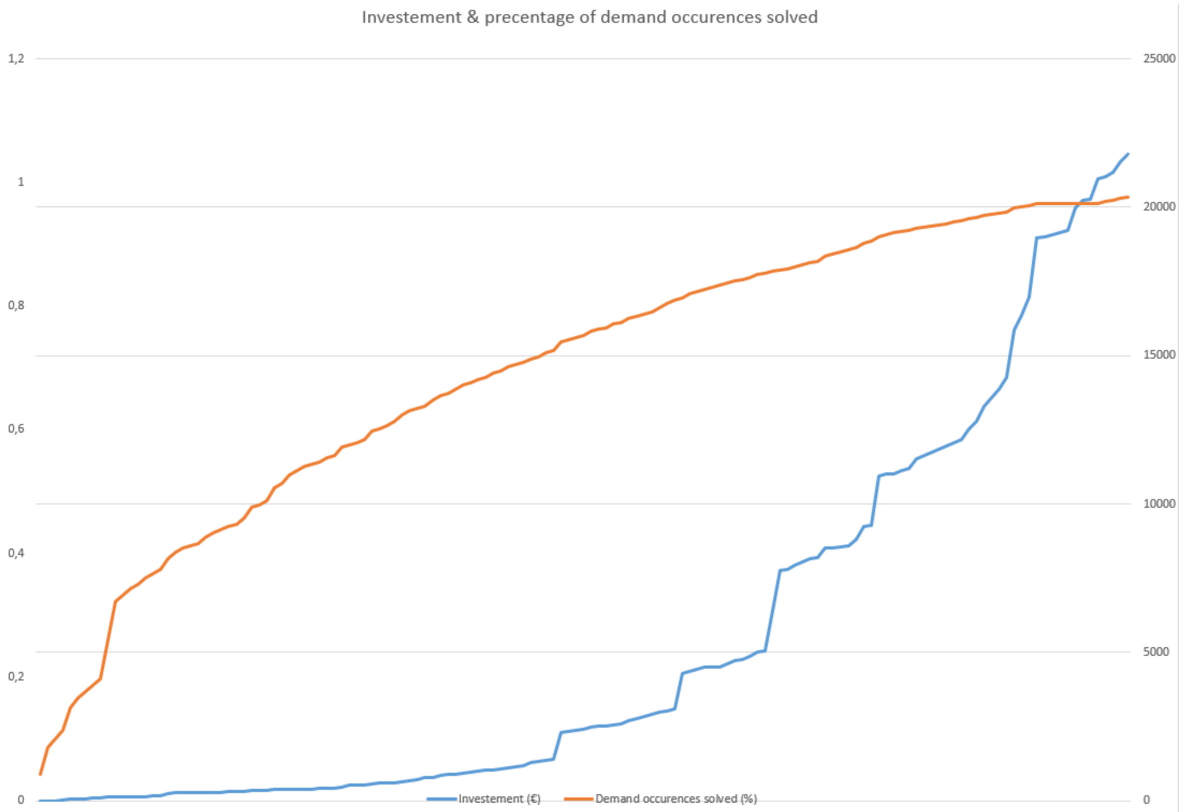

Figure 19. Relation of investments to the percentage of demand occurrences solved

The increase in system availability rate follows a similar curve as the demand scenarios solved. The relation of value invested to raise in availability rate by using machine one as an example is presented in figure 20.

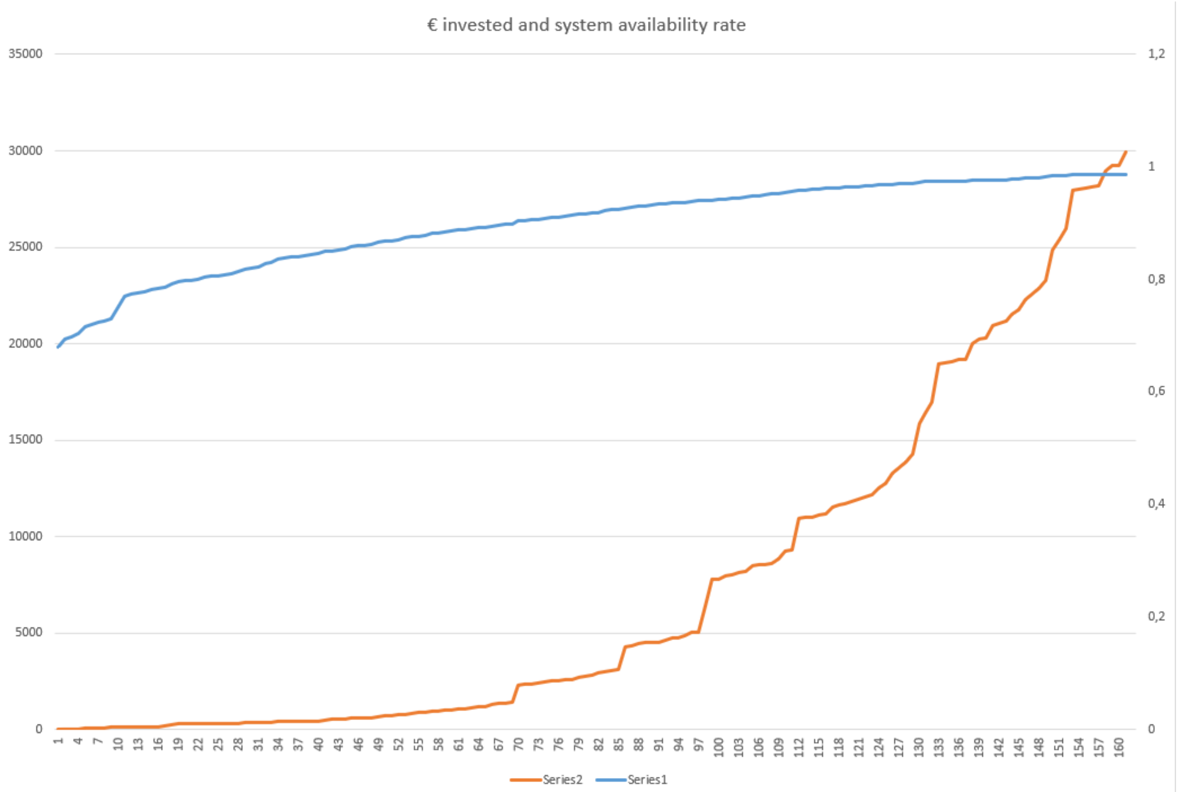

Figure 20. Investment compared to the system availability rate

Comparisons of system availability rates per machine for different demand coverage scenarios are presented in figure 21. From the figure it can be seen that the overall system availability rate where all of the machines are running simultaneously is raised the steepest.

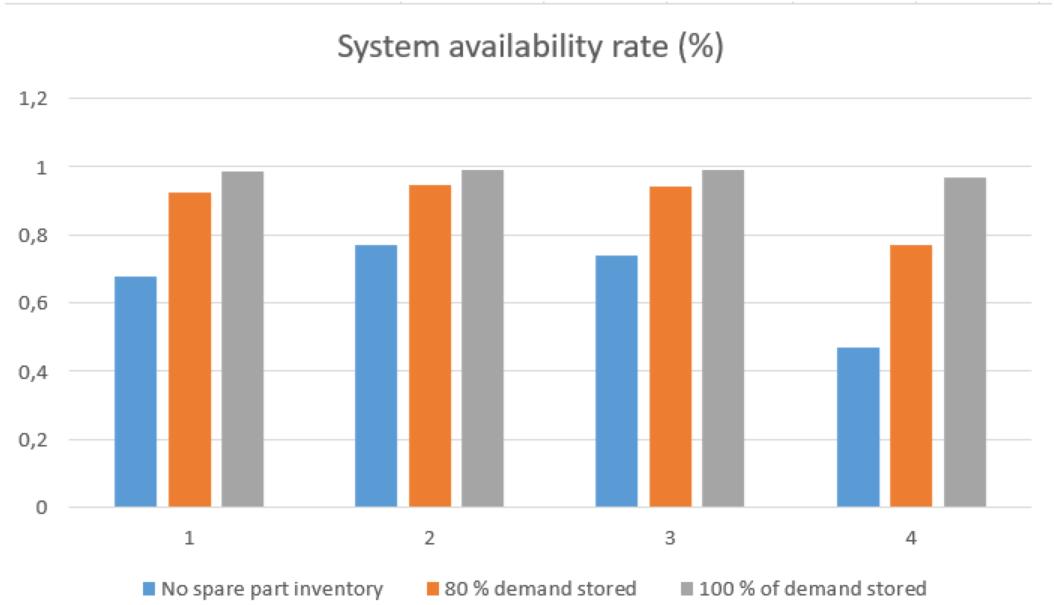

Figure 21. System availability for different scenarios per machine

The machinery in question had a lot of parts in it where the estimated demand was very similar. This has been further illustrated in figure 8. From figure 10 the payback times or in other words the relation of investment and advantages between different spare parts was also very similar. This can be explained by the fact that the prices and estimated failure rates of spare parts are quite similar whereas the incurred downtime costs are large compared to the price of spare parts. When the spare parts were prioritized it can be seen from figure 19 that the amount of demand situations solved and the increase in system reliability plateaus after the investment of approximately of 750 €. In this area of investment, the differences in payback times between spare parts are very small. In this area finding the best spare parts for investment is difficult as the estimated demand values given are never 100 % accurate. A large amount of different spare parts stored gives the most likely situation where the maximum number of demand scenarios are solved.

4.4 Buffer storage

Buffer storages are used in manufacturing to provide safety against sudden spikes in demand or unexpected manufacturing problems. The current spare part inventory proposed by this study was compared to a buffer storage of completed products, to examine would a buffer storage be a sensible alternative for a spare part inventory. The results of said comparisons are shown in table 7.

Table 7. Comparison of buffer and spare part inventory

	Coverage (%)	Holding costs
Buffer storage	0,62	12839
Spare part inventory	0,85	748

As seen from the values the spare part inventory provides larger coverage of demand scenarios for a lower investment. The lower coverage rate for buffer storages in this case is caused by the fact that multiple different products are produced on the same line. For these calculations the data for the most produced products was used. In this case one of the motivations for conducting this study has been the fact that the buffer storage levels agreed to with the customer have not been able to be maintained due to increased demand and unreliability regarding the machinery. In an instance like this where building up the buffer storage is a big challenge as the production is delivered immediately to satisfy the demand and buffer storages can be built up very slowly.

4.5 Relation of stock value, order intervals and service level

The effect of the review period on stock levels, stock value and the service level of the inventory system was investigated. A comparison was done for four different scenarios where the order intervals were continuous meaning orders are place immediately after demand occurs, two weeks, one month and three months. A histogram showing the average stock value compared to the average service level for the for different re-order intervals is shown in figure 21.

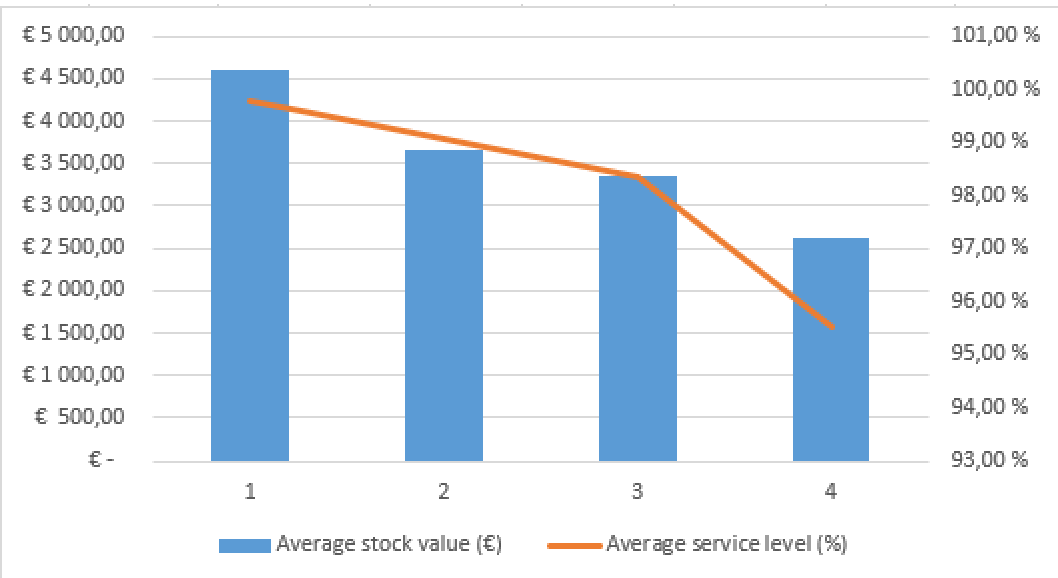

Figure 21. A histogram with average stock value compared to average service level

It was calculated that a drop of 1 % in service level would on average mean an increase of 150 € incurred downtime costs. The increase in incurred downtime costs was a constant meaning for example the difference between 99 and 98 percent was the same as the difference between 22 and 21 percent. The average stock value decreases more steeply during the higher service level percentages than it does during the lower percentages. For this reason, a point can, be found after which the increase in incurred downtime costs is higher than the reduction in average inventory holding costs. It was calculated that the optimal ratio between the service level and average stock value was found at a point where the service level was approximately 98 % and the average stock value was approximately

3400 €. From experiments with the inventory control Excel it was noticed that the service level of 98 % was achieved when spare parts were ordered once a month.

4.6 Notable trends

The recommendations on what where the parts most susceptible for were given by the suppliers. According to the machinery manufacturer the most likely items to be replaced were different types of springs and support pulleys. The springs in the machinery were part of moving mechanisms where the springs would be susceptible to repeated compressions and decompressions. From the generated movement the possible failures in springs would most likely be a result of fatigue. The springs suffer cyclical loads where fractures due to fatigue are likely to happen (Skewis 2019). The supporting pulleys are in a constant rotating movement while the machinery is running. The failure modes caused from this type movement could be similar as bearings for example mistakes in the installation of pulleys or improper lubrication and dirt getting into the pulley (Emerson Bearing Company 2019). From the demand history acquired in the factory the most likely items to fail were springs that had a failure rate of 6 failures per year. For these items the failure modes were thought to be caused by fatigue as the springs were under cyclical loads. The information regarding possible failure modes and most likely types of items to fail could be used for new preventive maintenance procedures. More on possible preventive maintenance procedures is discussed in chapter 6.1.

Two different items were noticed to have considerably larger failure rate in this machinery than what was proposed by the manufacturer of those items. These were a servo-controlled gripper module and a position sensor. The large failure rates of these items were thought of not to be the result of normal gradual wear. The failures of the servo. Controlled gripper module was the result of having the gripper in a wrong position when the machinery was put back running after stoppages. The sensor was installed in a location where a lot of metal dust and other dirt would get to it and most likely cause it to fail prematurely. The servo-gripper module was a critical part of the machinery. In addition, the gripper was expensive compared to most other spare parts in storage and had considerably longer delivery times. The financial impact of the failures of the sensor and gripper were calculated, to make the inspection of their effects and feasibility regarding investments to fixing the root cause or for preventive maintenance measures. The financial impact regarding these spare parts is shown in table 8.

Table 8. Impact of spare parts with large failure rates

Part	Expected failures (1/a)	Realized failures (1/a)	Extra downtime (h/a)	Extra capital spent (€/a)
Sensor	0.019	5	10	420
Gripper	0,666	2	3	1200

4.7 Suppliers & bidding

The suppliers were mainly compared by the availability of parts and the price of parts. It was noticed that the official importer of the manufacturer was generally the cheapest and had the availability and lead times for their products. In addition, the services and knowledge regarding their spare parts, including the failure rate data, was thought to be the best. The chosen suppliers had already been used by the company previously and had been proven to be reliable. The level of communication thought to be useful with the suppliers varied from supplier to supplier. For the machine manufacturer a closer relationship was thought to be important. The connections provided by this spare part projects can be used in future improvement projects. For the rest of the suppliers the number of different spare parts decided to be stored was considerably smaller and spending resources on closer communications is not as useful. The suppliers chosen were large reputable companies, which means that the risks related to the suppliers going bankrupt, providing unsatisfactory service or otherwise not providing on their responsibilities was thought to be small.

5 DISCUSSION

For some spare parts accurate demand data based on either supplier recommendations or demand occurrences in the factory was not available. This was because the parts had not failed during the inspection period of five years or the wear situations were not suitable for inspection within the scope of this study. Closer inspections of wear scenarios would mean more preventive maintenance measures. Some ideas about preventive maintenance related to this project are presented in chapter five. For stationary parts that do not experience wear during normal operation procedures, the exact demand data is also not known. For these parts the practical demand is thought to be zero.

The equipment in question consists of thousands of parts, so listing every single item was not feasible. Listing the most likely wear part based on history and major assemblies was a suitable way of analysis. Predicting the demand of non-wear parts without any data was not possible.

Downtime may cause the need for overtime to meet the production goals. In this case when the machinery is scheduled to run in three shifts the overtime would be done during weekends. In case downtime is compensated by overtime the lost production is made up but the labor costs are more than doubled. Overtime hours affect the calculated downtime costs. No exact policy on of overtime hours was in place and scenarios where overtime is conducted are decided on a case by case basis. Therefore, in this case they were not taken into consideration when calculating the downtime hours.

The proposed solutions were suitable to be implemented at the current state of the company. Even though the model can take some changes into account, some major changes may cause the need for modifications on the model. That is why regular monitoring on the workings of the model are required. Some modifications to the machines are already under planning. These would be large projects where the complete machine would be restored. This would mean changes in composition of the machine and spare parts needed. These projects are not completed for a period of years which means that an initial investment to take care of the running of the machine in the meantime is useful. The calculations in this project can be directly applied to the machinery after the restoration project and updating of the spare part lists. Other alternatives for the implemented Excel based system would be a system implemented to the ERP-system of the company. In this case it was not considered as it was thought to not have advantages to Excel based system and would have been more complicated to implement.

Some of the spare parts had a supplier warranty. The warranty does not remove the need for storage in case of a breakdown. In the instances where warranty is present the initial investment would be considered zero if the spare part fails during the warranty period. If, however the spare part lasts through the warranty period the initial investment is as much as the spare part has cost. Possible warranties were put on as notes next to the affected spares. No new classification category for spares under warranty were implemented. Warranty was not considered as a separate entity in the calculations.

5.1 Reliability

The value for holding cost was a good estimation for a manufacturing industry and has been widely used in multiple applications. More specific calculations were not deemed necessary. The biggest risk related to the reliability of this study come from the demand data used for the calculations. The demand data is based on approximations by the suppliers and special characteristics that may be present in this system have not been considered for those estimations. The special characteristics should be covered by the real demand data acquired from the spare part order history. During discussions with the operators it was also estimated that the actual demand values would be slightly lower than the ones given out by the machine supplier. Without no accurate data however, these estimated differences could not be compensated for in the calculations.

The values calculated are only looking at the realized risks with demand values that can be estimated somewhat accurately. The machinery considered is very complicated and parts that are not generally worn have not been suitable for being used in the calculations. Therefore, the real values for system availability rate are going to be lower than what has been calculated. No corrective measures for these measures have been taken in the scope of this study. The estimated advantages in this study are based on the planned situation where the machinery is run for 16 h in a 24 h period during workdays. The 16 h running time has considered tool changes and time that is spent when a production run has been changed. In reality the machinery has had problems in its reliability unrelated to spare parts and has not been running for the ideal rate. This means that the realized downtime costs might be slightly lower than calculated and the realized savings might be lower than estimated according to the data used in this study.

The calculated MTTF values were calculated from demand values from multiple sources. During discussions with the operators the acquired values were thought to be slightly lower than what has been observed directly from the operation. In addition, the demand values are only approximations so the values can't be used for any exact calculations. The values however give a good estimation and be used when estimating the incurred downtime during a longer period.

The methods for controlling spare part inventory and calculating stock levels and advantages can be applied to other spare part inventories. The scenario where a small part of spare parts has the biggest overall impact of the functionality of the machinery, can be thought as something that would apply to other spare part inventories as well.

5.2 Sensitivity

Two different EOQ methods were compared. The normal one as stated in (Kenton 2019) and a method where stockout costs are considered as stated in (Rodrigues 2012). Models provided only small differences which in the case of this project, where there were some uncertainties regarding the failure rates of the parts, were not deemed significant. Therefore, the normal EOQ method was used for simplicity and reliability. The comparisons of the EOQ methods and other formulations are presented in chapter 2.9. The example spare part used in calculation has a yearly failure rate of 0.5, ordering costs of 15 € for every order and a price of 10 € with yearly holding costs of 2 €. The values used as an example are very typical for the types of spare parts investigated in this project. The results between the different EOQ methods are presented on table 9.

Table 9. Comparison of EOQ-models

EOQ Model	Result
1	2.73861279
2	2.740322289

Comparisons between normal and Poisson distribution were conducted using the estimated demand during an inspection period of 3 days with an example spare part with a estimated failure rate of 0,5 failures/year. With normal distribution value of 0.5 was used for the standard deviation. The values used as an example are very typical for the types of spare parts investigated in this project. The results of the calculations are presented in table 10.

Table 10. Comparison between distributions

Distribution	Probability of demand
Normal	0.004092746
Poisson	0.012057324

5.3 Monitoring

The model has been designed to be used without too much extra input given to it during exploitation. Some changes in production might however result in the need to revise the calculations and input values. Changes in production schedules cause variations in the downtime costs. Changes to the regular operation such as number of shifts should always be updated, and the calculations should be revised. For items prioritized in this project the difference between spare part price and the incurred downtime costs are quite large so minor changes in downtime costs do not produce any necessary changes on the inventory. Regular quotations on the availability, lead times and prices of spare parts should be done. Spare parts have low demand which may mean a period of years between demand occurrences. During a long period, changes in the supplier's stock can occur and spare parts may be discontinued, lead times may increase, or the prices may change.

5.4 Preventive maintenance

From the trends discussed in chapter 4.6, some ideas for preventive maintenance measures can be had. For the rolling element installations could be done to measure the vibrations of the pulleys to detect when they are nearing the end of their usability. Measures regarding vibration measurement could be however quite expensive and they might be difficult to justify in this application. For the springs visual applications could be done. This would be time consuming and for those reasons would provide to be too costly. The two notable spare parts that had large financial impact compared to the manufacturer guidelines had failure modes where the utilization of failure modes would be difficult. For the gripper the failure comes from mistakes in operation that cannot be monitored preventively. The sensor breaks as metal dust cumulates to it, which is also difficult to monitor. For these spare parts improvements to the root cause are better suited for a practical application.

In this application however most spare parts that were deemed suitable for storing were relatively small. Therefore, large investments to condition monitoring would not be feasible. The failure rate data is not detailed enough to create a maintenance plan where spare parts are ordered for a pre-determined service break. Currently no plans for investments to preventive maintenance measures were made. The implemented spare part inventory however reduces the downtime typical with corrective maintenance actions.

5.5 Spare part management in maintenance and its advantages

After observing the daily operations of the factory with the help of experienced factory personnel from both operators and management, ideas on what kind of an effect the implementation of the spare part management system would have on the operations of the factory and company on multiple levels. Based on (Kelly 2006) the effects of the system were observed on three essential levels on the operation of the factory. Maintenance and production management, financial management and manufacturing engineering.

The control of spare part inventory has an effect on the production planning and maintenance management activities of the factory. The levels of spare parts can be observed without any extra effort spent by the management. This ensures that critical items that are below stock level can simply be observed by looking at a single Excel file. All this makes the duties of the maintenance manager easier. As discussed in chapter 4.3 the system availability rate of the manufacturing system increases as well as longer unexpected downtime instances are reduced. This makes production planning easier as the planner can be surer when forecasting the production. In addition, the reduction on unexpected downtime reduces the time that the management must be solving these instances. Time spent on solving an unexpected downtime scenario can now be spent better for example on developing the manufacturing operations further. The reduction in workload for both the operators and management reduces stress and creates a more pleasant working environment which improves productivity and quality.

Manufacturing engineering can gain a lot of useful information from the close monitoring of spare parts. Close monitoring of what are the most commonly used spare parts helps in finding the root causes for their breakdown, which could then be fixed to gain further improvements in the system availability rate. Developments in predictive maintenance are also possible on the identified spare parts. In the case of this project the data found warranted closer inspection on two different spare parts. More on these parts is explained in chapter 4.6. From observing the rates of failure plans for services could be done to change spare parts at a suitable moment before their breakdown causes unexpected need for actions. For the operators the system holds a lot of advantages. The time spent on looking for a spare part is significantly reduced. Especially cases where the operator has no knowledge whether a spare exists in stock are significantly reduced. As the spare part inventory is kept clean the working environment is a nicer place to work. The reduction in unexpected downtime reduces stress in both the operators and management creating a better working environment. The improved work environment leads to better efficiency and higher quality. The improved reliability of the system is an advantage when applying for new industrial standards.

The development of the spare part inventory system has provided new ways on how to look at the production line and the financial impact of its features. The increased system availability rate and the increased percentage of on time deliveries can be used when making new sales. For financial planning the knowledge of how much capital is tied to spare parts and how much capital is approximately going to be spent on spare parts in the future can be used for planning for example future investments. The financial knowledge can also be used when negotiating with the customer on whether they would also be invested in the capital cost for spare parts in turn for increased reliability and deliveries.

5.6 Future Considerations

The guidelines used when calculating the downtime costs of machinery could be applied to other machinery in the factory. The same methods of classification and calculations could be used on other machines in the factory. It has been suggested that for the most important machinery monitoring of the spare parts usage would be done alongside other production quality control measures to make the implementation of this spare parts control system as smooth as possible in the future. The calculations used here for downtime can in their current state only be applied to machinery where the production schedule can be easily forecasted. Other machinery like this exists in the company but for some machines the productions are difficult to forecast which means that calculating the real downtime incurred is more difficult. More discussions on how to calculate downtime costs on machinery like this have to be had before implementation of this system.

Inventory could be further reduced if preventive maintenance measures were implemented. Preventive maintenance means monitoring the wear of parts and then replacing or servicing those parts before they eventually fail. The advantages of this are that the service schedules can be planned beforehand, to match the production schedule and to eliminate unexpected downtime. With preventive maintenance inventories can be kept lower as the time of replacement can be estimated more closely and spare parts can be ordered when the need for them arises.

An overhaul process for the machinery is currently in the planning stage. With an overhaul process the machinery is modernized by the manufacturer. This means that all of the components inside will be inspected and worn and outdated pieces will be changed into new ones. The overhaul is a good chance to improve the maintainability of the machinery further. A new complete list of spare parts should be requested from the machinery supplier during the overhaul process. This should include a complete list of all spare parts and a list of the most likely to be replaced wear parts. The spare part inventory should be updated according to these new recommendations, as parts currently listed for storage may be removed from the machinery. A complete update of the inventory and lists is required. (Kelly, 2 s 16)

The inventory system should be monitored closely to make sure that it is working as planned. It should be made sure that both the management and operators are committed into keeping the stock levels updated and that the decided responsibilities of personnel are suitable and that the layout of spare part storage is suitable. The data should be updated whenever modifications are made to the machinery or some new information regarding the data is found, for example the failure rate of a certain spare part increases. The information acquired can be used in other production development cases not mentioned in this study.

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