Bachelor Thesis

Spare part management for wind farms

UNIVERSITY OF TWENTE.

In cooperation between
IEBIS and Fraunhofer IWES

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8/27/2017

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Management summary

Introduction:

This thesis is a research into the spare part management for operators of wind farms. It is made in cooperation with the German research institute IWES. Currently, the operators of the wind farms with whom IWES is partnered, outsource their spare part management to the original equipment manufacturers. This thesis researches how these operators could organize their own spare part management in the most cost-efficient way. To do this, the two research questions were drawn up:

1) *What are the optimal strategy and policy for the operators to organize their spare part management?*
2) *What is the influence of each input values on the choice of strategy and policy and how do they influence the total costs?*

Methods:

To answer the first of these two questions a model was implemented in excel for 2 of the phases of the bathtub curve, which explains the failure rate changes during the life cycle of a typical part, the early phase and the stable period. In this model, all relevant theory on spare part management was used to form a model which uses the input data to generate the total costs for each policy and strategy. The three strategies modelled in this thesis are the continuous review strategy with economic ordering quantity, periodic review strategy and individual ordering strategy, which is a form of continuous review strategy with an order size of 1 unit. The total costs consist of ordering costs, inventory costs and shortage costs. These total costs of multiple policies for each of these strategies were calculated using the model after which the service level with lowest total cost was chosen. The input values used by this model were compiled from data sent by IWES and industry data found in online research papers. Secondly, a sensitivity analysis was executed to determine the influence on the choice of policy and total costs of the following 5 input factors: average demand rate, ordering costs, inventory costs, lead time and operational revenue. All other input values are used to determine one of these 5 factors. Therefore, no further analysis is needed on other input values. The distribution of average demand rate is assumed to be a Poisson distribution for the stable period and Weibull distributed in the early phase.

Results:

The result of this thesis is that for both the stable period and the early phase of the lifetime of the wind turbines reviewing every time a part is taken from the inventory is the optimal strategy. Since the distribution of failures Poisson distributed in the stable period and Weibull distributed in the early phase, the parameters of the optimal policy change over time. For the early phase, the reorder point and economic order quantity both slowly decrease over time, until the policy equals the optimal values of optimal policy in the stable period, which is constant as long as seasonal variations are below 50% of the base values.

From the sensitivity analysis, the conclusion is drawn that the average demand rate is the most influential in the choice of policy and has the biggest influence on the total costs. For the stable period, small changes in the input values do not influence the choice of policy, therefore the input values do not need to be measured exactly. As long as the input values do not change drastically, the policy does not need adapting in the stable period.

Recommendations:

My recommendations for further research on this topic focus on testing and verifying the assumptions made in this thesis. Especially determining the distribution and the variance of the demand over the lifetime requires further research. Furthermore, the implementation of the strategy and policy needs to be studied, which is not within the scope of IWES, but will be important to the operators whom IWES are partnered with.

Preface

After more than three months of working on this thesis, my bachelor thesis is finally finished and lays here before you. I did this thesis for the BSc programme of 'Industrial Engineering and Management' at the University of Twente. I think my experience of working on this thesis has been very valuable to my personal progress and I will always value the time and effort others have put in helping me write this thesis.

Firstly, I want to thank my housemates and family for supporting me and keeping me motivated during the time it took me to write this thesis. If not for them, I doubt this thesis would have been finished by now and would certainly not be up to the quality it is now.

Secondly, I want to thank Volker Berkhout and Stefan Faulstich from Fraunhofer IWES for supplying the necessary data and giving feedback during the course of the thesis.

Thirdly and most importantly, I want to thank my supervisors Engin Topan and Ipek Seyran Topan for supplying very useful feedback during the course of the thesis and during the writing of this report of the thesis.

I hope this thesis and the attached Excel-file are useful for IWES and the operators in the wind-energy industry and can help them save costs on their spare part management.

Kind regards,

Michael Kleinhoven

BSc student 'Industrial Engineering and Management'

Contents

List of terms used in this thesis:

Spare part management strategy: The system used to organize spare part management. This term will often be referred to as “strategy”.

Spare part management policy: The input values for the CSL level for each of the strategies, this CSL value will determine the actual values for the EOQ, ROP and OUL the operators of the wind turbines will use to determine when to place a new order and how many units that order should contain.

On-hand inventory: This parameter indicates how many units a company currently has in its inventory that can immediately be used to satisfy demand. This is the only part of the inventory over which a company has to pay inventory costs.

Pipeline inventory: This parameter indicates how many units a company has ordered with its supplier, but these parts have not yet arrived in the warehouse so cannot yet be used to satisfy demand. This part of the inventory will be used to satisfy future demand.

Backorders: The backorders is the part of the demand that can not immediately be fulfilled by on-hand inventory, because inventory is 0 at the time the failure occurs. To fulfil the backorders, additional spare parts need to be ordered.

EOQ: The EOQ is an abbreviation for economic ordering quantity. This is the optimal order size to minimize the total costs.

ROP: The ROP is the reorder point. In a continuous review policy, if the amount of items in inventory on hand + pipeline inventory - backorders is equal to or lower than the reorder point, a new order will need to be placed by the supplier to increase the inventory levels.

ESC: ESC stands for estimated shortage per cycle. This parameter is in units of product and will usually not be an integer. This is the expected amount of units the company will need to backorder every cycle if they choose that policy.

Safety stock: The amount of inventory units that can be used to fulfil demand when demand is higher than expected without leading to stock outs.

Lead time: The time between placing the order with the supplier for new spare parts until the spare part arrives at the warehouse where it can be used to fulfil upcoming demand.

CSL: Cycle service level. This is one of the main inputs for the choice of policy. The cycle service level is the percentage of cycles in which all demand is fulfilled.

OUL: Order-up-to-level. The amount of units a company wants to have in their on-hand inventory + pipeline inventory at the start of each review period. This level of the inventory should be enough to fulfil most of the demand for the upcoming period.

Review period: Amount of time between monitoring the inventory in a periodic review strategy. Only at the start of each review period, the inventory will be counted and a new order can be placed.

1. Introduction

1.1 Company summary

IWES is a German research institute located in Kassel. They focus their research around the topic of wind energy systems and energy system technology. They work together with multiple partners from the industry where they have an advisory role and they do assignments given to them by these partners. They also created numeral interfaces to exchange ideas between the institute and the industry to develop solutions for acute and future problems (IWES, 2017).

My project in this is that I will work with data delivered by IWES and will report the results to them. This way I can do most of the work without having to stay in Germany. My role for this thesis is that of a partner to IWES and not an integral part of this institute.

IWES has been doing research on failure behavior of wind turbines for many years, so they have a great knowledge on failures; this makes them a key player in the industry. Recently, they started up a new project named WindPool. With this new project, they will pool all the operational and failure data into a large database from which they can give feedback to the operators of the wind farms on how well they are doing compared to the industry. This is necessary because none of the operators have a broad enough database to be able to determine the trends in failures by themselves. The data is entrusted to Fraunhofer IWES which will validate the data while protecting the confidentiality of the industry partners.

With this data, the trends in failure data will be determined after which spare part management can be introduced in the system, such that the expected downtime costs and inventory costs are minimized. IWES will not introduce this spare part management themselves, but only give an advice to the operators on how they could use the spare part management model to increase their efficiency.

1.2 Example of current system:

This system is an example for an operator who controls multiple offshore wind farms north of western Germany. This system does not change much between operators beside the locations of the different warehouses, wind farms and manufacturers. As can be seen in figure 1.1, the parts are made by the original equipment manufacturer (OEM) in Stade, Germany. When the parts are ordered by the operators they will be transported to one or multiple distribution warehouses. In this case, the distribution warehouse is located in Emden harbor, Germany. The operators will then transport the parts to local warehouses near the windfarms. The parts will then be used from the local warehouse to replace failed parts on the wind farms.

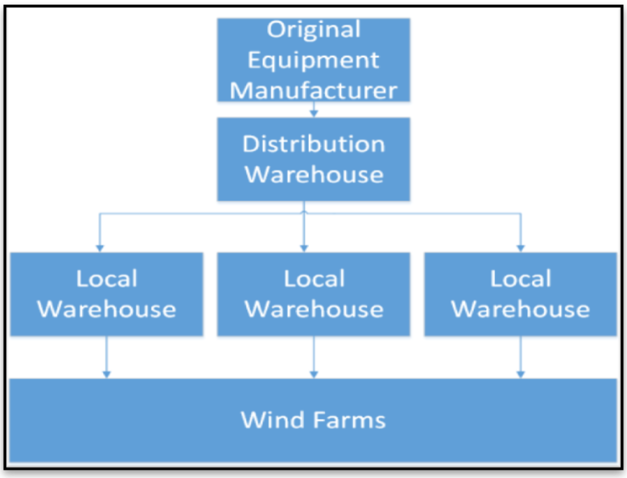

Figure 1.1: Overview of the system

Each arrow represents a lead time between the different parts of the system, from this overview it is obvious that the higher in the echelon the spare part is, the longer it will take for the spare part to reach its final destination in the wind farms.

Currently, the operators do not organize the spare part management of the inventory by themselves; instead they outsource the spare part management to the OEMs. This means that all maintenance activities are currently being done by the OEM's, ranging from the distribution of spare part between the warehouses to replacing failed parts. The operators' requirement is that the uptime of the turbine stays above a certain level. Outsourcing the spare part management and maintenance causes the operators to not have complete and organized data on each of their failures; therefore they cannot provide a full set of data to IWES. IWES would like to be able to give an advice to the operators on how they could organize the spare part management of their inventory themselves to save costs thereby increase the completeness and validity of their databases.

1.3 Research goals

The goal of this thesis is to determine the most cost-efficient strategy and policy for the operators to organize the spare part management for wind farms themselves. This leads to the first research question:

What are the optimal strategy and policy for the operators to organize their spare part management?

The second goal of this thesis is to determine the influence of each of the input data on the choice of policy and strategy. This leads to the second research question:

What is the influence of each input values on the choice of strategy and policy and how do they influence the total costs?

The sub-questions for this thesis are:

What part of the wind turbine should be focussed on?
What policies can be used to model the spare part management?
How can one determine the different costs of a policy?
What distributions should be used for the failure rate in the various stages of the lifetime?
How can we determine the initial base values for the model?

1.4 Scope

Since time is limited for this assignment. We have determined to start with only one spare part to model. The part to model will be researched in chapter 2.1 of this thesis. However, the model created for this part can probably also be applied to other parts of the wind turbine once the base values for the model are changed to suit the other parts.

Secondly, it is only focused on corrective maintenance. The corrective maintenance is assumed to be started as soon as a part is available to replace the failed part. The reason for excluding preventive maintenance is that it can be planned well in advance, so that the spare parts will be used as soon as they are delivered, there will also not be downtime, since the parts haven't failed yet in this scenario. We assume preventive maintenance does not change compare to the current situation, since we do not know the influence this would have on the failure rate.

The distribution of the parts between local warehouses is not part of this thesis. There was not enough data available, due to the fact that the OEM's currently control the distribution of the parts, to be able to model each of the local warehouses with lead times between them to provide an accurate model, therefore only the total amount of spare parts is calculated and the operators will be able to decide themselves if and how they distribute these parts between the warehouses.

Furthermore, this thesis will only focus on the early phase of the bathtub curve and on the stable period, thereby excluding late failures. The distribution during these two periods will be determined in chapter 2.3. These two phases were chosen by request of IWES, who told me that especially the early failures are important. The stable period is the longest phase of the lifetime and therefore the most influential on the total costs over the lifetime of the wind turbine.

However the goal of this thesis is not only to provide the optimal solution for the given data, but also to indicate how varying the input data can influence the choice of strategy and policy and how this could influence the total costs. This part is especially important for IWES, because if they can show to the operators how inaccurate data leads to significantly higher spare management costs, they have a good reason to collect more and more accurate data which they can use to give more accurate advice to the operators.

1.5 Deliverables

This project will have the following 3 deliverables:

1. Description of applied strategies and decision variables in current decision making systems –and its environment.
2. Create process model of spare part logistics in onshore wind industry (including information model for spare part stock keeping and identify relevant reliability information).
3. Create decision matrix for the spare part supply strategy choice under uncertainty.
4. Find optimal policy parameters during the lifetime of the wind turbines.
5. Determine the influence of changing input values on the policy parameters.

2 Literature review:

In this chapter, I will try to answer some of the sub-questions by analysing the research done by others in this field.

2.1 What part of the turbine to focus on?

According to Ribrant (2007) the failures are distributed over the different parts of the windmill as shown in figure 2.1. This shows that the most failures occur in the electrical system, the hydraulics the control system, the sensors, the blades and the gears. Of these parts, the most interesting for spare part management are the blades and the gears, since they usually cannot be repaired but have to be replaced. When one part of the wind turbine fails, the entire turbine will be shut down until a replacement part is installed.

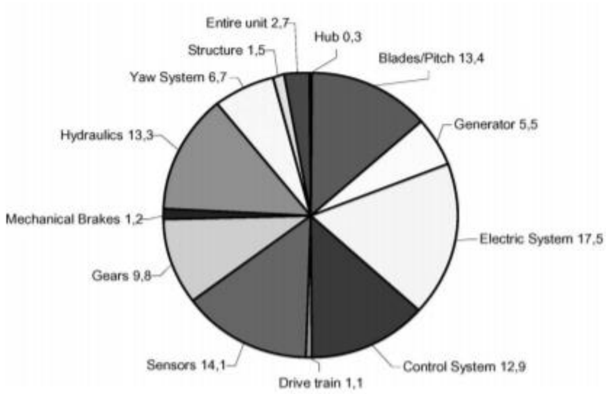

Figure 2.1: Distribution of number of failures (%) (Ribrant, 2007)

As seen in figure 2.2 (Ribrant, 2007): the gears provide a larger part of the downtime than the blades even though the blades fail more frequently. This means the average repair time for the gears is longer than the repair time for the blades. We can assume that the costs of downtime are equal, but we do not know the costs required to repair each failure; therefore we cannot say whether the blades or the gears provide more costs for the operators.

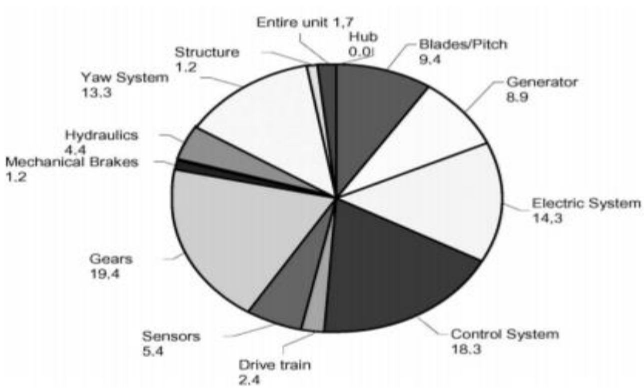

Figure 2.2: Distribution of Downtime (%) (Ribrant, 2007)

A more recent study on turbine failures was done for Chinese wind farms (Lin et al., 2016). In this research, the results varied slightly from the results of Ribrant (2007). In Lin et al. (2016), the downtime caused by the failures is not stated, only the distribution of failures between the different parts of the wind turbine as seen in figure 2.3. We can see that there are several differences compared to the failure distribution found by Ribrant (2007). The gears are failing relatively more often in the data studied by Lin et al. (2016).

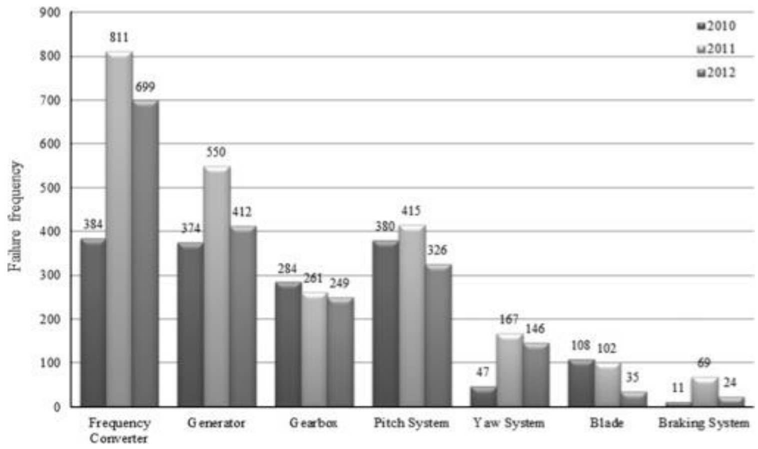

Figure 2.3: Distribution of failures (Lin, 2016)

The conclusion of this literature research is that there are several parts which can be interesting for modelling. As can be seen in table 1, the most critical parts are the gears, which usually cause the longest downtime, the electric system, which has the highest amount of failures and the blades which have the highest purchase cost. Other critical parts are the control system and the sensors of the wind turbine, which both have a high amount of failures and a significant amount of the downtime and purchase cost.

Table 1: Overview choice parts

Part	% failures	% downtime	% Purchase cost (Irena 2012)
Blade	13.4	9.4	22.2
Gearbox	9.8	19.4	12.91
Electrical system	17.5	14.3	0.96
Sensors	14.1	5.4	1.32
Control system	12.9	18.3	3.89
Hydraulics	13.3	4.4	1.22

In consultation with IWES, it was decided to focus on the blades of the turbine, since they cause a significant part of both failures and downtime and are the most expensive of these parts, therefore causing high inventory costs per part. Furthermore, blades are a stock keeping unit, which means that the entire blade needs to be replaced in case of failure. For the other 5 units usually only part of the system needs to be replaced.

2.2 Replacement strategies

There are multiple policies that can be implemented to arrange spare part management. These policies can be split up in two strategies: continuous review and periodic review (Muckstadt, 2005).

2.2.1 Continuous review

In a continuous review strategy, the inventory is always monitored and once the inventory decreases to below a certain predetermined point, a new order is placed to refill the inventory. How the inventory level changes can be seen in figure 2.4.

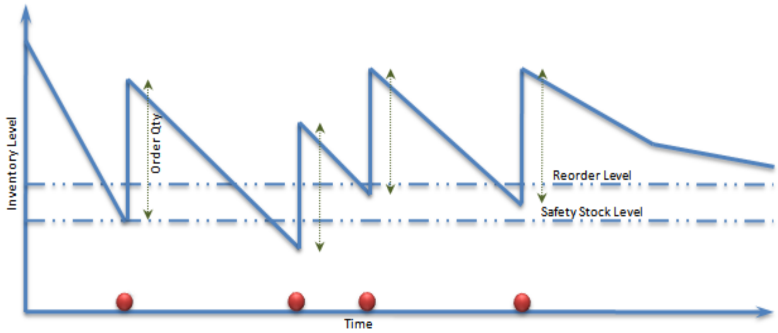

Figure 2.4: Continuous review policy (Sehgal, 2008)

This point is named the reorder point or ROP. The ROP can be determined by calculating the safety stock (ss) and adding the expected demand during the lead time. To calculate the safety stock with variable demand and constant lead time, we can use formula (1) (King, 2011):

$$ss = z * \sqrt{LT} * \sigma_d \qquad (1)$$

In equation 1, ss is the safety stock in units. z is the normal standard inverse of the cycle service level (CSL). LT is the lead time. σ_d is the standard deviation of the demand per unit of time. The CSL can be set to any decimal on the interval 0.5 < CSL < 1. This CSL determines the policy the company wants to use. After determining the safety stock, the ROP can be calculated by using formula (2) (Chopra & Meindl, 2013):

$$ROP = ss + D_l \qquad (2)$$

Where ROP is the reorder point in units of the product, ss the safety stock in units of the product and D_l is the average demand multiplied by the lead time. The ROP is always rounded up, to ensure reaching the CSL we started off with. This means we can end up with a much higher CSL than we started with.

Besides calculating when to place a new order, the optimal amount of units to order needs to be determined. This amount of units is called the Economic Ordering Quantity (EOQ). Since shortage costs are known in this model, the EOQ formula with shortages can be used. This EOQ with shortages can be calculated using formula (3) (Taylor, 2008):

$$EOQ = \sqrt{\frac{2KD}{h}\left(\frac{OR*LT+h}{OR*LT}\right)} \qquad (3)$$

In equation 3, the EOQ is the Economic ordering quantity in units of the product. K is the constant cost of placing an order, regardless of how many units are ordered. D is the average demand rate per year. h is the inventory costs as percentage of the purchase costs, OR is the operational revenue per wind turbine per day and LT is the lead time between placing the order and the order arriving in the warehouse. The EOQ will be rounded to the nearest integer.

Once the EOQ and ROP have been determined, everything we need to determine the average state of inventory throughout the year. Therefore we can determine the Expected shortage per cycle (ESC), the average inventory and the amount of orders placed throughout a year. With these three indicators we can calculate the total costs each of the spare part management policies will cost.

We start by determining the ESC, where we assume the demand is normally distributed; therefore formula (4) can be used (Chopra & Meindl, 2013):

$$ESC = -ss * (1 - F_s(\frac{ss}{\sigma_l})) + \sigma_l * f_s(\frac{ss}{\sigma_l}) \qquad (4)$$

The ESC and safety stock are in units of products. F_s is the cumulative standard normal distribution and f_s is the standard normal distribution. However, this formula does not work if the demand and variance are very low, because then the safety stock will not be an integer and the rounding of the ROP will play a large role, therefore ss should be replaced by ROP – D_L, which is the actual fractional safety stock applied in this situation.

Next up we calculate the amount of ordering cycles in a year, which is simply the demand per year (D) divided by the EOQ. The backorders (EBO) can now be calculated by multiplying the ESC with the amount of cycles of year.

To calculate the shortage cost of downtime (C_s) caused by backorders; the backorders are multiplied with the operational revenue of a wind turbine (OR) multiplied with the lead time (LT). Since we can assume a normal distribution during the lead time, we can assume the average failure that becomes a backorder happens in the middle of the lead time, so we can divide the shortage costs by 2. If we combine all of the above, we get formula (5):

$$C_s = \frac{ESC * D * OR * LT}{2 * EOQ} \qquad (5)$$

Where C_s and OR are in Euros; ESC, D and EOQ are in units of product, lead time in units of time.

The inventory costs can be calculated by multiplying the on-hand inventory with a percentage of inventory costs (h). To calculate the on-hand inventory, the pipeline inventory (PI) first needs to be calculated. The pipeline inventory can be calculated using formula (6) (Chopra & Meindl, 2013):

$$PI = EOQ * LT * \frac{EOQ}{D} \qquad (6)$$

The on-hand inventory (I) can then be calculated using formula (7):

$$I = ROP + 1 + \frac{EOQ}{2} - PI + ESC \qquad (7)$$

Formula 7 gives all the inventory influences per cycle. During the cycle, the total inventory varies between the ROP + 1 and ROP + EOQ, because as soon as the inventory reaches ROP, a new order with size EOQ will be placed immediately. During the cycle, the inventory will on average be equally divided between ROP + 1 and the ROP + EOQ. However, the company does not pay inventory costs over pipeline inventory, so the pipeline inventory can be subtracted from the total inventory. The shortage per cycle is added to the average inventory, to prevent subtracting that part of the demand twice, both for demand and pipeline inventory.

The total inventory costs (C_i) can then be calculated by multiplying the average on-hand inventory with the purchase cost of the inventory (PC) multiplied with an inventory cost percentage (h), which is usually around 10-20% of the purchase cost of the inventory as shown in formula (8) (Chopra & Meindl, 2013):

$$C_i = I * h * PC \qquad (8)$$

The ordering costs (C_o) can be calculated by multiplying the amount of orders with the cost of placing an order with formula (9) (Chopra & Meindl, 2013):

$$C_o = K * \frac{D}{EOQ} \qquad (9)$$

In which K are the one-time ordering costs per order the company places in euros, for this variable, it does not matter how many units are ordered, only whether an order is placed or not.

The total costs involved in a certain spare part management strategy (C_t) can now be calculated by adding up the different costs involved in the strategy with formula (10):

$$C_t = C_s + C_i + C_o \qquad (10)$$

This total cost does not include every cost involved when replacing a failure; it just calculates the costs that vary when using different policies. Certain costs like purchase costs, repair costs and downtime caused by the lead time between the failure and the replacement being installed are not included, because they are constant and do not change when applying different policies. Including these costs would only increase the total costs by a certain constant for each policy, thereby making it more difficult to differentiate the policies.

2.2.2 Periodic review

In a periodic review strategy, the year is split in constant review periods. At the start of each review period, the current inventory is measured and a new order can be placed. The size of this order depends on the current inventory level and the order-up-to-level (OUL). How the inventory level changes over time can be seen in figure 2.4.

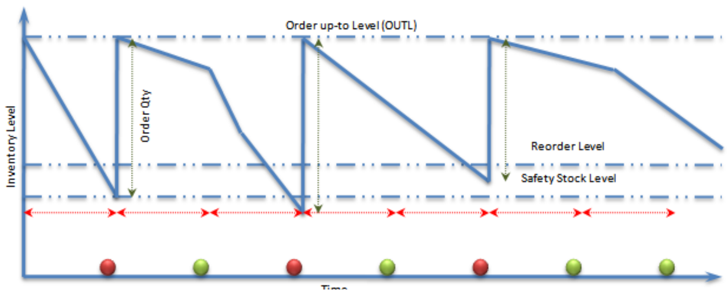

Figure 2.3: Periodic review strategy (Sehgal, 2008)

The order-up-to-level is the amount of spare parts the company wants to have in the inventory to fulfil most of the demand for this review period and the lead time into the next review period, so all demand until the next order will arrive. The OUL can be calculated using formula (11) (Chopra & Meindl, 2013):

$$OUL = D * (RT + LT) + ss \qquad (11)$$

Where RT is the amount of time in the review period and LT is the lead time. The OUL will always be rounded up to ensure the cycle service level which is determined when making the policy is reached. The optimal safety stock (ss) can be determined in the same way as the safety stock of the continuous review strategy in formula 1, except using review time plus lead time instead of lead time. This safety stock can be fractional, because it is included in the OUL which is an integer.

The average order size will be optimal if it is equal to the EOQ. Therefore, the review period (RT) needs to be adjusted accordingly. Since Q will be equal to the average demand in a review period, we can adjust the review period according to formula (12) (Chopra & Meindl, 2013):

$$Q = D/RT \text{ or } RT = D/Q \qquad (12)$$

The ESC of a periodic review strategy is very similar to the ESC of a continuous review strategy. However, there are a few differences which transform formula 4 into formula (13):

$$ESC = -(OUL - D_{r+l}) * \left(1 - F_s\left(\frac{OUL - D_{r+l}}{\sigma_{r+l}}\right)\right) + \sigma_r * f_s\left(\frac{OUL - D_{r+l}}{\sigma_{r+l}}\right) \qquad (13)$$

The safety stock has been replaced by OUL – D_{r+l}, which is not always equal to the optimal safety stock used in formula 11 due to the rounding of the OUL. Therefore the actual safety stock is the remains of the OUL – the demand until the next order arrives. Furthermore the standard deviation of the lead time has been replaced by the standard deviation of review time + lead time to include the uncertainty over the entire period.

The expected backorders per year (EBO) can be calculated by multiplying the expected shortage per cycle with the amount of review periods per year (R). Assuming all backorders will be ordered separately in an extra order outside of the regular review period, we can calculate the shortage costs per year for a periodic review strategy by using formula (14):

$$C_s = ESC * R * LT * OR \qquad (14)$$

The on-hand inventory in units in a periodic review strategy with normally distributed demand can be calculated by using formula (15) (Chopra & Meindl, 2013):

$$I = OUL - \frac{Q}{2} + ESC * R \qquad (15)$$

Formula 15 applies because the on-hand inventory at the start of each review period is the OUL, during the review period the average sales equal Q, the backorders are added to prevent subtracting them with the average sales, because since they are not sold from the inventory, they did not decrease inventory.

The inventory costs (C_i) can be calculated in the same way as in the continuous review policy with formula 8.

The order costs (C_o) for the amount of orders placed in a periodic review policy can be calculated with formula 16:

$$C_o = R * (1 + ESC - e^{-Dr}) * K \qquad (16)$$

In formula 16, K is the cost per order placed. R is the amount of review periods in a year. There is one order placed every review period, unless there is a shortage or no units were sold in the previous review period. If there is a shortage, R * ESC are the additional order due to backorders per year. e^{-Dr} is the chance that no units were sold in the previous period when the demand has a Poisson distribution, so therefore the inventory level is already equal to the OUL and no new order needs to be placed.

The total costs can again be calculated with formula 10 by adding up the individual parts of the total costs. Similar to the continuous review policy, these costs do not include costs not influenced by the choice of policy or strategy.

2.3 Distribution

There are several distributions which are relevant in spare part management:

2.3.1 Normal distribution

The normal distribution is a symmetric continuous distribution with parameters μ en σ (Khan 2010). The mean of a normally distributed variable is μ and the variance is σ^2. The normal distribution is a symmetric distribution which peaks at μ and decreases on both sides. This decrease is steeper for lower values of σ and less steep for higher values of σ. The normal distribution is one of the most commonly used distributions, especially in sampling experiments. This is because of the Central Limit Theorem, which says that if you average enough independent variables, you eventually get the Normal distribution (Khan, 2010). Since the normal distribution is continuous, the probability at any point is 0, only the integral of the normal distribution is interesting for the statistics.

The sum of c independent normally distributed variables results in a new normally distributed variable with mean μ * c and variance c * σ^2.

2.3.2 Poisson distribution

The Poisson distribution is a discrete distribution with parameter μ (StatTrek, 2017). The Poisson distribution is used when the occurrences are independent, the occurrences can be counted in integers, the average frequency is known and the amount of times it happened can be counted, but the amount of times the occurrence did not happen is not applicable (Umass, 2007).

The mean of a Poisson distributed variable is equal to the variance of the Poisson distribution is equal to μ. The probability of any given amount P(k) of expected occurrences can be calculated with formula (17) (StatTrek, 2017):

$$P(k) = e^{-\mu} * \frac{\mu^k}{k!} \quad (17)$$

The sum of c independent Poisson distributed variables results in a new Poisson distributed variable with parameter μ * c.

2.3.3 Weibull distribution

The Weibull distribution is a continuous distribution with shape parameter β, scale parameter η and location parameter γ. The location parameter is frequently not used, in which case it can be set to 0. If β < 1, the function is decreasing, if β = 1 the function is constant and if β > 1 the function is increasing. The Weibull distribution is often used in reliability analysis due its versatility and it being a relatively simple distribution. (Topan, 2015)

If the location parameter is set to 0, the mean is $\Gamma\left(1-\frac{1}{\beta}\right)*\eta$ and the variance is $\eta^2 * (\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma\left(1-\frac{1}{\beta}\right)^2)$, where Γ is the gamma function. The probability at time t can be calculated with the formula: $f(t)=\frac{\beta}{\eta^{\beta}}*t^{\beta-1}$

The sum of c independent Weibull distributed variables results in a new Weibull distributed variable with shape parameters β' and scale parameter $\eta' = \eta * c^{-\frac{1}{\beta}}$ (Topan, 2015).

2.4 Similar research

Many reports and discussions have been written on spare part management, each with their own specialty and curious cases. A small part of this research has been done in the wind energy industry, the most recent and complete being the research done by Schuh et al. (2015). Most of this research does not focus on a single part, but rather tries to provide a complete model that has been validated using the wind farm's current failure data. This thesis is different from the other research, because it is focusses on only a single part, therefore it is possible to go deeper into the spare part management of this particular part and can calculate the specific optimal parameters and the influence of the different input values on the values of the policy.

3. Methodology

To apply the theory described in the previous chapter, I made an excel sheet with two tabs. The first tab is for the stable period and the second tab is for the early phase of the lifetime of a wind turbine. On both of these tabs, the first 3 columns were used to put in the input data and next to these input data the different policies were calculated using the formulas mentioned in the theory so that the data is automatically adjusted when the input data changes. The details can be found in Appendix A.

3.1 Base case for the stable period

For the initial input data for the stable period, the following base values were used:

- Lead time from order placed to warehouse: 20 days.
  This value was given by IWES as a good indicator for the time between placing the order and the order arriving at the warehouse, this lead time is split up in receiving the order, making the blade and transporting the blade to the warehouse. We assume the lead time is constant.
- Failure rate: 0.01 failures per blade per year
  This value is an estimate by IWES based on the data reported in their database; this parameter will be higher in the early phase and might alter slightly with seasonal variations, which will be discussed in chapter 6.2, sensitivity analysis. This figure is multiplied with the amount of blades in the system to calculate yearly demand.
- Amount of wind turbines: 250 turbines
  This value provides an indication for which size of wind farm the spare part management strategies can apply. The figure of 250 turbines was chosen as a base for a warehouse serving 3-4 medium wind farms. This is multiplied by 3 to account for the amount of blades in system.
- Capacity rating of turbine: 5000 kW
  This value was provided by IWES as an average for the wind farms their industry partners serve. This figure defines how much energy can be generated per hour by a wind turbine if the turbine is used on full capacity. This value is multiplied with the average capacity factor, the feed in tariff and the amount of hours per day to calculate the operational revenue of a turbine.
- Average capacity factor: 40%
  This value was provided by IWES and defines how much of the total capacity is used on average. The capacity factor changes throughout the year and averages around 50% in winter, while in summer it is around 30%.
- Feed in tariff: €0.15 per kWh
  This value was provided by IWES and defines for how much the energy generated by the wind turbines is sold.
- Inventory cost percentage per year: 12%
  Industry data from other countries estimated the inventory cost between 15% and 20% (James & Goodrich, 2013). However, IWES thought the actual value should be somewhat lower, therefore 12% was chosen. This value multiplied by the purchase costs gives the inventory cost per part per year.
- Purchase cost: €430,000 per blade
  This value was provided by IWES and defines the price per blade used in the wind turbines.

- One-time ordering costs: €10,000 per order.
  This value is an estimation based on industry data in the USA where transport by barge for a 45m blade per 1100 miles is estimated to be around $15,000 (James & Goodrich, 2013). In our case the blades are larger, but the distance is shorter yet busier around the harbours of Stade and Emden. Therefore, the costs are estimated to be slightly lower than the estimation of James and Goodrich, a sensitivity analysis will be executed in chapter 4.2 to determine how much impact a different input value for this parameter would have.

All the necessary input values for the theory can be calculated from these input values. For example, the demand per year is calculated by multiplying the failure rate per blade with the amount of turbines multiplied by three to account for the fact that each turbine consists of three blades, therefore giving a value of 7.5 blades per year. The operational revenue per day was calculated by multiplying the capacity rating with the capacity percentage and the spot price and 24 to account for 24 hours per day.

The distribution for the stable period is assumed to be Poisson distributed with μ = 7.5 blades per year, this assumption is made due to the independent memoryless occurrences of failures and the constant failure rate, no separate variance or standard deviation was given, so the normal distribution could not be used. The variance for the stable period is therefore equal to the mean at 7.5 blades per year.

With these input values we calculate the total costs according to the theory for a continuous review strategy, a periodic review strategy and an individual order strategy, the last strategy is a special case of continuous review strategy where the order size is permanently set to 1 part per order instead of the EOQ calculated in formula 3.

I calculated the total costs for 8 different policies for each strategy to find the most cost-efficient policy. The different policies are for CSL values $\geq$ 0.5, 0.55, 0.6, 0.7; 0.8, 0.9, 0.95 and 0.99. CSL values lower than 0.5 do not exist, since that would lead to negative safety stock values. After calculating the total costs, consisting of inventory costs, shortage costs and ordering costs, for each of these CSL values, the CSL value with lowest total costs is chosen as the optimal policy with its associated EOQ and ROP/OUL values. The CSL value does not dictate that there is a service model in place, it is only used as the indication for which EOQ and ROP/OUL values are optimal, since it would take too long to calculate the total costs for every combination of EOQ and ROP/OUL. These 8 CSL values give a good range over the possible range with some additional focus on both of the extremes of the range. Especially for smaller values of the demand and variance, there will be overlap between the policies due to the rounding of the ROP and OUL, which is an effect that will disappear for larger values. The final excel sheet with calculations can be found in Appendix A.

3.2 Early phase

For the early phase of the lifetime of the wind turbines, a separate excel sheet was created with two additional input values, the early lifetime failures and the point in the lifetime of the wind turbines.

For the early lifetime distribution, a Weibull distribution is used, where the data point of 0.03 early failures per blade per year halfway year two was given by IWES and beta = 0.5. The second parameter of the Weibull distribution associated with this distribution could be calculated from formula 18 (Siebenlist, 2017):

$$\lambda\,(t) = \frac{\beta}{\eta} * \frac{t}{\eta}^{\beta-1} \qquad (18)$$

Where $\lambda\,(t) = 0.02$, $\beta = 0.5$ and t = 2.5. The resulting η is 83.23.

The new failure rate during the early phase can now be calculated by applying formula 18 with input values $\beta = 0.5$ and $\eta = 83.23$ and the input value of t in years. The result added to the constant failure rate of 0.01 will give the total failure rate at any point t in the early phase of the lifetime.

The early failure rate of all turbines can now be modelled as a Weibull distributed variable with parameters $\beta' = 0.5$ and $\eta' = \eta * c^{-\frac{1}{\beta}} = 0.22$. This gives a mean of $\Gamma\left(1 - \frac{1}{\beta}\right) * \eta$ = 0.44 blades per year over its lifetime and variance of $\eta^2 * (\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma\left(1 - \frac{1}{\beta}\right)^2)$ = 0.968 blades per year. This gives us a total variance of variance early failures + variance stable period = 0.968 +7.5 = 8.468

The other input values and calculations remain the same compared to the stable period.

3.3 Sensitivity analysis

For the sensitivity analysis, the different strategies were evaluated in the stable period. Initially, I wanted to do a second analysis for the early phase, but this was not done due to time constraints. The stable period was chosen to have one less variable in the point in lifetime, which makes it easier to analyse the differences varying the different input factors make. To analyse the influence of the input values, the results of the original base value were compared with 6 other values. These six values are 50% of the base value, 75% of the base value, 90% of the base value, 110% of the base value, 150% of the base value and 200% of the base value. These new values will be entered in the input data in the excel file, after which the total costs will be plotted in a graph as value of the input data for each of the three strategies. In the graph, the difference between adjusting policies for varying the base values are compared to not changing the initial decisions. In the base policy, the ROP, EOQ and OUL are used, which were optimal for the initial input values. In the optimal policy, all policies are recalculated with new ROP, EOQ and OUL values after which the optimal policy is chosen.

For each of the input values, not the total costs will be analysed, but the costs per replacement, which is more valuable, because it is obvious the costs will rise for higher demands. It is more interesting to see whether combining demand for more wind farms can lead to savings.

4. Results

In this chapter, the results of the model are discussed. Firstly, I will analyse what the optimal policy looks like for the values delivered by IWES and thereafter we will analyse the sensitivity of the policy parameters from the input values. All of these results are derived from the attached Excel model, where the input values start at the base values delivered by IWES.

4.1 Base values

Firstly, the excel sheet was filled in for the base values delivered by IWES, which can be found in chapter 3: methodology.

4.1.1 Stable Period

In the stable period, the costs per unit are calculated for each reorder point between 0 and 5 units and for ordering sizes between 1 and 4 units per order.

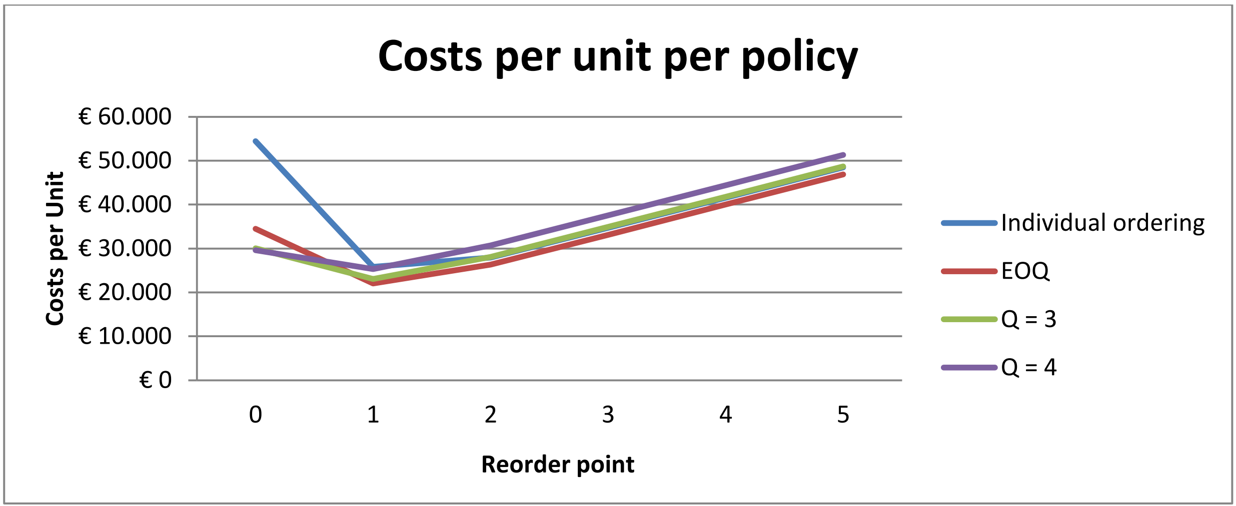

Figure 4.1: Total costs per Reorder Point for Continuous review

From the formulas in the theory we can see that for the stable period, the optimal order quantity is 2 units and the optimal review rate is 3.75 times per year. In figure 4.1 and 4.2, the different ROP and OUL values are set out against the costs per unit. As can be seen in this graph, the optimal choice of policy is to use an order size of 2 units and an ROP of 1 unit which gives a cost per unit of € 22,039. This gives us a CSL value of 0.6. The second choice of strategy is using the individual ordering strategy, which has an order size of 1 unit and an ROP of 1 unit. Order sizes higher than 3 units per order lead to higher inventory costs and therefore even higher costs per unit. As can be seen from figure 4.1, the order size has less influence on the costs per unit than the ROP. Increasing or decreasing the ROP significantly increases the costs per unit. From ROP = 3 to higher then costs increase nearly linearly, because shortage costs become insignificant therefore an increase in ROP leads to an increase of “inventory costs per unit per year” in the total costs.

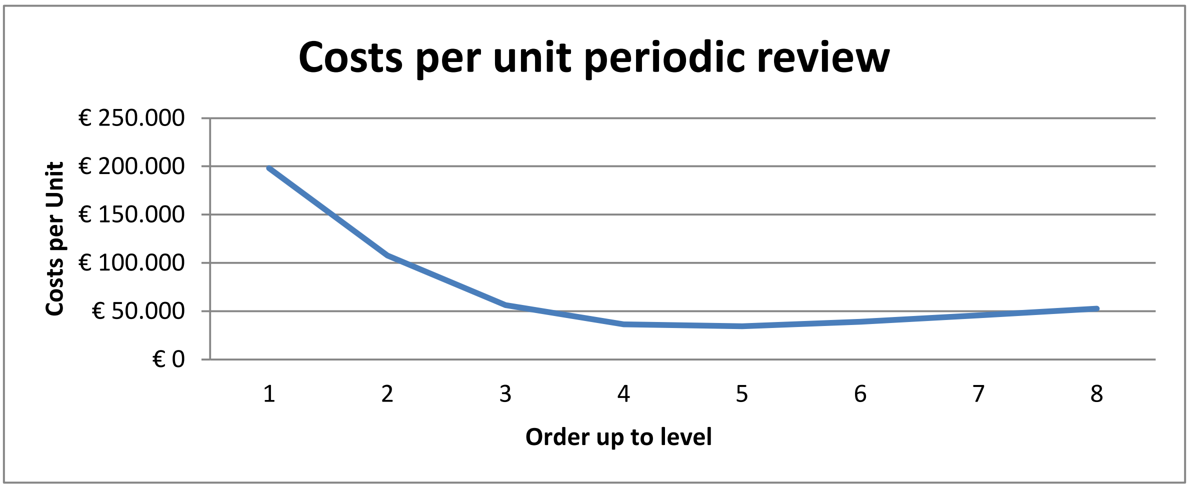

Figure 4.2 Cost per unit per policy for periodic review

Since the EOQ is equal to 2 units, the optimal review rate is 3.75 times. Increasing this rate will lead to lower shortage cost, yet higher ordering costs and inventory costs assuming the OUL stays the same. As seen in figure 6.2, the optimal policy for a periodic review strategy has an OUL of 5 units. For low OUL's the shortage costs increase quickly, while for high OUL's the inventory costs increase, in figure 4.2, we can see that these increases even out at an OUL of 5 where the minimum costs per unit apply. Minimum costs per unit for a periodic review policy are €34,304. This is nearly €12,000 more than the optimal value for a continuous review strategy. Therefore, periodic review should only be considered during the stable period if this saves the operator over €90,000 per year.

To further analyse how the costs in the individual strategies are build, figures 4.3 was made. It shows the cost build-up for the continuous review policies with an order quantity that is equal to the EOQ.

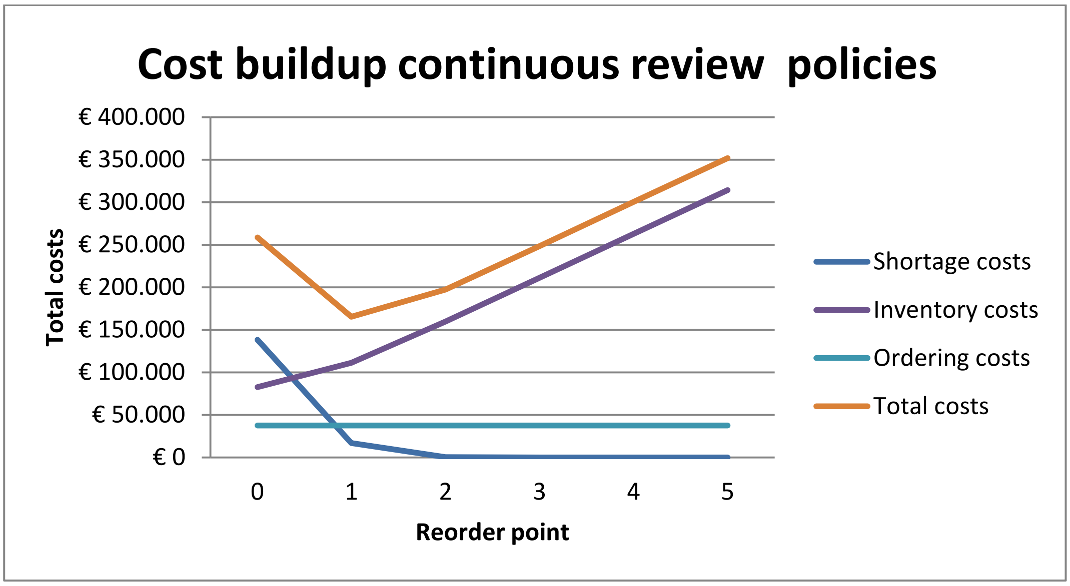

Figure 4.3: Cost build-up per policy for a continuous review strategy

In figure 4.3 we can see that the inventory costs occupy the biggest part of the total costs. Shortage costs are only significant for an ROP of 0 or 1 and ordering costs remain constant throughout all CSLs. This is to be expected, because the EOQ does not depend on the ROP, so the amount of orders placed per year remains constant for changing ROPs. Lower ROPs appear to be optimal; even though the shortage costs decrease at higher ROPs this influence is not large enough to negate the increasing inventory costs. For other order sizes, this figure will look similar; the main difference is that for higher order sizes inventory costs will take up a bigger percentage of the total costs, while shortage costs will decrease. For lower order sizes, this effect is reversed.

For the full data of each of the strategies and policies, see appendix B.

4.1.2 Early phase

The early phase is harder to analyze, since the costs vary depending on the lifetime of the turbine. The later the turbine gets in the lifetime, the lower the demand and the lower the variance. This means the costs will decrease over time until the turbine reaches the stable period. Figure 4.4 shows the optimal policy for each strategy during the early phase of the lifetime of a wind turbine. It is shown that both EOQ and ROP/OUL decrease during the early phase of the lifetime. This decrease will continue until the optimal values of the stable period are reached. There is one weird instance at year 4 in the lifetime where the ROP increases. This increase is caused by the EOQ decreasing compared to half a year earlier. Increasing the ROP back up to the level of year 3 gives a small € 1000 advantage over keeping the ROP at 2 at the start of year 4.

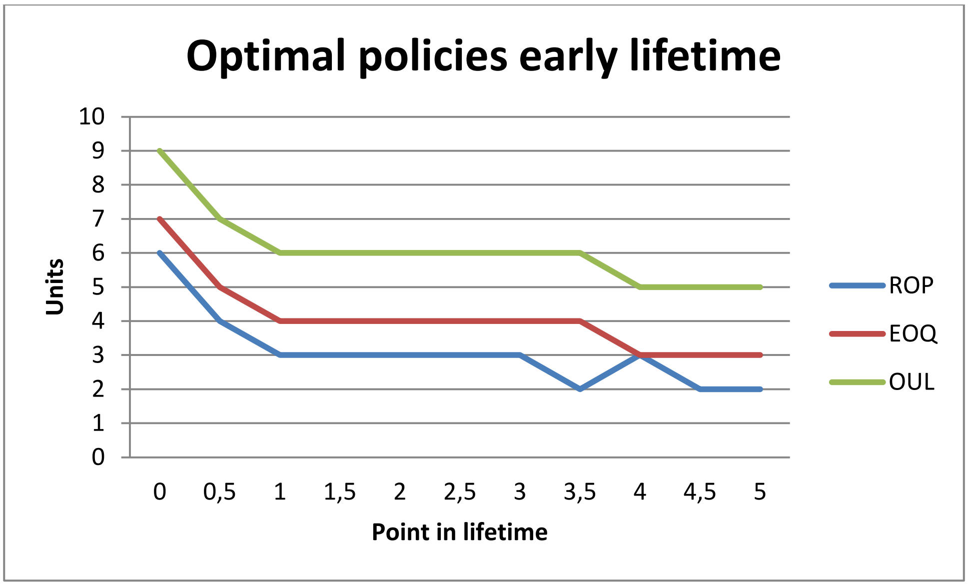

Figure 4.4: Optimal policy during the early lifetime

As shown in figure 4.5, the costs per unit increase over time. While this figure only shows the values for continuous review and periodic review with order size equal to EOQ, this same result can be found in other order sizes. The influence of order sizes is insignificant compared to the increase and decrease in costs when the ROP or OUL are adapted. This does not apply for large changes in order size like doubling each order, but increasing or decreasing order size by 1 or 2 units leads to an increase in cost per unit of under €1000. The increase in costs per unit over time is due to the diminishing demand when lifetime advances, for higher failure rates; there is a high turnover in the spare parts, which means that even though the average inventory doesn't change much, the yearly inventory costs are spread out over many more parts, thereby reducing the costs per part significantly.

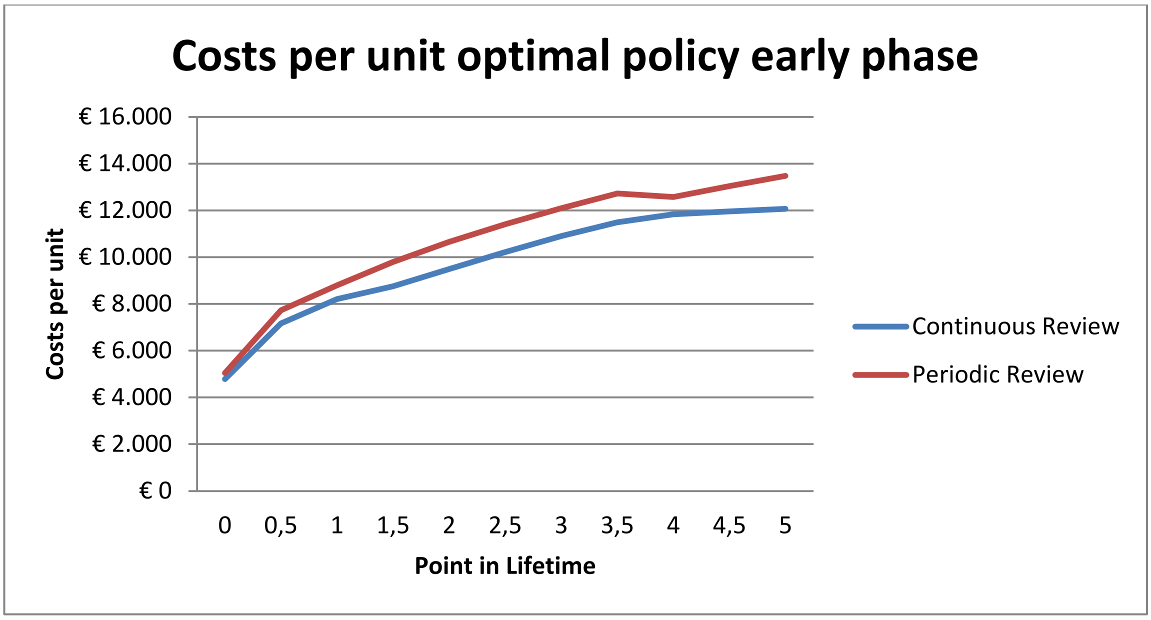

Figure 4.4: Costs per unit for the optimal policy at each point in the early lifetime of the wind turbine

4.1.3 Changing policies

This begs the question, at what point should the operators of the wind farms switch to a different policy and when should they adjust the ROP? For example, we know the ROP should be 4 at the start of year 2 and the ROP should be 3 at the start of year 3. If the inventory near the end of year 2 is at 4, should the company reorder?

Assuming they use a continuous review strategy with a set EOQ, this can be answered by looking back at the theory: The ordering costs become slightly smaller if the company does not place another order, so the saved costs would be the one time ordering costs/EOQ. The inventory costs also decrease by 1 * the percentage of time left in year two * inventory costs per part per year. However, the shortage costs will increase by (new ESC – old ESC) * amount of cycles left in year 2.This means that when the saved inventory costs + saved ordering costs are bigger than the added shortage costs, the ROP should be decreased. There will always be a point in time where the changes in inventory costs + ordering costs and shortage are equal, because the inventory costs change at a constant rate with the inventory costs per part, while the rate of demand is Weibull distributed, thus the shortages decrease exponentially over time during the early phase. If an order is placed before this point in time, the ROP should not yet be adjusted, after this point in time, the ROP should be decreased. To calculate this point, formula 19 can be used and solved for t. In this formula t is the point of time in the current year.

$$\frac{k}{EOQ} + \frac{1-t}{h*PC} = (ESC_{new} - ESC_{old}) * (LT * OR) * (1-t) * \frac{D}{EOQ} \qquad (19)$$

In the example given earlier, this function becomes:

$$\frac{10000}{4} + \frac{1-t}{51600} = (0.09 - 0.01) * (20 * 7200) * (1-t) * \frac{29.5}{4}$$

Solving for t gives t = 0.97, this means orders received after December 21st should take a reduced ROP into account so if the inventory reaches 4 before December 2nd a new order should be placed, but after December 2nd a new order should only be placed if the inventory reaches 3.

4.2 Sensitivity analysis

For each of the parameters where a sensitivity analysis has been executed, a graph was plotted to show how the costs for each strategy vary for increases or decreases in the parameter. For each increase or decrease of the initial value, the total costs of the optimal base policy and the new optimal policy are compared.

4.2.1 Average demand rate

There are many reasons why demand rate can vary from the initial values. From the model the two input values that determine the demand are the failure rate and the amount of wind turbines. Both of these input values linearly influence the demand, so if the failure rate increases by 10%, the demand will also increase by 10%. In Figure 4.6, it is shown that for varying rates of demand, the costs per unit change significantly.

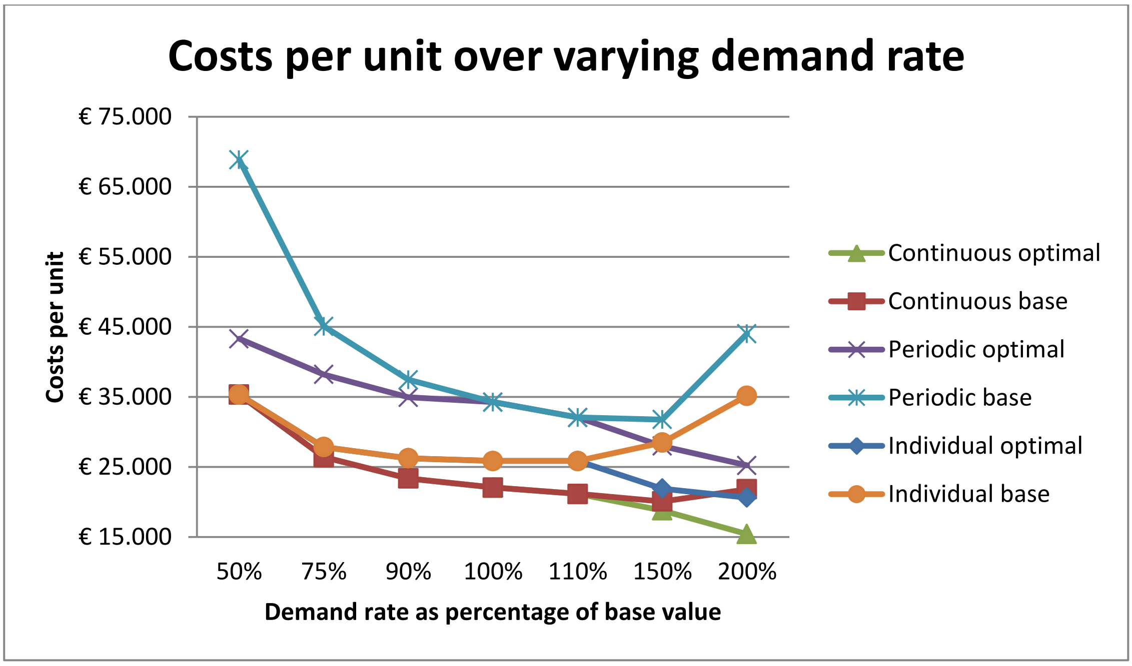

Figure 4.6: Costs per unit over varying demand rate

For continuous review, the optimal ROP and EOQ stay at the same point of one unit and two units respectively, so there is no reason to change policies for small changes in demand due to e.g. seasonal variations. However for an increase of 50% or higher both the EOQ and ROP increase. If an increase in demand of 50% does occur and the operator does not adjust his EOQ or ROP, this will lead to an increase in the total cost per unit of 7%. If the demand doubles, the cost of not changing policies is over 40%. This increase in difference is mainly due to more backorders and therefore higher shortage costs, by increasing the ROP, the shortage per cycle can be reduced, thereby reducing shortage costs.

For periodic review, the choice of policy seems to influence the total costs more for high increases or decreases in demand. Especially when demand doubles or halves, the costs per unit almost doubles if the policy is not changed accordingly. For small increases or decreases in demand, the changes in costs per unit are within 7%, which is still significant, but the operators should be able to handle such small increases. This increase in costs at high demands is mainly due to shortages and therefore backorders. If the demand increases but the OUL is not increased to account for this increase, there is a high chance of backorders every review period, which lead to shortage costs and additional ordering costs. The higher costs at low demands are due to higher inventory costs, there will likely be multiple units in stock every cycle that are not used to fill demand, yet the operators still need to pay inventory costs for these units.

For individual ordering, the situation is very similar to continuous review, the choice of policy only matters for increases of 50% or higher, after which the difference in costs per unit between the policies increases rapidly. For decreases in demand or small increases, costs per unit do not change between policies. The reason for the increasing difference is again the increased shortage per cycle, which causes more backorders and shortage costs.

4.2.2 Operational revenue

The operational revenue depends on the capacity factor, the capacity rating and the feed-in tariff, all of which are linearly influencing the operational revenue. As can be seen in figure 4.7, there is hardly a significant difference in the total costs for varying operational revenue.

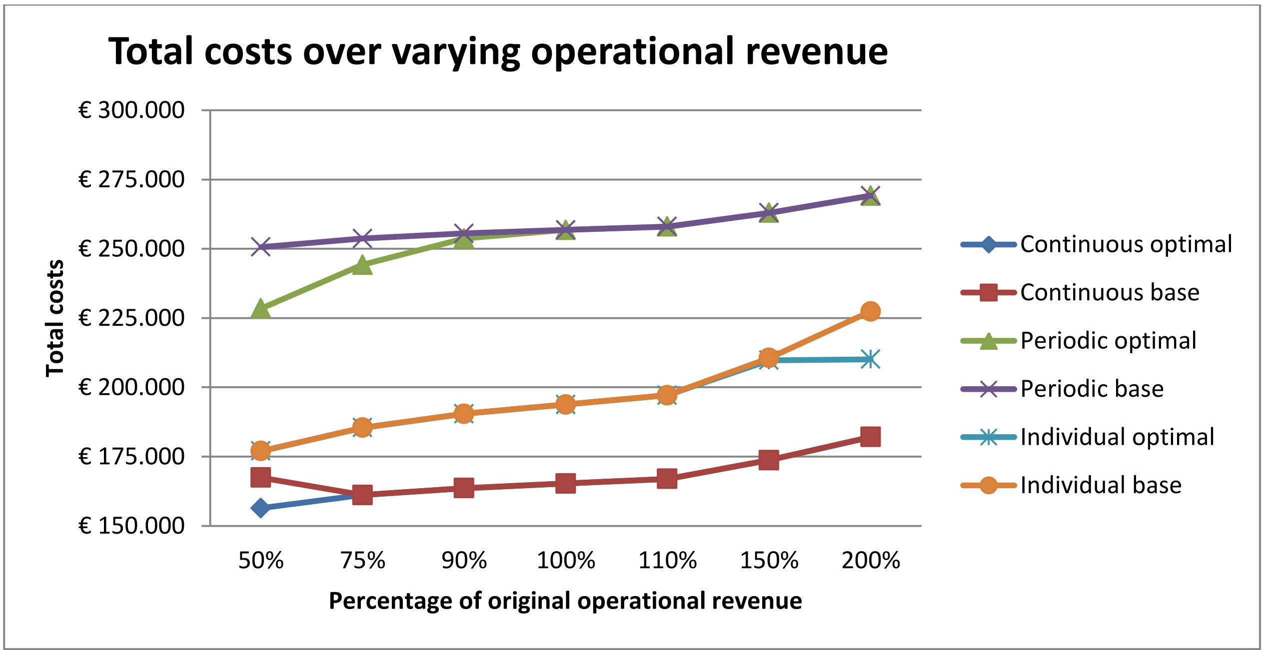

Figure 4.7: Total costs over varying operational revenue

As shown in figure 4.7, the base policy with an ROP of 1 unit and an EOQ of 2 units is still optimal for all values of operational revenue between 0.75 and 2 times the base value if operational revenue is halved, the total costs can be decreased by 6.5% by increasing the EOQ to 3, which reduces the amount of ordering cycles per year and thus the ordering costs and backorders, although it does increase inventory costs.

For Periodic review, there is only a difference between the base policy and optimal policy for lower operational revenues than the base value. This difference is due to the decrease in downtime costs, which means the operators of the wind turbines can afford to lower the OUL, which slightly increases shortage and ordering costs, yet reduces inventory costs by a bigger margin.

For individual ordering, the only difference between the original policy and the optimal policy is when the operational revenue doubles. The optimal policy here has a ROP of 2 units instead of the original 1 unit, which causes a sufficient decrease in shortage costs to cover the increase in inventory costs.

4.2.3 Lead time

As can be seen in figure 4.8, varying the lead time can lead to large differences between the different policies. Varying lead times can have various causes, such as not enough capacity or other problems at the OEM to produce enough units to fill the demand or problems with transporting the blades from the OEM to the warehouse.

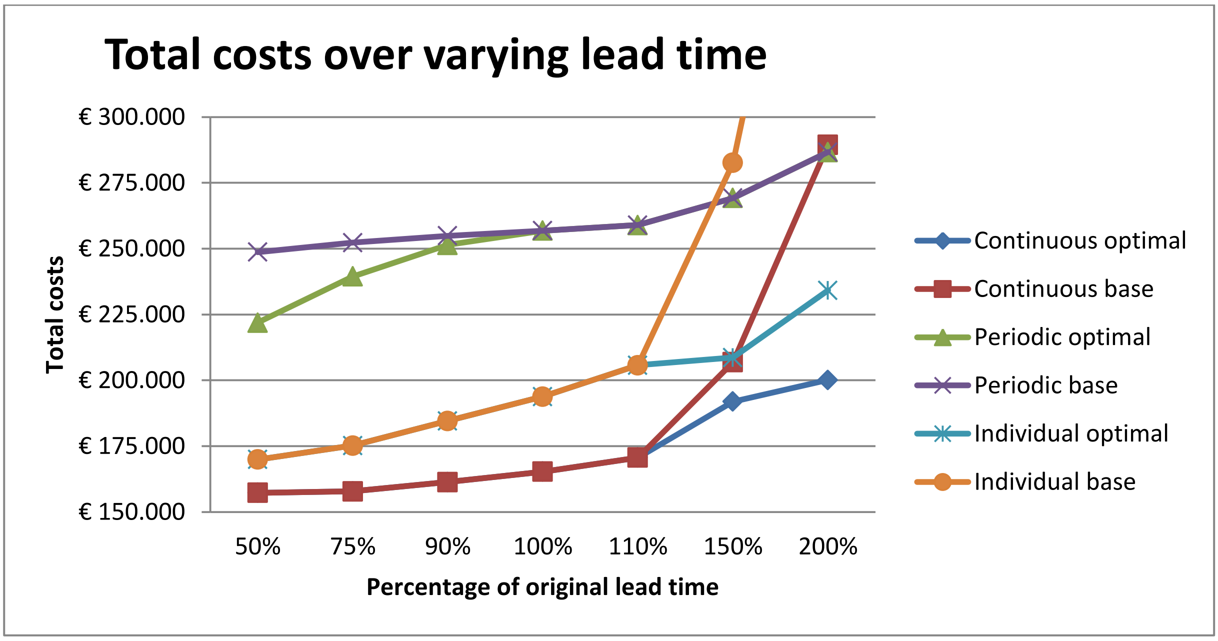

Figure 4.8: Total costs over varying lead time

The continuous review base policy is the optimal policy for lead times up to 22 days, if the lead time is longer than 22 days, the ROP of 1 unit is no longer enough to fill demand during lead time every cycle, causing a significant increase in shortage costs. For longer lead times, the ROP should be increased to 2 units so the shortage costs are kept in hand.

The periodic review base policy remains the optimal policy for lead times of 20 days or longer, for shorter lead times, the OUL should be decreased from 5 units to 4 units, which reduces inventory costs enough to cover the increase in shortage costs.

The individual ordering strategy shows the biggest changes for increasing lead times. For lead times up to 22 days, the base value policy remains the most cost-efficient policy, but with a lead time of 30 days or higher, the ROP of 1 unit will often not be enough to fill demand until the next order arrives, thereby causing high shortage costs of over €300,000 when the lead time is 40 days. To reduce these shortage costs, the ROP should be increased.

4.2.4 Ordering costs

The ordering costs can vary over time, this can be caused by changing transporters or setting different requirements for current transporters.

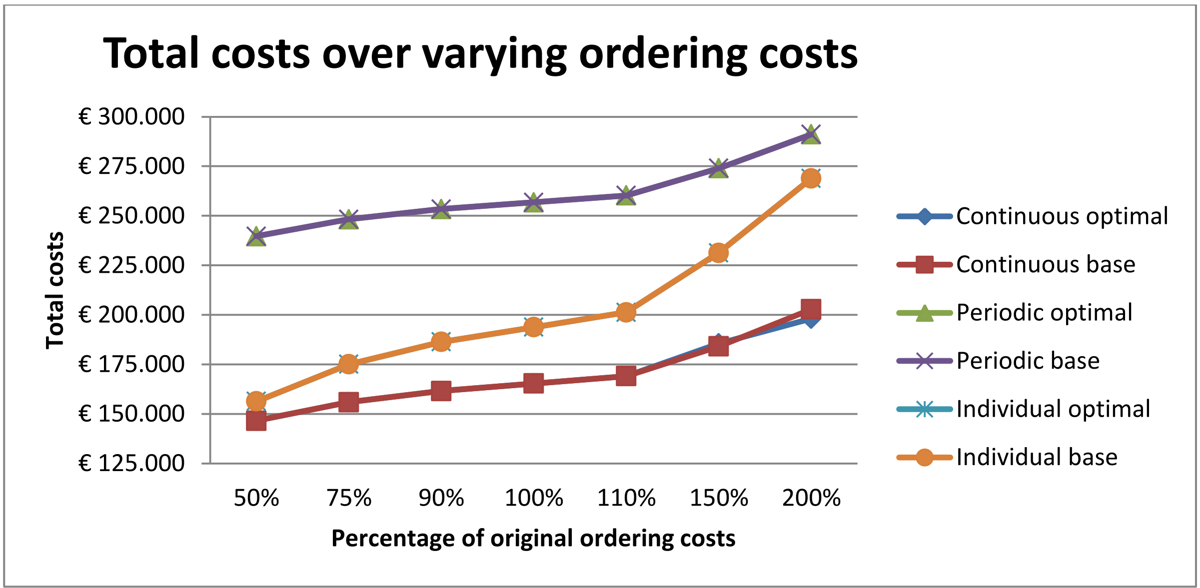

Figure 4.9: Total costs varying over ordering costs

As is shown in figure 4.9, changing the value of the ordering costs hardly influences the choice of policy within the strategies. The only point where the base value policy is no longer optimal is for the continuous review with 200% of the original ordering costs. At this point, increasing the EOQ from 2 to 3 will save 3% of the total costs, which is hardly significant compared to the differences shown in the previous sensitivity analyses.

4.2.5 Inventory costs

Inventory costs depend on three factors, purchase costs, inventory cost percentage and average inventory, each of these three is linearly related to the inventory costs. As is shown in figure 4.10, varying the inventory costs hardly changes the optimal choice of policy. While the total costs rise quickly for increasing inventory costs, the base value policies are still the optimal policy for most of the data points.

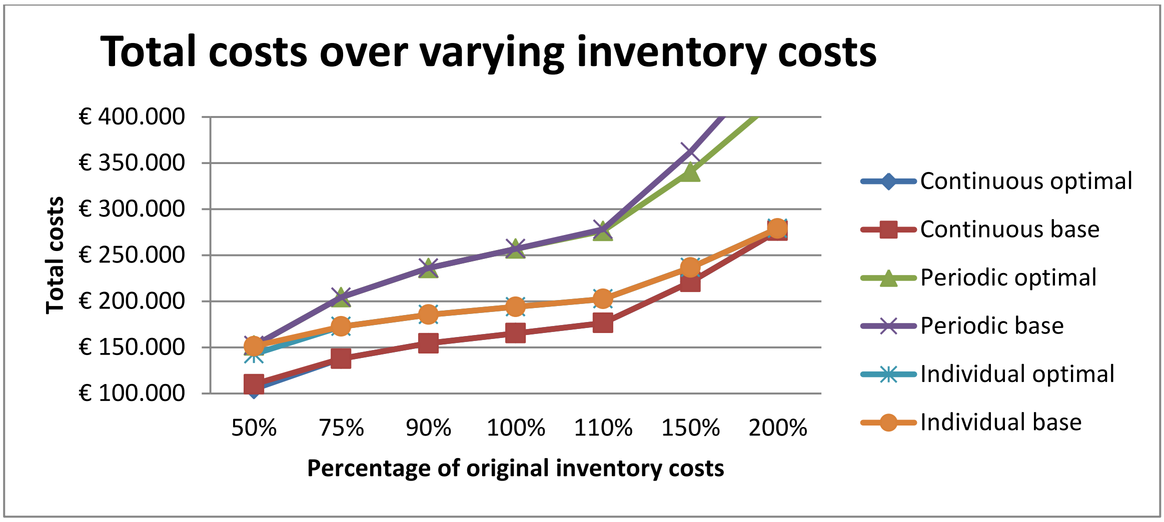

Figure 4.10: Total costs over varying inventory

For continuous review strategy, the only value for which the base value policy is suboptimal is at 50% of the initial inventory costs, where the operator could save around 4% by increasing the EOQ from 2 units to 3 units.

For periodic review strategy, the base value policy remains the optimal policy for inventory costs up to 110% of the base value. For higher inventory costs, the OUL should be decreased with which the operators could save 6% of the total costs for 150% of the inventory costs and 10% for 200% of the inventory costs.

For individual ordering strategy, the base value policy is only suboptimal when inventory costs are halved. Operators could save 6% of the total costs for these inventory costs by increasing the ROP from 1 to 2 units.

5. Conclusion

From the research in this thesis, the answer to the first part of the first main question becomes quite obvious:

What are the optimal strategy and policy for the operators to organize their spare part management?

If the initial values are correct, the continuous review strategy is the most cost-efficient strategy. For changes between 50% and 200% in the base value during the stable period, the continuous review strategy remains the optimal strategy. For the early phase, continuous review also remains the most cost-efficient strategy at any point of the lifetime of the wind turbine.

The second part of the first main question is less obvious. It is shown that for the stable period the base value policy with a ROP of one unit and an EOQ of two units is usually a good choice, unless the actual values differ a lot from the initial values in this case, the model should be reapplied with the new data to get a better idea of which policy is suitable for this new set of input values.

For the early phase of the lifetime, the optimal policy for a continuous review strategy requires changing the policy after a set time to account for demand decreasing over time. The optimal policy at the start of the lifetime uses a ROP of 8 units and an EOQ of 7 units per order. One year into the lifetime, the values for an optimal policy have decreased to a ROP of 5 units and an EOQ of 4 units, this decrease continues until the stable period is reached. Until this point the optimal policy during the early phase requires constant changing where both the ROP and EOQ decrease until the reach the values of respectively 2 and 1 unit in the stable period.

We do not have initial values of how these new policies compare to the current situation, since it is not known what strategy or policy the OEM's currently apply in the spare part management of the operators, therefore the potential gain from applying this model and the optimal policies it suggests cannot be determined.

The second question was:

What is the influence of each input values on the choice of strategy and policy and how do they influence the total costs?

All of the input values are analysed in chapter 4.2 of this thesis. From this subchapter the conclusion can be drawn that the biggest factor in choice of policy is the demand. Once the demand increases, this quickly leads to the base value policy no longer being the optimal policy for the new situation. The second biggest influence on the choice of policy are the lead times, especially large lead times lead to huge increases in the cost of the policy. To cover large lead times, higher safety stocks need to be set to cover the bigger variations in demand during the lead time. The values of operational revenue, inventory costs per part and ordering costs do not cause large variations in the choice of policy unless the values are doubled or halved.

One other interesting result of this thesis is how the individual ordering strategy relates to the other two strategies. In each of the 5 input values analysed in chapter 4.2 besides ordering costs, the difference between the individual ordering strategy and continuous review strategy decreases for smaller input values and increases for higher input values, while the difference between the individual ordering strategy and periodic review strategy increases for smaller input values, but decreases for larger input values.

The main point for IWES to consider is that if they want to advice the operators on how to organize their spare part management, they need to consider all the input variables to give a reliable advice. While none of the input values are very sensitive in regards to the choice of policy and order levels, the influence on costs increases quickly when the actual values differ more than 50% from the values put in the model. Secondly, they need to consider that this is not a one-time advice. Especially at the start of the early phase, when the failure rate decreases quickly, the policy needs to be flexible and adapted multiple times to prevent unnecessary high costs.

5. Limitations

There were several limitations involved in the research done in this thesis:

The first limitation is due to the assumption of Weibull and Poisson distributed demand in the early phase and the stable period. This has several influences on the final result. Poisson distribution means that the demand is spread constantly over time, independent from each other, which is probably not true in real-life situations. For instance, multiple failures can be caused by a single storm, which will cause backorders if not there is insufficient demand on-hand.

Secondly, the sensitivity analysis was only executed for the stable period of the lifetime of the wind turbines due to lack of time for this thesis. Some of the input values might have different influences in the early phase of the lifetime compared to the stable period.

Thirdly, the lead time is assumed to be constant at every point in time, independent of the order size or time between orders. In reality, the lead time will likely be higher for high order sizes, because the OEM is likely to not have sufficient stock to immediately send the order towards the warehouse. Therefore, the OEM needs time to produce additional units which will increase the lead time. Furthermore, for periodic review, the OEM will know when to expect orders and can therefore prepare sufficient stock to fulfil the order as soon as it is placed, thereby reducing lead time. Varying lead times will lead to changes in the ESC and therefore the shortage costs.

Fourthly, the input values used in the model do not include every single part of the costs this strategy and policy causes. For example, there might be additional costs involved for checking the inventory every time a blade is used to replace a failure, which is necessary in continuous review.

Finally, the initial plan of the thesis was to model the different spare part management strategies and policies, so the total costs for each of these policies could be compared to the total costs of the current spare part management policy. However, IWES nor the operators could grant direct access to the total costs of the current spare part management strategy, therefore the final results could not be compared to the current situation and we cannot say by much the different strategies and policies reduce or increase the costs of the spare part management.

6. Recommendations

For further research into this topic I recommend five topics:

The first recommendation is to research in how far the lead times vary in reality and what the influence of varying lead times is on the spare part management. I had no information on the variance in lead time and kept my model simpler by assuming the lead time to be constant.

The second recommendation is to research how well the distributions used in this thesis fit to the data IWES receives from the operators. While Poisson and Weibull distributions quite commonly used in reliability analysis, the parameters might not fit the data well, which can influence the results found in this thesis.

The third recommendation is to research the constant costs of replacing a failed part of the wind turbine, including all the costs in the total costs will give a better overview for the operators and allow them to build a more precise budget for replacing failed parts.

The fourth recommendation is to research the implementation of the different strategies. While in this model it seems like continuous review is always the best strategy, it might be unfeasible for some of the operators to implement this strategy. Furthermore, setting up a strategy with changing policies throughout the lifetime of the wind turbine might not be feasible due to factors not considered in this thesis.

The fifth recommendation is to include other parts of the wind turbine which might cause downtime due to failures such as the gears, electrical system and sensors. If the orders for multiple parts can be combined, this might save ordering costs and therefore reduce the costs of the total spare part management. Furthermore, there might be opportunities to save ordering costs for corrective maintenance when an order for preventive maintenance is placed, even though the inventory has not reached to ROP in a continuous review strategy or the previous review period has not yet ended in a periodic review strategy. Combining orders for both ways of maintenance can save ordering costs.

The sixth and last recommendation is to execute a sensitivity analysis for the early phase of the lifetime. This was part of my original set-up for this thesis, but had to be removed due to time constraints, but could still be of significant value to IWES and other players in similar industries.

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Appendix A: Excel model

	A	B	C
1	Input data		
2		Quantity	Unit
3	Lead time from order to warehouse	20	Days
4	Failure rate	0,01	Failures/blade/year
5	# Wind turbines	250	Wind turbines
6	Capacity rating of turbine	5000	kW
7	Avg.Capacity factor	0,4	[]
8	Feed-in-Tariff / electricity price	0,15	€ct/kWh
9	Inventory cost percentage per year	0,12	Percentage/year
10	Blade cost	=ROUND(1600*B6*0,64*0,25/3;-4)	Euro/blade
11	One time ordering costs	10000	Euro/order
12			
13	Results		
14	Operational revenue	=B6*B7*24*B8	Euro/day/turbine
15	Demand	=B4*3*B5	Blades/year
16	Variance per year	=B15	(Blades/year)^2
17	St.dev lead time	=SQRT(B3/365)*SQRT(B16)	Blades/Lead time
18	Demand during lead time	=B15/365*B3	Blades/Lead time
19	St. dev Cycle + lead time	=SQRT(1/B22+B3/365)*SQRT(B16)	Blades/response time
20	Inventory cost	=B9*B10	Euro/part/year
21	Downtime costs	=B3*B14/2	Euro/backorder
22	Review intervals	=B15/F4	Review intervals/year
23			
24			
25			
26	Optimal policy	=IF(MATCH(B28;Q4:Q33;0)<8;E2;E13)	
27	Optimal CSL	=VLOOKUP(B28;Q4:S31;3;FALSE)	
28	Minimum total costs	=MIN(Q4:Q11;Q15:Q22;Q26:Q33)	

Figure A.1 Input data stable period

	E	F	G	H	I	J
1						
2	Continuous revie					
3	CSL >	EOQ	Safety Stock	ROP	ESC	Cycles per year
4	0,5	=MAX(ROUND(SQRT(2*$B$11*$B$15/$B$20*(($B$21+$B$20)/$B$2	=(NORM.S.INV(E4)*SQRT($B$3/365)*$B$16)	=CEILING(G4+$B$15*$B$3/365;1)	=-(H4-$B$18)*(1-NORM.DIST((H4-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H4-$B$18)/$B$17;	=$B$15/F4
5	0,55	=MAX(ROUND(SQRT(2*$B$11*$B$15/$B$20*(($B$21+$B$20)/$B$2	=(NORM.S.INV(E5)*SQRT($B$3/365)*$B$16)	=CEILING(G5+$B$15*$B$3/365;1)	=-(H5-$B$18)*(1-NORM.DIST((H5-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H5-$B$18)/$B$17;	=$B$15/F5
6	0,6	=MAX(ROUND(SQRT(2*$B$11*$B$15/$B$20*(($B$21+$B$20)/$B$2	=(NORM.S.INV(E6)*SQRT($B$3/365)*$B$16)	=CEILING(G6+$B$15*$B$3/365;1)	=-(H6-$B$18)*(1-NORM.DIST((H6-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H6-$B$18)/$B$17;	=$B$15/F6
7	0,7	=MAX(ROUND(SQRT(2*$B$11*$B$15/$B$20*(($B$21+$B$20)/$B$2	=(NORM.S.INV(E7)*SQRT($B$3/365)*$B$16)	=CEILING(G7+$B$15*$B$3/365;1)	=-(H7-$B$18)*(1-NORM.DIST((H7-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H7-$B$18)/$B$17;	=$B$15/F7
8	0,8	=MAX(ROUND(SQRT(2*$B$11*$B$15/$B$20*(($B$21+$B$20)/$B$2	=(NORM.S.INV(E8)*SQRT($B$3/365)*$B$16)	=CEILING(G8+$B$15*$B$3/365;1)	=-(H8-$B$18)*(1-NORM.DIST((H8-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H8-$B$18)/$B$17;	=$B$15/F8
9	0,9	=MAX(ROUND(SQRT(2*$B$11*$B$15/$B$20*(($B$21+$B$20)/$B$2	=(NORM.S.INV(E9)*SQRT($B$3/365)*$B$16)	=CEILING(G9+$B$15*$B$3/365;1)	=-(H9-$B$18)*(1-NORM.DIST((H9-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H9-$B$18)/$B$17;	=$B$15/F9
10	0,95	=MAX(ROUND(SQRT(2*$B$11*$B$15/$B$20*(($B$21+$B$20)/$B$2	=(NORM.S.INV(E10)*SQRT($B$3/365)*$B$16)	=CEILING(G10+$B$15*$B$3/365;1)	=-(H10-$B$18)*(1-NORM.DIST((H10-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H10-$B$18)/B	=$B$15/F10
11	0,99	=MAX(ROUND(SQRT(2*$B$11*$B$15/$B$20*(($B$21+$B$20)/$B$2	=(NORM.S.INV(E11)*SQRT($B$3/365)*$B$16)	=CEILING(G11+$B$15*$B$3/365;1)	=-(H11-$B$18)*(1-NORM.DIST((H11-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H11-$B$18)/$B$1	=$B$15/F11
12						
13	Periodic review					
14	CSL >	Average lot size	Safety stock	OUL	ESC	Orders
15	0,5	=$B$15/$B$22	=(NORM.S.INV(E15)*SQRT(1/$B$22+$B$3/365)*SQRT($	=CEILING($B$15*(1/$B$22+$B$3/365)+G	=-(H15-F15)*(1-NORM.DIST((H15-F15)/$B$19;0;1;1))+$B$19*NORM.DIST((H15-F15)/$B$19;0;1;0)	=$B$22-$B$22*EXP(-F15)-
16	0,55	=$B$15/$B$22	=(NORM.S.INV(E16)*SQRT(1/$B$22+$B$3/365)*SQRT($	=CEILING($B$15*(1/$B$22+$B$3/365)+G	=-(H16-F16)*(1-NORM.DIST((H16-F16)/$B$19;0;1;1))+$B$19*NORM.DIST((H16-F16)/$B$19;0;1;0)	=$B$22-$B$22*EXP(-F16)-
17	0,6	=$B$15/$B$22	=(NORM.S.INV(E17)*SQRT(1/$B$22+$B$3/365)*SQRT($	=CEILING($B$15*(1/$B$22+$B$3/365)+G	=-(H17-F17)*(1-NORM.DIST((H17-F17)/$B$19;0;1;1))+$B$19*NORM.DIST((H17-F17)/$B$19;0;1;0)	=$B$22-$B$22*EXP(-F17)-
18	0,7	=$B$15/$B$22	=(NORM.S.INV(E18)*SQRT(1/$B$22+$B$3/365)*SQRT($	=CEILING($B$15*(1/$B$22+$B$3/365)+G	=-(H18-F18)*(1-NORM.DIST((H18-F18)/$B$19;0;1;1))+$B$19*NORM.DIST((H18-F18)/$B$19;0;1;0)	=$B$22-$B$22*EXP(-F18)-
19	0,8	=$B$15/$B$22	=(NORM.S.INV(E19)*SQRT(1/$B$22+$B$3/365)*SQRT($	=CEILING($B$15*(1/$B$22+$B$3/365)+G	=-(H19-F19)*(1-NORM.DIST((H19-F19)/$B$19;0;1;1))+$B$19*NORM.DIST((H19-F19)/$B$19;0;1;0)	=$B$22-$B$22*EXP(-F19)-
20	0,9	=$B$15/$B$22	=(NORM.S.INV(E20)*SQRT(1/$B$22+$B$3/365)*SQRT(	=CEILING($B$15*(1/$B$22+$B$3/365)+G	=-(H20-F20)*(1-NORM.DIST((H20-F20)/$B$19;0;1;1))+$B$19*NORM.DIST((H20-F20)/$B$19;0;1;	=$B$22-$B$22*EXP(-F20)
21	0,95	=$B$15/$B$22	=(NORM.S.INV(E21)*SQRT(1/$B$22+$B$3/365)*SQRT($	=CEILING($B$15*(1/$B$22+$B$3/365)+G	=-(H21-F21)*(1-NORM.DIST((H21-F21)/$B$19;0;1;1))+$B$19*NORM.DIST((H21-F21)/$B$19;0;1;0)	=$B$22-$B$22*EXP(-F21)-
22	0,99	=$B$15/$B$22	=(NORM.S.INV(E22)*SQRT(1/$B$22+$B$3/365)*SQRT(	=CEILING($B$15*(1/$B$22+$B$3/365)+G	=-(H22-F22)*(1-NORM.DIST((H22-F22)/$B$19;0;1;1))+$B$19*NORM.DIST((H22-F22)/$B$19;0;1;	=$B$22-$B$22*EXP(-F22)
23						
24	Individual orderin					
25	CSL >	Q	Safety Stock	ROP	ESC	Cycles per year
26	0,5	1	=(NORM.S.INV(E26)*SQRT($B$3/365)*$B$16)	=CEILING(G26+$B$15*$B$3/365;1)	=-(H26-$B$18)*(1-NORM.DIST((H26-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H26-$B$18)/$B	=$B$15/F26
27	0,55	1	=(NORM.S.INV(E27)*SQRT($B$3/365)*$B$16)	=CEILING(G27+$B$15*$B$3/365;1)	=-(H27-$B$18)*(1-NORM.DIST((H27-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H27-$B$18)/$B	=$B$15/F27
28	0,6	1	=(NORM.S.INV(E28)*SQRT($B$3/365)*$B$16)	=CEILING(G28+$B$15*$B$3/365;1)	=-(H28-$B$18)*(1-NORM.DIST((H28-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H28-$B$18)/$B	=$B$15/F28
29	0,7	1	=(NORM.S.INV(E29)*SQRT($B$3/365)*$B$16)	=CEILING(G29+$B$15*$B$3/365;1)	=-(H29-$B$18)*(1-NORM.DIST((H29-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H29-$B$18)/$B	=$B$15/F29
30	0,8	1	=(NORM.S.INV(E30)*SQRT($B$3/365)*$B$16)	=CEILING(G30+$B$15*$B$3/365;1)	=-(H30-$B$18)*(1-NORM.DIST((H30-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H30-$B$18)/$B	=$B$15/F30
31	0,9	1	=(NORM.S.INV(E31)*SQRT($B$3/365)*$B$16)	=CEILING(G31+$B$15*$B$3/365;1)	=-(H31-$B$18)*(1-NORM.DIST((H31-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H31-$B$18)/B	=$B$15/F31
32	0,95	1	=(NORM.S.INV(E32)*SQRT($B$3/365)*$B$16)	=CEILING(G32+$B$15*$B$3/365;1)	=-(H32-$B$18)*(1-NORM.DIST((H32-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H32-$B$18)/$B	=$B$15/F32
33	0,99	1	=(NORM.S.INV(E33)*SQRT($B$3/365)*$B$16)	=CEILING(G33+$B$15*$B$3/365;1)	=-(H33-$B$18)*(1-NORM.DIST((H33-$B$18)/$B$17;0;1;1))+$B$17*NORM.DIST((H33-$B$18)/$B	=$B$15/F33

Figure A.2 Calculations stable period part 1

K	L	M	N	O	P	Q	R
Backorders	Shortage costs	Pipeline Inventory	Average inventory	Inventory costs	Ordering costs	Total costs	Costs per unit
=I4*J4	=$B$21*K4	=J4*F4*$B$3/365	=(F4+1)/2+H4-M4+I4	=N4*$B$20	=J4*$B$11	=SUM(L4+O4+P4)	=Q4/$B$15
=I5*J5	=$B$21*K5	=J5*F5*$B$3/365	=(F5+1)/2+H5-M5+I5	=N5*$B$20	=J5*$B$11	=SUM(L5+O5+P5)	=Q5/$B$15
=I6*J6	=$B$21*K6	=J6*F6*$B$3/365	=(F6+1)/2+H6-M6+I6	=N6*$B$20	=J6*$B$11	=SUM(L6+O6+P6)	=Q6/$B$15
=I7*J7	=$B$21*K7	=J7*F7*$B$3/365	=(F7+1)/2+H7-M7+I7	=N7*$B$20	=J7*$B$11	=SUM(L7+O7+P7)	=Q7/$B$15
=I8*J8	=$B$21*K8	=J8*F8*$B$3/365	=(F8+1)/2+H8-M8+I8	=N8*$B$20	=J8*$B$11	=SUM(L8+O8+P8)	=Q8/$B$15
=I9*J9	=$B$21*K9	=J9*F9*$B$3/365	=(F9+1)/2+H9-M9+I9	=N9*$B$20	=J9*$B$11	=SUM(L9+O9+P9)	=Q9/$B$15
=I10*J10	=$B$21*K10	=J10*F10*$B$3/365	=(F10+1)/2+H10-M10+I10	=N10*$B$20	=J10*$B$11	=SUM(L10+O10+P10)	=Q10/$B$15
=I11*J11	=$B$21*K11	=J11*F11*$B$3/365	=(F11+1)/2+H11-M11+I11	=N11*$B$20	=J11*$B$11	=SUM(L11+O11+P11)	=Q11/$B$15
Backorders	Shortage costs	Pipeline Inventory	Average inventory	Inventory costs	Ordering costs	Total costs	
=I15*$B$22	=K15*$B$14*2*$B$3	=((J15-K15)*F15+K15)*$B$3/365	=H15-F15/2+I15	=N15*$B$20	=$B$11*J15	=L15+O15+P15	=Q15/$B$15
=I16*$B$22	=K16*$B$14*2*$B$3	=((J16-K16)*F16+K16)*$B$3/365	=H16-F16/2+I16	=N16*$B$20	=$B$11*J16	=L16+O16+P16	=Q16/$B$15
=I17*$B$22	=K17*$B$14*2*$B$3	=((J17-K17)*F17+K17)*$B$3/365	=H17-F17/2+I17	=N17*$B$20	=$B$11*J17	=L17+O17+P17	=Q17/$B$15
=I18*$B$22	=K18*$B$14*2*$B$3	=((J18-K18)*F18+K18)*$B$3/365	=H18-F18/2+I18	=N18*$B$20	=$B$11*J18	=L18+O18+P18	=Q18/$B$15
=I19*$B$22	=K19*$B$14*2*$B$3	=((J19-K19)*F19+K19)*$B$3/365	=H19-F19/2+I19	=N19*$B$20	=$B$11*J19	=L19+O19+P19	=Q19/$B$15
=I20*$B$22	=K20*$B$14*2*$B$3	=((J20-K20)*F20+K20)*$B$3/365	=H20-F20/2+I20	=N20*$B$20	=$B$11*J20	=L20+O20+P20	=Q20/$B$15
=I21*$B$22	=K21*$B$14*2*$B$3	=((J21-K21)*F21+K21)*$B$3/365	=H21-F21/2+I21	=N21*$B$20	=$B$11*J21	=L21+O21+P21	=Q21/$B$15
=I22*$B$22	=K22*$B$14*2*$B$3	=((J22-K22)*F22+K22)*$B$3/365	=H22-F22/2+I22	=N22*$B$20	=$B$11*J22	=L22+O22+P22	=Q22/$B$15
Backorders	Shortage costs	Pipeline Inventory	Average inventory	Inventory costs	Ordering costs	Total costs	
=I26*J26	=$B$21*K26	=J26*F26*$B$3/365	=(F26+1)/2+H26-M26+I26	=N26*$B$20	=J26*$B$11	=SUM(L26+O26+P26)	=Q26/$B$15
=I27*J27	=$B$21*K27	=J27*F27*$B$3/365	=(F27+1)/2+H27-M27+I27	=N27*$B$20	=J27*$B$11	=SUM(L27+O27+P27)	=Q27/$B$15
=I28*J28	=$B$21*K28	=J28*F28*$B$3/365	=(F28+1)/2+H28-M28+I28	=N28*$B$20	=J28*$B$11	=SUM(L28+O28+P28)	=Q28/$B$15
=I29*J29	=$B$21*K29	=J29*F29*$B$3/365	=(F29+1)/2+H29-M29+I29	=N29*$B$20	=J29*$B$11	=SUM(L29+O29+P29)	=Q29/$B$15
=I30*J30	=$B$21*K30	=J30*F30*$B$3/365	=(F30+1)/2+H30-M30+I30	=N30*$B$20	=J30*$B$11	=SUM(L30+O30+P30)	=Q30/$B$15
=I31*J31	=$B$21*K31	=J31*F31*$B$3/365	=(F31+1)/2+H31-M31+I31	=N31*$B$20	=J31*$B$11	=SUM(L31+O31+P31)	=Q31/$B$15
=I32*J32	=$B$21*K32	=J32*F32*$B$3/365	=(F32+1)/2+H32-M32+I32	=N32*$B$20	=J32*$B$11	=SUM(L32+O32+P32)	=Q32/$B$15
=I33*J33	=$B$21*K33	=J33*F33*$B$3/365	=(F33+1)/2+H33-M33+I33	=N33*$B$20	=J33*$B$11	=SUM(L33+O33+P33)	=Q33/$B$15

Figure A.3 Calculations stable period part 2

	A	B
1	Input data	
2		Quantity
3	Lead time from order to warehouse	20
4	Constant Failure rate	0,01
5	# Wind turbines	250
6	Capacity rating of turbine	5000
7	Avg.Capacity factor	0,4
8	Feed-in-Tariff / electricity price	0,15
9	Inventory cost percentage per year	0,12
10	Blade cost	=ROUND(1600*B6*0,64*0,25/3;-4)
11	One time ordering costs	10000
12	Point in lifetime	2
13		
14	Results	
15	Operational revenue	=+B6*B7*24*B8
16	Mean failure rate coming year	=B17/B5/3
17	Demand	=(WEIBULL.DIST(B12+1;B31;B33;1)-WEIBULL.DIST(B12;B31;B33;1)+B4)*B5*3
18	Variance per year	=B4*B5*3+0,968
19	St.dev lead time	=SQRT(B3/365)*SQRT(B18)
20	Demand during lead time	=B17/365*B3
21	St. dev Cycle + lead time	=SQRT(1/B24+B3/365)*SQRT(B18)
22	Inventory cost	=B9*B10
23	Downtime costs	=B3*B15
24	Review intervals	=B17/F4
25		
26	Optimal policy	=IF(MATCH(B28;Q3:Q32;0)<8;E2;E13)
27	Optimal CSL	=VLOOKUP(B28;Q3:R32;2;FALSE)
28	Minimum total costs	=MIN(Q3:Q10;Q15:Q21;Q26:Q32)
29		
30	Weibull distribution early failures	
31	Beta	0,5
32	Eta all blades	=B33*(B5*3)^-1/B31
33	Eta one blade	83,2301264817277

Figure A.4: Input values early phase

Appendix B: Results

Continuous review							
CSL >	EOQ	Safety Stock	ROP	Inventory costs	Ordering costs	Total costs	Costs per unit
0,5	2	0,0	1	€ 111.003	€ 37.500	€ 165.294	€ 22.039
0,55	2	0,2	1	€ 111.003	€ 37.500	€ 165.294	€ 22.039
0,6	2	0,4	1	€ 111.003	€ 37.500	€ 165.294	€ 22.039
0,7	2	0,9	1	€ 111.003	€ 37.500	€ 165.294	€ 22.039
0,8	2	1,5	2	€ 159.465	€ 37.500	€ 197.336	€ 26.311
0,9	2	2,2	3	€ 210.995	€ 37.500	€ 248.496	€ 33.133
0,95	2	2,9	3	€ 210.995	€ 37.500	€ 248.496	€ 33.133
0,99	2	4,1	5	€ 314.195	€ 37.500	€ 351.695	€ 46.893
Periodic review							
CSL >	Average lot size	Safety stock	OUL	Inventory costs	Ordering costs	Total costs	
0,5	2	0,0	3	€ 115.772	€ 41.562	€ 420.477	€ 56.064
0,55	2	0,2	3	€ 115.772	€ 41.562	€ 420.477	€ 56.064
0,6	2	0,4	3	€ 115.772	€ 41.562	€ 420.477	€ 56.064
0,7	2	0,8	4	€ 158.541	€ 35.144	€ 271.992	€ 36.266
0,8	2	1,3	4	€ 158.541	€ 35.144	€ 271.992	€ 36.266
0,9	2	2,0	5	€ 207.215	€ 33.017	€ 257.279	€ 34.304
0,95	2	2,6	5	€ 207.215	€ 33.017	€ 257.279	€ 34.304
0,99	2	3,6	7	€ 309.614	€ 32.435	€ 342.337	€ 45.645
Individual ordering							
CSL >	Q	Safety Stock	ROP	Inventory costs	Ordering costs	Total costs	
0,5	1	0,0	1	€ 85.203	€ 75.000	€ 193.785	€ 25.838
0,55	1	0,2	1	€ 85.203	€ 75.000	€ 193.785	€ 25.838
0,6	1	0,4	1	€ 85.203	€ 75.000	€ 193.785	€ 25.838
0,7	1	0,9	2	€ 133.665	€ 75.000	€ 209.406	€ 27.921
0,8	1	1,5	2	€ 133.665	€ 75.000	€ 209.406	€ 27.921
0,9	1	2,2	3	€ 185.195	€ 75.000	€ 260.197	€ 34.693
0,95	1	2,9	4	€ 236.795	€ 75.000	€ 311.795	€ 41.573
0,99	1	4,1	5	€ 288.395	€ 75.000	€ 363.395	€ 48.453

Figure B.1: Results for each policy for the base values in the stable period

Continuous review							
CSL >	EOQ	ROP	Shortage costs	Inventory costs	Ordering costs	Total costs	Cost per unit
0,5	4	2	€ 358.962	€ 166.261	€ 73.729	€ 598.953	€ 20.309
0,55	4	3	€ 94.695	€ 205.017	€ 73.729	€ 373.441	€ 12.663
0,6	4	4	€ 15.901	€ 252.788	€ 73.729	€ 342.418	€ 11.611
0,7	4	6	€ 97	€ 355.220	€ 73.729	€ 429.046	€ 14.548
0,8	4	8	€ 0	€ 458.415	€ 73.729	€ 532.145	€ 18.044
0,9	4	11	€ 0	€ 613.215	€ 73.729	€ 686.944	€ 23.293
0,95	4	13	€ 0	€ 716.415	€ 73.729	€ 790.144	€ 26.792
0,99	4	18	€ 0	€ 974.415	€ 73.729	€ 1.048.144	€ 35.540
Periodic review							
CSL >	Average lot size	OUL	Shortage costs	Inventory costs	Ordering costs	Total costs	Cost per unit
0,5	4,0	6	€ 279.714	€ 219.994	€ 91.804	€ 591.512	€ 20.057
0,55	4,0	6	€ 279.714	€ 206.400	€ 91.804	€ 577.918	€ 19.596
0,6	4,0	7	€ 123.103	€ 258.000	€ 80.928	€ 462.031	€ 15.666
0,7	4,0	7	€ 123.103	€ 258.000	€ 80.928	€ 462.031	€ 15.666
0,8	4,0	8	€ 47.387	€ 309.600	€ 75.670	€ 432.657	€ 14.670
0,9	4,0	9	€ 15.836	€ 361.200	€ 73.479	€ 450.515	€ 15.276
0,95	4,0	10	€ 4.567	€ 412.800	€ 72.696	€ 490.063	€ 16.617
0,99	4,0	12	€ 239	€ 516.000	€ 72.396	€ 588.635	€ 19.959
Individual ordering							
CSL >	Q	ROP	Shortage costs	Inventory costs	Ordering costs	Total costs	Cost per unit
0,5	1	2	€ 1.435.849	€ 4.041	€ 294.918	€ 1.734.807	€ 58.823
0,55	1	3	€ 378.778	€ 55.641	€ 294.918	€ 729.336	€ 24.730
0,6	1	4	€ 63.604	€ 107.241	€ 294.918	€ 465.762	€ 15.793
0,7	1	6	€ 387	€ 210.441	€ 294.918	€ 505.745	€ 17.149
0,8	1	8	€ 0	€ 313.641	€ 294.918	€ 608.559	€ 20.635
0,9	1	11	€ 0	€ 468.441	€ 294.918	€ 763.358	€ 25.884
0,95	1	13	€ 0	€ 571.641	€ 294.918	€ 866.558	€ 29.383
0,99	1	18	€ 0	€ 829.641	€ 294.918	€ 1.124.558	€ 38.131

Figure B.2: Results for the base values in the early phase at t=2 years