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Spare Part Logistics and Optimization for Wind Turbines

- Methods for Cost-Effective Supply and Storage

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Abstract

Spare Part Logistics and Optimization for Wind Turbines - Methods for Cost-Effective Supply and Storage

Mattias Lindqvist & Jonas Lundin

The wind power industry is maturing and the amount of electricity produced by wind turbines in the world is rapidly increasing every year. Service and maintenance of wind turbines has proven to be difficult and expensive, especially offshore. A well coordinated support organisation and optimized maintenance strategies are required to effectively reduce the costs associated with WT support, where cost-efficient supply and storage of spare parts are important. The aim of this thesis is to model spare part logistics for wind turbines to analyse different strategies and compare the profitability. Optimal stock levels and reorder sizes have been calculated with the software tool OPUS10. Wind turbine and spare part data have been provided by Vattenfall Vindkraft AB and field studies were made to the wind farms Lillgrund and Horns Rev to gather information.

Our analyses show that different spare part strategies only affect a minor part of the total support costs generated for a wind farm. Still there are many improvements possible and money to be saved if using an optimal spare part strategy instead of one based on personal experiences and intuition. For a large wind power system, including a number of wind farms with the same wind turbine types, we also show convincing results that pooling of spare parts are a much more cost-efficient spare part strategy compared to local storage and handling only. Using a central depot for spare part reordering and storage of critical spare parts, such as gearboxes, generators and blades, are more profitable.

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Populärvetenskaplig beskrivning

Vindkraftsindustrin växer över hela världen och branschen är inne i en mognadsprocess. Under en snabb expansionsfas har många aktiviteter blivit eftersatta, då målet ofta varit att bygga fler och större vindkraftverk. Underhåll av vindkraftverk och reservdelshantering är exempel på sådana aktiviteter. Underhållsarbetet utförs vanligtvis utav tillverkaren de första åren. När elproducenten senare tar över service och underhåll kan det uppstå problem eftersom kunskapen inte finns inom organisationen. Ett sådant problem kan vara hur lagerhållning och inköp av reservdelar till en vindkraftspark ska utformas. En viktig del i ett väl fungerande underhållsarbete är att de reservdelar som behövs för reparationer finns tillgängliga när de behövs. Om en reservdel inte finns tillgänglig så kan det leda till långa uppehåll i produktionen vilket leder till stora inkomstförluster för elproducenten. Lösningen på detta problem är inte att fylla lagren till bredden då detta blir alldeles för dyrt. Därför är det viktigt att ha en så kostnadseffektiv reservdelsstrategi som möjligt.

Syftet med examensarbetet är att studera reservdelslogistiken för några av Vattenfall AB:s vindkraftsparker och hitta de mest vinstgivande reservdelsstrategierna, detta med hjälp av optimeringsverktyget OPUS10. En stor del av arbetet handlar om att ta fram data för att kunna bygga en modell av vindkraftssystemen och underhållsorganisationerna, exempelvis specifika reservdelsegenskaper såsom priser, efterfrågan (som uppstår av olika delars felintensiteter), reparationstider och leveranstider. För att ta fram data genomfördes intervjuer på fyra av Vattenfalls servicestationer. Utifrån aktivitetsrapporter och lagerlistor kunde reservdelar identifieras och viktig data uppskattas, såsom genomsnittlig efterfrågan. Det insamlade datamaterialet sammanställdes och fyra olika modeller byggdes upp i OPUS10; två med enskilda vindkraftsparker samt två där flera parker kopplats samman i en större underhållsorganisation.

Våra resultat visar på att de kostnader som går att påverka med en optimal lagerstrategi är små i förhållande till de fasta underhållskostnaderna för en vindkraftpark. Men genom att optimera reservdelshanteringen och hitta den mest vinstgivande strategin så kan en elproducent ändå spara mycket över en vindkraftsparks livstid. De mest kritiska och kostnadsdrivande reservdelarna för vindkraftverk, som påverkar kostnadseffektiviteten mest, är växellådan och generatorn.

Vidare såg vi att det fanns mycket att tjäna på att koordinera reservdelshanteringen vindkraftsparker emellan, då de innehåller samma typ av turbin. Det var klart mer kostnadseffektivt att ha en underhållsorganisation med ett centrallager varifrån alla icke-reparerbara reservdelar återbeställs och där dyra delar kan lagras i en så kallad reservdelspool, istället för endast lokala lager. En viktig aspekt är också att dyra delar repareras om det finns möjlighet för detta. Idag slängs de flesta komponenter som går sönder men en hel del skulle vinnas på att identifiera fler reparerbara delar samt hitta lokala reparatörer.

Acknowledgements

This thesis has been done at Vattenfall Power Consultant, sponsored by Vattenfall Vindkraft AB. We would like to start by thanking Martin Reinholdsson and Magnus Jansson for creating the possibility of writing such a fulfilling and interesting master thesis. Furthermore we would like to give our greatest gratitude to all within the Vattenfall organisation that has shown interest in our work, given us time for interviews and especially for helping us with fast responses on the several questions that arose afterwards.

Finally we would like to thank Tor Isdal, our supervisor at Vattenfall Power Consultant, Tomas Eriksson at Systecon AB, and Bengt Carlsson at Uppsala University, who have helped us throughout the whole process. Your help and commitment to our work have been paramount for our possibilities to write and finish this thesis, thank you.

Uppsala, Mars 2010

Mattias Lindqvist and Jonas Lundin

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Abbreviations

Demand	D
Demand rate	DT
Discardable item	DU
Failure rate	λ
Hours	h
Interest rate	i
Item price	P
Kilowatt hours	kWh
Life support cost	LSC
Mean downtime	MDT
Mean logistic delay time	MLDT
Mean time between failures	MTBF
Mean time to repair	MTTR
Mean waiting time (for spare parts)	MWT
Megawatt hours	MWh
Meters	m
Net present value factor	NVP
Number of backorders	NBO
Number of items	n
Operational availability	A
Probability of k demands	p(k)
Reorder cost	CR
Reorder point	r
Reorder quantity	Q
Repair turn-around-time	TAT
Repairable item	LRU
Risk of shortage	ROS
Stock size (level)	s
Storage cost	CS
Time horizon (scenario length)	T
Wind turbine	WT

1 Introduction

1.1 Background

The development of wind power has been steady for the last ten years in Europe and North America. Several large wind turbine (WT) projects are under way, both onshore and offshore. During the last three years there has been a rapid, worldwide increase in installed wind power capacity of about 25 percent per year. This is to a large extent due to developing programs in China and India. In 2008 the total installed capacity where 92 GW which generated 194 TWh. [1]

In a time period of a couple of years wind power has gone from a minor energy source to a large-scale industry. However, the adoption of wind power has not come with ease. A lot of teething troubles have been causing problems to the relatively new technology. For example there have been a lot of failures of gearboxes and electric equipment, especially on larger WTs. Operating wind power systems have proven to be difficult, especially offshore wind farms, with WTs shutting down due to various types of failures. Hence, proper and well-planned service and maintenance is very important to ensure an efficient energy production.

A well coordinated support organisation and optimized maintenance strategies is required to effectively reduce the costs associated with WT support. This also includes handling and storage of spare parts. These types of problems are apparent in most industries and are not in any way unique for WTs. If these processes are optimized there is a paramount of money to be saved over time. These circumstances have built the ground for the scientific field of Operational Research (OR) and it has also been driving it forward.

OR was originally used by military forces trying to optimize their operations during World War II, but is now used by companies worldwide to find optimal solutions for different logistic problems, such as transportation routes, resource allocation and stocking polices. To be able to optimize any system there needs to be a clear goal of what parameters to be optimized. For a transportation system it can be to minimise the total transportation distance or to maximize the profitability of transportations. Regardless of the goal or objective of the optimization it has to be made under certain conditions. After the problem is formulated and it is decided under which conditions the optimization has to be made, a mathematical problem can be formulated. Difficult optimization problems are built up of several advanced and integrated mathematical algorithms. To solve these algorithms in a limited time computers are needed. Therefore much of the industrial applications in OR are customised computer programs developed to solve distinct problems such as route optimizations or process optimization. In many ways the computer was the tool that made OR applicable in real life and not only in theory.

1.2 Problem formulation

Inadequate spare part stocks can lead to WT unavailability and loss of revenue if subsystems or items fail and cannot be replaced. When a spare part is needed but missing in stock, it has to be ordered from a supplier. Depending on the lead time of the spare part this causes operational downtime. On the other hand, handling and storage of spare parts can be a cost driver for any company operating and maintaining wind farms. Hence it is important to find a strategy which can balance these problems; *optimizing* spare part investments and logistics. With the use of theories developed from OR and the subfield Inventory Theory, mathematical models of WT support organisations and spare part logistics can be formulated and thereafter analysed. Advanced software can be used for this type of modelling and to find optimal spare part stocks and analyse different strategies.

1.3 Objective

The aim of the thesis is to model WT spare part logistics and analyse support organisation efficiency. Moreover we will compare the cost-efficiency and profitability for different scenarios to find optimal spare part strategies. Modelling and optimisation will be done with the software tool OPUS10. Wind turbine, spare part and support organisation data are provided by Vattenfall Vindkraft AB (hereinafter "Vattenfall"). These are our question formulations:

- How can a WT support organisation be modelled and which are the most critical data?
- Which are the most important spare parts to model, affecting the support organisation cost-efficiency the most?
- Which are the most profitable spare part strategies for the wind power systems modelled?

1.4 Definitions

Definitions of some of the most important terms used in this thesis:

Spare part is a replaceable unit for a technical system, e.g. a wind power system. Spare parts are used to repair a WT when an *item* has failed.

Spare part stock, or only *stock*, is the spare parts stored for later use. The facility were this is done will in this thesis be referred to as a *depot* (a warehouse). A depot can be located right next to a WT site or some distance away.

Spare part strategy is in this thesis the fixed results of a number of decision variables regarding initial spare part investment, reorder points (resulting in a fixed reorder size for each non-repairable item) and allocation between depots.

Support organisation is the whole organisation that maintains a technical system, such as a wind power system, and provide it with personnel and equipment to be operable (available for use). A support organisation has a certain *structure*, where depots, service stations and work shops, in some way are connected to each other.

1.5 Delimitations

When optimizing spare part logistics for a wind power system it is critical to know exactly which part of the WT that causes it to fail, hence which spare parts are needed. Although most modern WTs have the same subsystems, every model have an almost unique set of mechanical, hydraulic and electrical components (hereinafter referred to as *items*), chosen by the manufacturer. Because of this we have narrowed our study by only analysing two different WT models, Siemens SWT-2.3 and Vestas V80-2.0. Vattenfall are projecting for another Vestas WT model, V90-2.0, which consists of almost the same set of items as the V80. We have in our OPUS10 models assumed that all V80 spare parts included can also be used for the V90s.

A WT consists of thousands of different items, which many are relatively cheap, such as screws and bolts. Optimal strategies and policies for stocks are often more manageable and profitable when including only eligible spare parts, possessing certain requirements on various parameters, such as price, demand, criticality, etc. We have included about 30-40 items of each WT model, that costs more than EUR 100 and are critical for the WT to function. That is, if there is a failure on one of these items the WT shuts down and becomes unavailable until it is repaired (and the faulty item is replaced by a spare part). A description of the WTs and items selected for analysis is found in Chapter 6. Additional items could easily be found and included in the analysis, but to get all the sufficient data more resources and time would be needed than assigned for this thesis.

Normally a wind power system would include foundation, electric cables and other equipment related to the operation of a number of WTs. In this thesis we have limited our study to spare parts associated with the nacelle, including the main switch and transformer which sometimes are located at the ground. When replacing large WT items offshore a *crane ship* is needed. These ships are very expensive and have extremely long lead time, between one to six months (sometimes up to a year). Hence they can be rather difficult to model and we have not included them in our support organisation models.

Another delimitation when doing our analysis with OPUS10 will be to only categorize spare parts as repairable or non-repairable (see chapter 5). Many items in technical systems though, are sometimes repaired and sometimes discarded, depending on failure modes and other circumstances. Hence, our models will be a bit simplified. One important assumption regarding repairable items is also made. If a faulty item have been repaired and added to the spare part stock we assume it is operational when later needed. That is, reparation at the workshop is always successful (an item sent back to stock is as good as new) and a repaired item cannot fail in the warehouse.

1.6 Outline of the thesis

In the next chapter our research method will be discussed. This will include how data was collected, interviews were performed and the computer analyses were done. Chapter 3 is a background on wind power technology, how a wind turbine is composed and which subsystems there are. Furthermore, we will explain how these subsystems can fail. This is for understanding which spare parts are critical for the WT to function, hence important to include in our case study and OPUS10 analyses. This chapter is not vital for understanding the rest of the thesis, which is more concentrated on modelling and optimization of the WT support organisations. Chapter 4 contains the theoretical background of the thesis. Optimization theory will be discussed and moreover how this can be applied on spare part logistics. Important concepts will be highlighted and defined. In Chapter 5 the reader will be introduced to the software OPUS10. We will go through what type of input data is needed and how it is structured. This chapter is important to understand classifications and parameters in the empirical results from our field studies (Chapter 6) and later on our OPUS10 analysis and results in Chapter 7. The field study chapter is divided into two parts. The first contains information about the Siemens SWT-2.3 support organisation and then the Vestas V80 and V90 support organisation is described. Here we report our empirical findings, including information and data from interviews and reports. Scenarios analysed are then presented in the following chapter, together with the results. These results are then discussed in chapter 8, with the theoretical findings from Chapter 3, 4 and 5 in mind. Finally our conclusions are presented in the last chapter.

The work on this thesis has been almost equally divided between the both authors. This included interviews and field studies, data collection and processing, modelling and analysis with OPUS10. The literature studies and writing of Chapter 3 and Chapter 4 were to some extent dived, where Mattias had the main responsibility for Chapter 3 while Jonas was responsible for Chapter 4.

2 Methodology

2.1 Research approach

To fulfil the objective of this thesis there are *three main components* needed; WT data, support organisation data and an analysis and optimization tool. For WT and support organisation data collection, Vattenfall granted us to study their WT fleet. The collected data is then analysed with the software tool OPUS10, provided by Systecon AB. Our research approach can be summarized with four method elements, shown in *Figure 2.1*. To have a better understanding on how to approach our problem formulation and objective, literature studies were performed. Later, field trips were made to four Vattenfall WT service stations (close to some major WT sites), where several interviews with service technicians and managers were conducted. This was primarily done to collect data, but it also contributed with a real image of the systems being studied in this thesis. Finally the data collected was analysed with the support organisation optimizing software OPUS10. In sections below there is a thorough description of the method elements used to complete the three main components presented above.

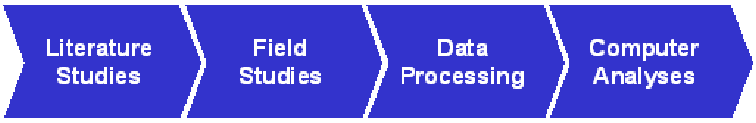

Figure 2.1: The working process

2.2 Literature studies

Our literature studies were concentrated on two different scientific areas, WT technology and optimization theory with focus on optimizing spare part stocks. Since WTs are the central study object of the thesis we used two educational books on WTs, [5] [7], which contributed with basic knowledge of the advanced systems that unitise a WT. To get some insight on WT failures and maintenance we looked into a few scientific articles discussing operations and maintenance (O&M) of wind farms.

To get a general overview on how a problem like ours could be solved two books, [4] [6], guided us. While [4] gave a broad background to OR and basic *inventory theory*, [6] described the theory behind modelling and optimizing support organisations, including spare part storage and logistics. Further research on this subject, including some of the OPUS10 algorithms, were given in [1]. Moreover, to get a greater understanding of the OPUS10 techniques and important model parameters, a lot of internal Systecon documents and software user manuals were used. After the literature studies we had a very clear idea of what information and data we needed to collect. Therefore it was also essential that the literature studies were executed prior to the field studies.

2.3 Field studies

Four Vattenfall WT service stations were visited during our field studies, performed during four weeks in the fall of 2009. Our aim was to collect information and data for our analysis, via interviews with WT maintenance staff. The interviews were performed in an open to semi-structured manner. Except from the information compiled via interviews we were also interested in any information gathered on WT failures and spare parts used. The service stations visited are located in Bergkvara, Näsudden, Klagshamn and Esbjerg.

The first trip was made to Vattenfall service station in Bergkvara where we carried out a group interview with the service coordinator and three persons from the maintenance staff. The service personnel in Bergkvara execute the maintenance work on two offshore sights, Yttre-Stengrund and Utgrunden. Their experience and knowledge contributed greatly by complementing the theoretical WT knowledge we achieved from literature studies.

The second trip was made to Näsudden, Gotland, where the personnel responsible for Vattenfall's onshore WTs are situated. Näsudden wind farm are foremost used for research, containing prototype WT types. Therefore the WTs running on Näsudden are all serviced by the manufacturers own service staff. The Vattenfall staff interviewed primarily provided us with information on Vestas V80 2.0 MW and V90 2.0 MW, as well as some future plans for the Swedish onshore WT development.

The third visit was made at the service station in Klagshamn south of Malmö. Klagshamn service station is supporting the 48 WTs running at Lillgrund WT farm. In Klagshamn we interviewed Vattenfall's technical support manager for Lillgrund and the former Lillgrund project manager. They were not directly involved in the daily maintenance, performed by Siemens personnel, but provided us with insight on how the WT support where organised. They also had access to service reports from the WT farm at Lillgrund. The service reports included information on replaced items and the time required for each replacement.

The fourth and last stop for our field studies was Vattenfall service station in Esbjerg, Denmark. The station in Esbjerg is supporting the 80 WTs running on Horns Rev but it is also the main control room for all of Vattenfall's WTs. In Esbjerg we interviewed the site coordinator and the stock manager for Horns Rev. They had information on the general service procedures for the WTs on Horns Rev and could also provide us with a spare part list. This list contained prices and quantities of the spare parts used for Horns Rev. In our second meeting in Esbjerg we interviewed the service manager for Denmark onshore who informed us how the onshore service and maintenance is organised.

2.4 Data processing

To be able to use the data collected from the field studies in our analysis the data has to be pre-processed and verified. First and foremost we selected which items to include in the study. Items were selected from the storage list for Horns Rev and from the service protocols from Lillgrund. As previously mentioned we were only interested in items with a price exceeding EUR 100. We also tried to include items from different subsystems and with a wide spread of failure rates and prices. Some important WT items were not included in the documentation we received. These were large and expensive items and for those we had to rely on information collected during interviews and later mail contacts. This method was also used when studying the different support organisations used at the separate WT farms. A more exact description of the data included in the study and how it was collected, is presented in Chapter 6. After we had decided which information to include in our study, the data collected needed to be transformed to the format used in OPUS10. Since most of the data collected is uncertain we decided to categorise/group it. All categories are presented in Appendix A. For item prices four intervals were used. If an item was within one of the first three intervals it got a price based on the geometric mean of the interval, rounded up to the nearest hundred. If items had a price exceeding EUR 3000 an estimated price was necessary to be given either from exact price information or by a qualified estimate. For failure rates four intervals were set up and an item got the geometric mean of its group interval as failure rate. There was no need for a group that needed an estimate since no item failure rate calculated exceeded 30 failures per million operating hours. For item replacement, item repair and item lead times there were no exact data to analyse. Therefore items were given the value of the group it was closest to.

2.5 Computer based analysis

When modelling a complex system it is almost mandatory to use computers and advanced software. It is then important to get a greater understanding of the software and how to use it, including some basic theory behind the algorithms and how different parameters interact. We have been using the optimization software OPUS10, created for solving logistics problems, especially concerning maintenance support organisations. When doing calculations on the data collected in OPUS10 the main result presented is Life Support Costs (LSC) for different average operational availability levels (A), for the model of a the real WT farm or farms. There are several points representing a certain A and LSC. We chose which point to further analyse by finding the point that maximised the WT profits, hence had the best balance between production and costs. We tested this for several different scenarios which we modelled in OPUS10. There were also several sensitivity analysis performed to see how our model handled changes in input data and how robust the optimal spare part strategies were. More information on how a mathematical model is built and how they are analysed in OPUS10 is presented in Chapter 5. To secure that our models were built correctly we have been supported by Systecon. In total we had one week of consulting with a technical sales manager from Systecon. During the meetings we have discussed our OPUS10 models and results.

3 Wind Power

3.1 Wind Energy

Sailing boats and windmills are examples of prominent wind driven devices, which have contributed greatly to the development of our modern society. Today there are more modern sources of energy such as oil, coal and nuclear power, which have supported our development the last 150 years. Although, during the last 50 years it have been discovered that these new power sources have an environmental downside. This has created a political climate where the power producing industry is pushed to look at alternatives to capture and transform the energy from our natural and almost infinite power sources, water, wind and solar power.

The actual energy in the wind is kinetic. Air has a density of 1.225 kg/m^3 (sea level and 15 degrees Celsius), and when this mass is set in motion it gets kinetic energy. The energy in wind depends on the cube of the wind speed, meaning that a doubling of the wind speed results in an eight-fold increase in energy. Today most modern WTs have a rated power around 2 MW, even though there are a few really large WTs reaching up to 5 MW. A WT produces rated power during wind speeds from approximately 14 m/s to 25 m/s. When the wind speed passes 25 m/s the WT is shut down because of safety reasons. This is called the *cut-out (wind) speed*. The *cut-in speed*, when a WT starts to produce electricity, is around 3-4 m/s. The power output is then lower than the rated output, but increases with higher wind speeds until the rated power of production is reached (see figure 3.1). Wind speeds can fluctuate during short time periods, often to increase or decrease by 3-4 m/s in a few seconds of time. [7]

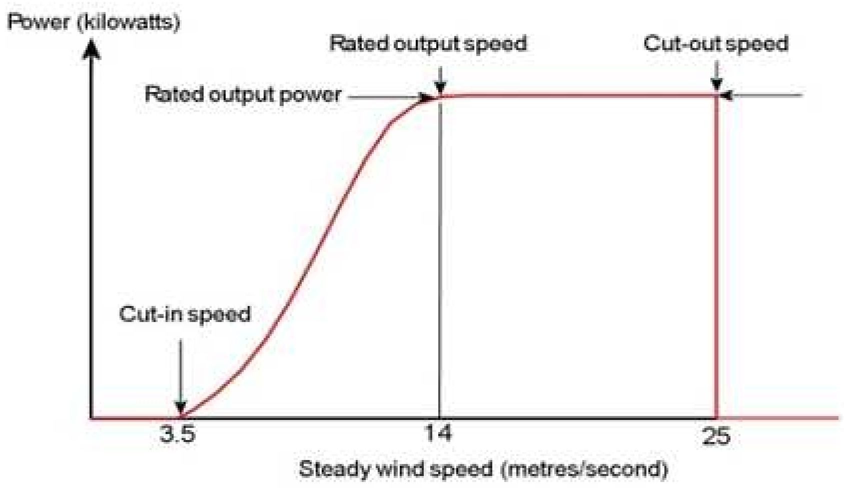

Figure 3.1: Power production of a wind turbine during different wind speeds

To calculate the predicted power production over a year a *power output curve* for the specific WT and a *wind speed table* for the WT location is needed. When multiplying the two curves the result is the expected power production for a WT over a year. This is the most formal way to calculate the predicted power output from a WT. Using this method the WT is assumed to be operational ready at all times. Since this seldom is the case, many WT corporate promoters and operators use the term *capacity factor*. The capacity factor is a measure of how much of the time a WT is producing at its rated power. If the capacity factor is estimated, an approximation of the yearly production can be done. [7] Example 3.1 shows how this factor is calculated.

Example 3.1
Consider a 2.0 MW WT that produces 4.000.000 kWh during a year. To calculate the capacity factor for the WT, the following expression is used:

$$\frac{\text{WT yearly production (kWh)}}{\text{WT rated power (kW)} * \text{hours in a year}} = \text{capacity factor}$$

Hence the capacity factor for the WT in this example is:

$$\frac{4.000.000}{2.000 * 8760} = 0.23$$

3.1.1 Wind turbine technology

The windmill concept, with a vertical axis, is the most common for transforming wind energy into electric energy. A modern wind turbine consists of two or three blades that are set in motion by the passing wind. This rotating motion is either transferred directly to a generator, or via a gearbox which increases the rotational speed into the generator. All the WTs in our study uses a gearbox, which is the most common type of WT. Another fundamental difference in WT design is in what way the blades handle fluctuating winds. There are three types of regulation; stall, pitch or a combination of stall and pitch. With stall regulation the blades are formed with an aerodynamic structure causing turbulence near the blade at high wind speeds. The turbulence decreases the lifting power of the blades and thereby limiting the rotational speed to acceptable levels. Compared to stall regulation, WTs using pitch regulation have rotational blades. During high speeds the blades are rotated from the wind, letting more wind through which decreases the lifting power, and thereby the rotational speed. The WT models included in our study all have pitch regulation. For further reading on other WT types we recommend, [5], [7]. The following parts are to a large extent based on these two books.

3.1.2 Wind farms

Block 2 at Forsmark nuclear power plant has a rated power of 990 MW corresponding to about 500 large WTs, producing at rated power. [22] One WT looks very small in this context but if put together in large groups, i.e. *wind farms*, they are merged into a power plant with a capacity of 100 MW or more. Therefore the construction of wind farms has lead wind power into a new era. When moving from these single scattered WTs to larger production facilities the maintenance work is simplified. Instead of long travelling distances between a few WTs, service technicians are able to work at one location, performing daily maintenance work on a close range. This also leads to a greater knowledge of a certain WT type and quicker repairs, since a technician is in the area.

A wind farm is a number of WTs connected with electric cables, either located onshore or offshore. To minimize effect losses due to turbulence the WTs are placed 400-700 meters apart, depending on the rotor size. Offshore wind farms are placed on shallow waters since they need solid ground to be attached to. At wind farms the WTs are connected to a main transformer station which is stepping up the voltage before sending it out to the electric grid. [7]

3.2 Wind turbine parts

When looking at spare part logistics for a wind power system it is important to know which subsystems and parts a WT is composed of, and how often they fail. In this section will describe most of the main components of a WT and their function. Throughout the rest of the thesis we will refer to all of these components as *items*. A WT is to a large extent built with standardised items used in many other industrial applications. Therefore there is an open market, especially for the majority of the mechanical items. Thus, many of these items have been used and tested over a long time period. The picture below presents the most important components in a WT. Most of the parts or systems addressed in the picture will be mentioned in the following part.

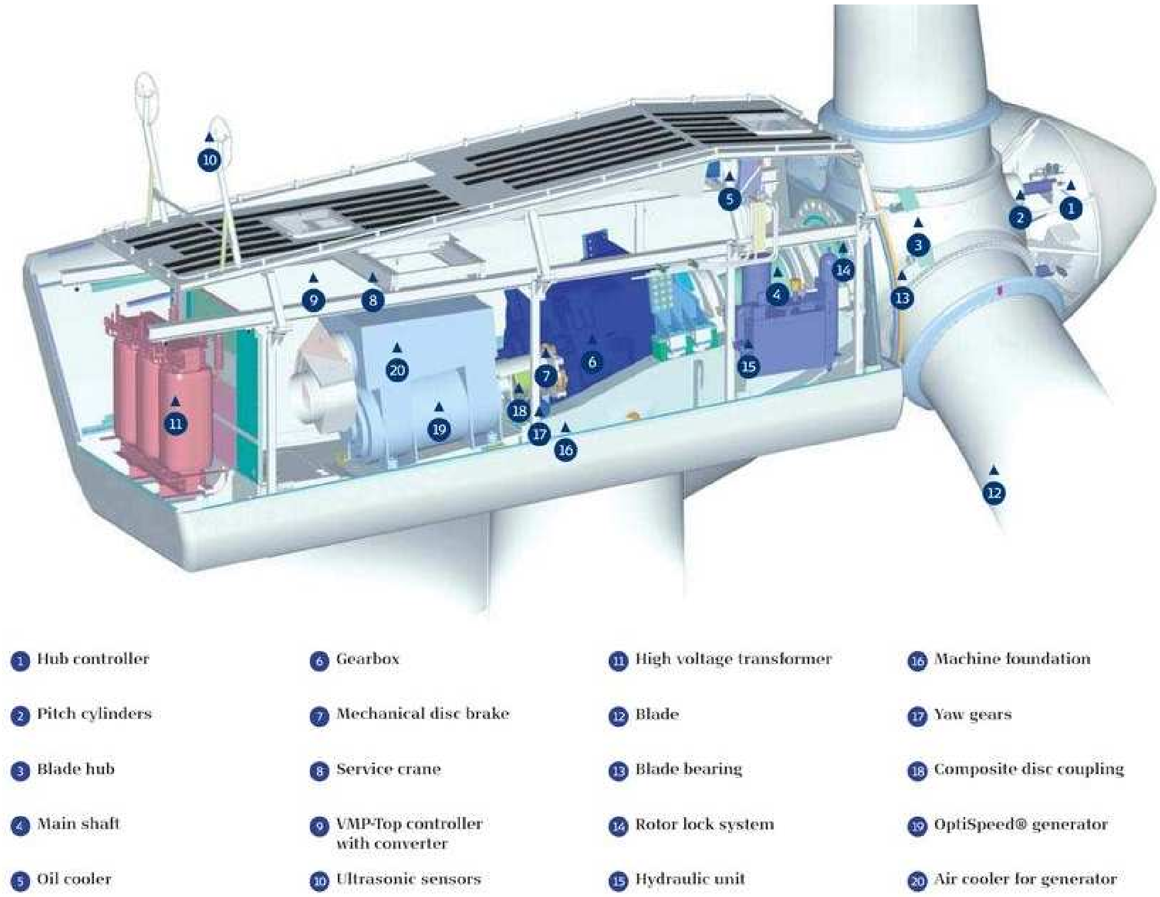

Figure 3.2: The nacelle of a Vestas wind turbine [18]

3.2.1 Blades

Blades are shaped so that the wind creates a vertical force on the blade. Since the blades are fixed to a hub, a rotating motion is created. Blades are manufactured from two important perspectives, structure and aerodynamics. Aerodynamics for a blade is decided from the regulating principle, stall or pitch. The aerodynamic setting of a blade has little influence on its endurance performance, so focus will be on blade construction. A blade is built up of an outer skin which is supported by an inner core or spar. The outer skin of modern blades is made of several layers of fibreglass. These layers must be designed to resist harsh weather conditions for several years. Cracks can occur on the surface of the blade. The cracks are not harmful for a WT to function but they still need to be repaired so they do not get worse. The core of a blade is the part that receives the main load. The most important design factor for the core is that it has to be light and flexible and still be able to handle heavy loads. The core is often built up off fibreglass, where plywood is used as a complementary structural part. [5] When there are sights of cracks or other weakening in the supporting structure the blade needs to be replaced immediately. It is difficult to evaluate and repair a blade with a broken structure, hence a completely new blade is mounted and the old one is discarded. [26]

3.2.2 Pitch system

For WTs with pitch regulation, the hub provides bearings for the blades allowing them to rotate relative to the hub. No other movement of the blades is allowed. Within the hub the pitch system is performing the rotation of blades. Blades can be pitched individually or by a common, central pitch mechanism. Today most WTs have an individual pitch system, which is either controlled electrically or hydraulically. An electrical pitch uses a *slip ring* to transfer electric power from the nacelle and out to the hub. If it is a hydraulic pitch system a *rotating union* is used to transfer pressure. Some years ago there were a lot of problems with leakages in rotating unions, but during the last couple of years there have been paramount improvements in their reliability. [5] Within the hub, the pitch system uses electric motors and gears or hydraulic cylinders to change the position of the blades. It is important that the blades can be pitched even if the slip ring, rotating union or some cables or hoses fail. Therefore batteries or hydraulic accumulators are installed in the hub as a backup system. Faults can also occur with the mechanical parts, hydraulic cylinders or electric motors and accumulators. Batteries deplete within some time and have to be changed. [25]

3.2.3 Drive train

In nearly every WT there is a *main shaft* connecting the rotor to the drive train. The shaft is connected to a *gearbox*. From the gearbox a shaft is connected to the *generator*. Shafts are used to transmit torque within the WT. The gearbox is also built up of one ore more shafts ending with a final shaft entering the generator. Shafts are not only under stress from torque load, there is also a bending load on the shaft. These loads are time-varying so fatigue of the shafts is an important factor. Problems can also occur with shafts if they are often operating under critical speed. At some turning speeds shafts have resonant frequencies, creating vibrations in the shaft. *Bearings* are closely connected with the shafts since they are carrying the weight of the rotating shafts. Bearings have an important function for the drive train, as well as for rotating the blades (pitch system) or the whole nacelle (yaw system). [5] There are seldom any problems with shafts, but bearings are known create some problems. Since they are heavy, replacement of bearings and the drive train are complicated procedures, where a large crane is needed to lift them up and down the nacelle. [25] Bearings are usually not repaired after they have been exchanged. [31]

3.2.4 Gearbox

Gearboxes in WTs are used to increase the speed from the main shaft to the generator shaft, which turns at 1500 rpm (with mains frequency 50 Hz) for conventional generators. The gearbox is one of the heaviest and most expensive components in a WT. In this context, it is unfortunate that under-dimensioned gearboxes have had a large part in WT failures. The reason for under-dimensioned gearboxes can be that the gearbox manufacturers do not fully understand the operating conditions. Gearboxes are built up of shafts, gears, bearings and seals, mounted in a metal cover. The weight of the gearbox increases dramatically in relation to the rated power of the WT. The main load a gearbox has to handle is torque of the rotor. This load is, as earlier mentioned, sometimes constant and sometimes fluctuating. It also suffers loads from the generator when starting up. These loads mainly affect bearings, gear teeth and seals, causing them to fail. To minimize fatigue of gearbox parts, a functional and efficient lubrication system is highly relevant. [5] A problem with the gearbox is that even if it is only a small cog breaking. The whole system needs to be cleaned out and thoroughly tested. Faults with gearboxes are primarily discovered within the first two years of operation. If a gearbox last the first two years it is likely that it will last for many years. [27]

3.2.5 Generator

Generators convert mechanical power from the rotating blades to electrical power. The most common type of generator today is the induction generator, also referred to as an asynchronous generator. This type of generator is used in modern type of WTs with variable speed. Their popularity is based on the following characteristics. Asynchronous generators have a simple and rigid construction, they are relatively inexpensive, and they are easily connected and disconnected to the grid. A generator needs to be protected from water, dust and other foreign particles. There are two common types of protection, totally enclosed fan cooled (TEFC) or an open drip protection. The open drip cover has often been considered to be enough because of the belief that the nacelle itself would give sufficient protection to the generator. Many WT producers though have discovered that a TEFC system can be worth the extra cost. There are only a few components in a generator that are exposed to electrical or physical stress. The windings in the rotor and stator are sensitive to high currents leading to increased temperatures that are wearing the windings and can lead to a failure. These windings can be replaced but the generator has to be taken out from the nacelle in turn to make this type of repair possible. The *generator bearings* and different *fans* are subject to an almost constant mechanical wear and have to be exchanged from time to time. Asynchronous generators in modern WT are, as previously mentioned, not using permanent magnets in the rotor or stator. Instead they are using the windings to create the magnetic fields which make it dependent upon an external electrical force. The windings must be provided a current with specific frequency and voltage to be able to function correctly. [5] Therefore asynchronous generators need an advanced electrical support and control system which is presented in the following chapter.

3.2.6 Electrical system

The electrical generation from a WT requires an advanced electrical system. The actual generation performed by the generator is only a small part of the whole electrical system. Below there is a description of the three most important parts of the electrical system, *power converters*, *power transformers* and *ancillary electrical equipment*.

Power Converters

Power converters are devices changing electrical power from one form to another. Switching currents properties e.g. between different frequencies and voltages, and changing DC to AC, AC to DC. Converters consist of a vast amount of electrical switches which are opened or closed by an advanced electrical control system. Key components of an converter are diodes, thyristors, gate turn off thyristors (GTOs) and power transistors. Power transistors and GTOs have similar functions. There are many types of power transistors but the trend is towards an increasing use of insulated gate bipolar transistors (IGBT). All these electrical parts can fail due to short-circuit and the magnitude of the damage is different from time to time. [5] For example an IGBT can be replaced, were the failed item is analysed, then repaired if possible or otherwise discarded. [25] The use of these different types of power converters lead to distortion in the electric frequencies called harmonics which is an integer multiple of the grid frequency. The harmonics can hurt other electrical equipment such as transformers and motors, often due to heated windings. To protect the electrical equipment, *electrical filters* are installed. Using different configurations of impedance, parallel impedance and *capacitors* these filters even out the harmonic distortion. [5]

Power Transformers

A transformer is a crucial component in nearly all AC power systems. A transformer changes the voltage of a current. The largest, main transformer in a WT (often referred to as *the transformer*) is used to change the voltage of the generated power into the voltage used in the internal distributing network. This type of transformer typically operates in the range from 5-50 kVA. Power cables from individual WTs in a farm are connected to a central substation where the produced current is transformed yet again. The last transformation takes place before the current reaches the high voltage network operating at 60000 kVA. In a WT there are also smaller transformers (often referred to as *power supply*) which are used to step down the incoming current into a voltage suitable for all the electric driven components in a WT e.g. electric motors, lights, control systems and monitoring. Transformers have two or more metal coils that are insulated from an outer layer of cooper windings. The transformer is a robust construction with few moving parts. Still there are several causes that can cause a failure in a transformer. The most common faults are due to deterioration of the insulation caused by heat, acidity and oxidation. Another common cause of failure is design and manufacturing errors such as loose or inadequate core insulation, poor brazing, unsupported leads, loose blocking or inferior short circuit. [5] Because of their failure modes transformers can seldom be repaired. [28]

Ancillary electrical equipment
Several other components are included in the construction of a WT, both high and low voltage items. Power cables and slip rings can easily be worn out and in need of reparation. The slip rings are rotating electrical contacts used between for example the generator and the converter. There are also many *circuit breakers* and *fuses* which are opened if the current gets to strong. Fuses must be replaced when used and circuit breakers can be reset after being switched on or off. Finally there is a *main switch* which is closed during production, and is only used when maintenance work is done on the electrical system. [5]

3.2.7 Mechanical brakes

Mechanical brakes in a WT have two functions. Usually they are used as parking breaks, when power production is down, but occasionally they are used for emergency breaking. A mechanical brake can be located somewhere along the drive train. There are two main types of brakes, disc brakes and clutch brakes. Disc brakes need a hydraulic pressure, supplied from a hydraulic pump or accumulator, to operate. Springs are often used to activate clutch brakes, using hydraulic or pneumatic pressure to release it. Most of the wear on breaks comes from emergency breaks, creating a large amount of heat tearing on the break system. [5]

3.2.8 Yaw system

The yaw system is used to set the nacelle and rotor in an effective position against the wind. A rotating nacelle requires a *yaw bearing* supporting the load of the nacelle. The circumference of the bearing has gear teeth which are connected to a *yaw gear*. The yaw gears are driven by electrical motors (called *yaw motors*), shifting the speed of the pinion conducted to the bearing's tethering. Rapid wear or breaking of the yaw system is a problem due to continuous small movements of the nacelle. To limit the wear on the yaw system, *yaw breaks* are installed to hold the nacelle in place when the WT is not running. [5] The electrical motor can often be repaired after they have been exchanged. Broken pinions and yaw gears are harder to repair and are therefore discarded. [28]

3.2.9 Sensors

The necessary information about the processes in a WT is collected from sensors placed at critical functions. Sensors in a modern WT measure:

- Speeds (wind speed, rotor speed, generator speeds)
- Temperatures (oil temperatures, bearing temperatures, electronics temperature)
- Position (yaw position, blade pitch)
- Electrical characteristics (current, voltage, converter operation)
- Fluid flow parameters (hydraulic or pneumatic pressure, oil levels and flow) [5]

All these parameters need to be measured correctly for the WT to function properly. Typical items that fail are *encoders* which measure the position of the yaw system and pitch system. Sensors measuring wind speed and wind direction, for example *ultrasonic sensors*, placed at the top of the nacelle, are also known to fail from time to time. [25]

3.2.10 Control system

WTs need an efficient control system in order to produce electricity of the right form and standard, and to ensure a safe and reliable power production. Control systems have two main functions: to monitor item functionality and to operate the WT. The *control unit* is the core of the control system. These units consist of hardware logic (e.g. thyristors and transistors) or software deciding on what actions to take depending on the incoming information from the sensors. A controller can be a mix of computers, electrical circuits and mechanical systems. [5] The control unit often fails when one of the many circuit boards fails. Most circuit boards are discarded, but if the damage is not that severe expensive circuit cards are repaired. [25]

3.2.11 Hydraulics

The control signals, from the control unit out to WT actuators often need to be amplified (since the power in the signal is not sufficient to operate the actuator). Common amplifiers in WTs are *hydraulic pumps*. The pumps can be either electrical driven or mechanical driven, creating pressure which is distributed to various functions within WT (such as the pitch system or the yaw system). [5] Leakage from the pump or pistons is a common problem. There can also be a problem with the pump itself, or the motor driving it. Most faults occurring with the hydraulic system can be repaired within the nacelle or after the failing part have been exchanged. [31]

3.3 Wind turbine service and maintenance

When looking on maintenance of a technical system it is often divided into preventive and corrective maintenance. For a WT preventive maintenance is performed one ore two times per year, depending on what requirements the WT manufacturer has set up. During the preventive maintenance parts are controlled and some are exchanged. Oils and lubricating greases are also changed or refilled for several different parts. Normally it takes a couple of days for two persons to perform this type of maintenance work. This type of service actions is often planed to be performed during the summers when wind speeds are low. [27] The corrective maintenance is performed when a fault signal is sent from the WT to the control room. The signal contains one or several codes explaining which type of fault that has occurred. [25]

When buying a WT there is often a service contract included. A normal service contract last from 2-5 years, but some manufacturers prefer longer. Normally a service contract state that the manufacturer has full responsibility for the WT function over the contractual time. This means that the WT manufacturer handle all maintenance and provides personnel and spare part storage for the wind farm. [27]

3.4 Previous studies on wind turbine reliability

Most previous studies on WT reliability and availability are Meta studies which have used large data sets. The data sets used, have been a mix of different WT types and compilations making the results indistinct. Even more troubling is the fact that the results are presented for several WT functions and are not specified on an item specific level.

Two major studies on WT failures and downtime have been performed in Sweden and Germany, [3], [10]. Except from looking on total operational availability for WTs the studies have examined WT subsystem reliability. The different subsystems are similar to those discussed earlier in this chapter. One of the most important conclusions from the studies is that statistical data covering WT failure rates are hard to find. This is due to several reasons, for example is no statistical data collected, wind turbine manufacturers hold on to data, and different WT types are not comparable. WT manufacturers are strict on revealing data about their WTs, especially WT failures. Furthermore, the studies showed evident data revealing trends towards increasing failure rates as the WT grows larger in size and rated power. With increasing failure rates modern WTs still have an operational availability around 98 percent. Figure 3.3 shows some results from [10] regarding the distribution of failures between different WT subsystems. The category "other" includes drive train and structural parts.

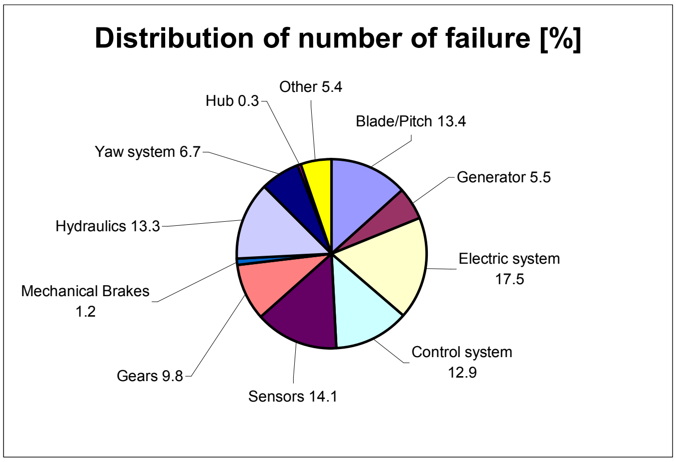

Figure 3.3: Distribution of number of failures

As we can see here there are similarities in the results but also some disparities. Notably when studying the results is that all functions are not parts in all WT types included in the studies for example, Hydraulics, Gears, and Pitch. Therefore the results for these functions may have higher percentages when looking only on WT types where the functions are included. It is evident that there are four, failure intensive systems; electric system, control system, sensors and hydraulics. There are not as many faults on generators, gears and yaw system but this could depend on the lesser amount of components included in these three subsystems. The least amount of failures occurred for the hub, mechanical brakes and other. In *Figure 3.4* below the failure rate results from [3], for different WT subsystems, are presented.

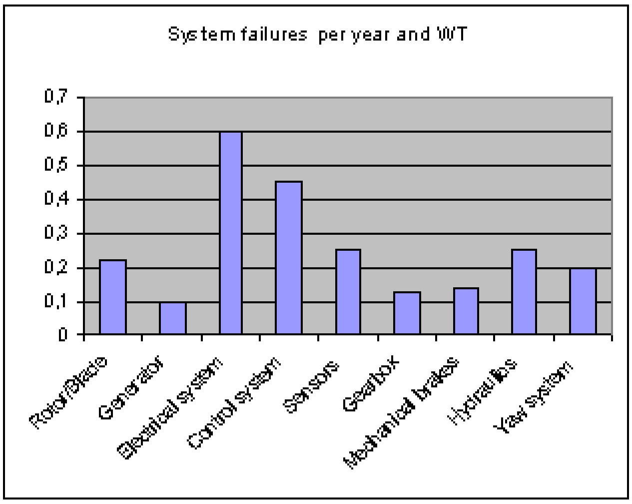

Figure 3.4: Average number of failures per year per wind turbine subsystem

An important measure when looking at the operational availability is the downtime caused by different WT failures. In *Figure 3.5* below is the subsystem downtime results from [3] presented.

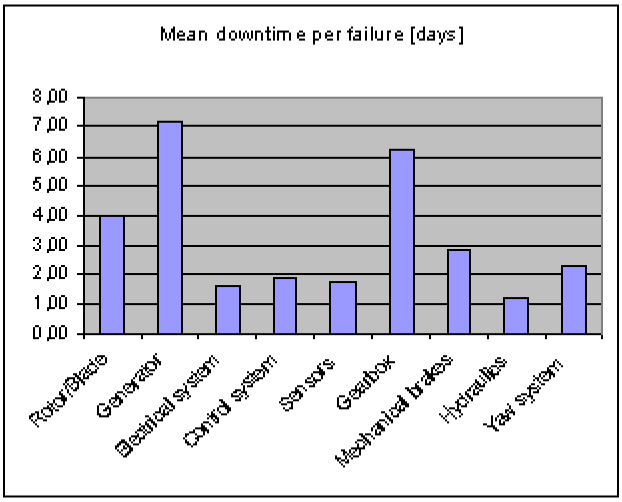

Figure 3.5: Wind turbine subsystems downtime

When studying failure rates it is interesting to see how they are distributed over time. The data material in the German study includes modern and large WTs and is therefore most representative to the current situation. According to this study a WT suffers on average 2.4 failures per year. The average downtime these faults cause are 149 hours per year and WT and the average repair time for a failure is 62.6 hours. [3]

Results from the German study also highlighted the problems with increased WT sizes. For WTs with a rated power below 500 kW there were on average approximately 1 failure per year. When looking at WTs with a rated power between 0.5 and 1 MW, the failure rates are almost doubled and for WTs with a rated power over 1 MW the failure rates are much higher (see Figure 3.6).

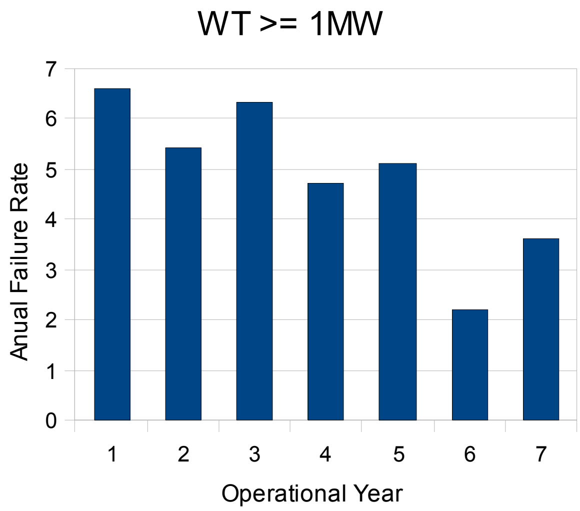

Figure 3.6: Annual failure rate per wind turbine and operational year

4 Theoretical Background

4.1 Technical systems and support organisations

In this chapter we shall introduce the reader to basic optimization theory. We will look into some methods for solving optimization problems concerning spare part storage and logistics. This includes some important concepts that will be used later on in the thesis.

First is an introduction to the *support organisation* and what variables there are to consider when operating and maintaining a complex *technical system*, and moreover, when building a model of the support organisation. In this thesis, the technical system is a wind power system, which consists of a number of identical WT models (a *fleet*). Each WT is composed of the different subsystems described in chapter 3, which all consists of a set of *items*. The support organisation of a wind power system consists of all resources and activities needed to support and maintain the WTs. Designing the support organisation in an optimal way is crucial for cost-efficient energy production.

4.1.1 Basic support organisation characteristics

Since the end of the 19th century there has been an enormous growth in the number of complex technical systems. There are various systems for transportation, for communication and for energy production. Our society today is totally dependent on these systems, that they work satisfactorily and provide the service requested. Hence, operations and maintenance (O&M) has become an important part of many organizations. An efficient support organisation is needed in case the technical system fails, ready to restore it to the normal state as fast as possible. A vital part of the support organisation is spare parts logistics, including allocation, storage, replenishment and transportation of replacement items for the technical system. Strategies for spare part acquisition and management will have a clear impact on the efficiency of the wind power system. Other support organisation variables are for example staff size, skill-level of the service personnel and type of equipment to acquire.

As mentioned above, the support organisation is used to restore the technical system when it fails. This is normally referred to as *corrective maintenance*. In a wind turbine, different subsystems can fail due to broken items, which have to be repaired or replaced. Service personnel are used to perform these tasks. Another way for the support organisation to ensure high availability is to perform maintenance with the aim of preventing break-down, so called *preventive maintenance*. This type of maintenance can either be done within given intervals, e.g. yearly service, or when the condition of the system are below a certain level (or some specific items are poor or worn out).

There are many costs related to support of the technical system, for example costs for maintenance personnel, discardable items, repair costs, facilities, maintenance tools and equipment. The most important cost parameters will be discussed more in depth later in this chapter. All these costs are often called support costs and over the system life cycle the total *Life Support Cost* (LSC) is a significant cost parameter. Other cost parameters are acquisition/development costs, operating costs and phase-out costs. Together with LSC these cost parameters account for the L*ife-Cycle Cost* (LCC) of the system. When designing the support organisation there are two fundamental objectives to consider:

- Minimize the support costs
- Maximize the efficiency of the support organisation

4.1.2 Modelling the availability of a technical system

The *operational availability* (*A)* of a technical system is an important measurement of its effectiveness, and therefore also the efficiency of the support organisation. [6] There are various definitions of availability; different organisations have different views on what is to be included in the term. *A* can be seen as the probability the system is operating at a specified time t. [2] That is, the percentage of time that the system is working, when needed. The term "*A*" can be compared to the reliability of the system. Reliability solely gives information about properties of the technical system, not taking into account success of the support organisation. If a technical system almost never breaks down it has a high reliability. But if the few system failures lead to long downtime because no one is repairing the system, the availability of the technical is low. In case the system provides a service or is producing something, for example a wind power system, availability also means profitability for the owner. When the system is down, due to some sort of failure, the owner can't sell their services. The operational availability, A, of a technical system is given as

$$A = \frac{MTBF}{MTBF + MDT} \tag{4.1}$$

where MTBF is the *mean time between failures* and MDT is the *mean downtime*. Downtime refers to the time the system is unavailable and fails to provide its primary function. MTBF is a result of the design of the technical system, the reliability of the system. [6] MDT depends on how the support organisation is designed and can be split up into three parts

$$MDT = MTTR + MLDT + MWT \tag{4.2}$$

where MTTR, *mean time to repair*, is the active repair time of the system, on site. That is, the time it takes to find and repair or replace faulty items with a spare part and then restore the system (often a test period is also needed before the system is fully operational ready). MLDT, *mean logistic delay time*, is the average time for service personnel to get to the faulty technical system. This time include for example all sorts of transportation time, delays because the system is unmanned (e.g. during nights and weekends) or because of difficult weather conditions. MWT is the *mean waiting time* for spare parts, and depends on stock levels and lead times for different spare parts. [6] MLDT and MWT can sometimes occur at the same time, but at steady state they can be seen as independent parameters. The preventive maintenance, i.e. planned downtime, also contributes to unavailability and can be added to equation (4.1), as a time component in the nominator. MTBF is then replaced by *mean time between maintenance* (MTBM), which now includes the average time between corrective and preventive maintenance. [6]

As seen in equation (4.1) there are two parameters affecting the availability of a system. The most effective way to ensure a high availability is obviously to have long MTBF and low MDT. A problem is that improvements on MTBF and MDT are expensive. MTBF can mainly be affected by investing in more reliable, often more expensive, items (if there are any). A support organisation can also increase MTBF by doing more frequent inspections of item condition and/or introduce shorter service intervals. There are two downsides to be taken into consideration when performing these types of changes. However, this tactic is expensive and it increases MDT. Compared to MTBF there are more ways in which a support organisation can affect MDT:

- Faster transportations of staff and items
- Stock optimization
- Shortening of lead times

These are all effective measures to maximize *A*, but yet again the cost of these actions have to be taken into consideration. Since economical factors are very important availability optimizations are preferably made with different limited budgets as limitation. Herby it is easier to see the LSC needed to achieve certain goals for A set by the support organisation.

Example 4.1

Consider a technical system, for example a wind power system, consisting of one WT. There are no preventive maintenance done on the turbine, it is only repaired when a failure occur. The WT is also expected to be operating (needed) at all times, 24 * 365 = 8760 h per year. On average there are roughly ten failures per year, which takes about two hours to repair. In this first case we do not take any logistic delay times or waiting time for spare parts into account. Approximately, we now have:

MTBF = 900 h
MTTR = 2 h

Given equation (4.1) and (4.2) the availability for the WT is:

$$A_1 = \frac{900}{900+2} = 0.998$$

In the second case we also consider the effects of delays such as waiting for a service technician and that some spare parts are not in stock. When the WT shuts down because of a failure, we assume the technician needs a spare part to repair the system. In 75 percent of the time the spare parts are in stock and the waiting time then is 0 h. Although, there is a 20 percent chance that the service team have to wait 24 h for the specific spare part to be delivered from another stock. In 5 percent of the time the spare part needs to be ordered from the manufacturer, with a one week lead time (7 * 24 = 168 h).

$$\text{MWT} = 0.75 \cdot 0 + 0.2 \cdot 24 + 0.05 \cdot 168 = 13.2 \text{ h}$$

The service team is located in a service station (including the local spare part stock) about half an hour from the WT. They do not work during the night (12 h) which makes the mean waiting time for a technician to be available for work 6 hours. MTBF and MTTR are the same as above.

$$\text{MLDT} = 0.5 + 6 = 6.5 \text{ h}$$

The availability for the WT now is:

$$A_2 = \frac{900}{900+2+6.5+13.2} = 0.976$$

We can see that given this more realistic scenario, considering a more realistic estimate of the delays, A drops over two percentage points. This means many hours of loss of production for the company operating the WT. The conclusion is that waiting time for spare parts has a substantial impact on A.

The example above emphasises the importance of easy access to spare parts within a support organisation. In the next section we will define some important support organisation parameters concerning storage and repairs of spare parts.

4.1.3 Storing and repairing spare parts

Spare parts are often stored in some sort of warehouse, if possible close to the WTs. For efficient operations service personnel maintaining WTs needs easy access to spare parts. This type of warehouse can also include a small workshop to enable repairs of certain items. We shall hereinafter refer to this type of facility as a *depot*. A support organisation can consist of a number of depots where spare parts can be allocated. In a depot both repairable and discardable (i.e. non-repairable) items may be stored, and the quantity of each item is normally called *stock level* (or stock size). Often when referring to the term stock level it means the *nominal* stock level, i.e. the largest quantity of an item in stock. There is also an *average stock size,* representing the item quantity when a stock is scrutinised at any given time. This implicates that there is an average number of that item in stock, i.e. the average stock size. An important cost parameter is the *storage cost*, which represents all costs associated with storage of spare parts, until they are used. This includes space, insurance, protection, capital costs, etc. This cost is usually expressed as a proportion of the value of an item and/or proportional to the stock level (a constant cost per item). Discardable items are reordered when the stock level has reached the so called *reorder point.* The cost associated with acquiring new item(s), apart from the item price, is the *reorder cost*. This cost parameter consists of administrative and set up costs when placing a new order, and also transportation costs (freight) and tolls. [4]

Apart from (minor) repairs done at the depot, most broken items are sent to a workshop for repair. For advanced equipment it can often be a workshop of the manufacturer. The time it takes for an item to be repaired is called *turn-around-time* (TAT), a very important parameter when optimizing stocks for repairable items. TAT is the average time it takes for an item to be repaired in a workshop and ready to be sent back to a depot. [1] Item repair costs are often expressed as a proportion of the value of the item, e.g. 25 percent of purchase price. In some cases operators get a new item from the manufacturer in exchange for sending a broken item. Then a corresponding deduction on the price can be made. [28]

4.1.4 Multi-echelon support organisations

The support organisation can be structured in various ways. In the simplest case there is a technical system operating, supported by *one* facility where spare parts are stored and repaired (if possible), a depot. When dealing with a wind power system this type of scenario is quite uncommon, especially when operating a number of larger WTs. Modern WTs are equipped with advanced control systems and electrical system, containing state of the art items that may require high skills and/or special tools to repair. These items are often sent back to the manufacturer. This also includes main components such as gearbox, generator and transformer. Large items such as blades are hard to accommodate in a local depot and therefore often stored at some large warehouse of the WT manufacturer. If spare parts are repaired and stored on multiple levels within the support organisation, it is called a *multi-echelon system*. [6]

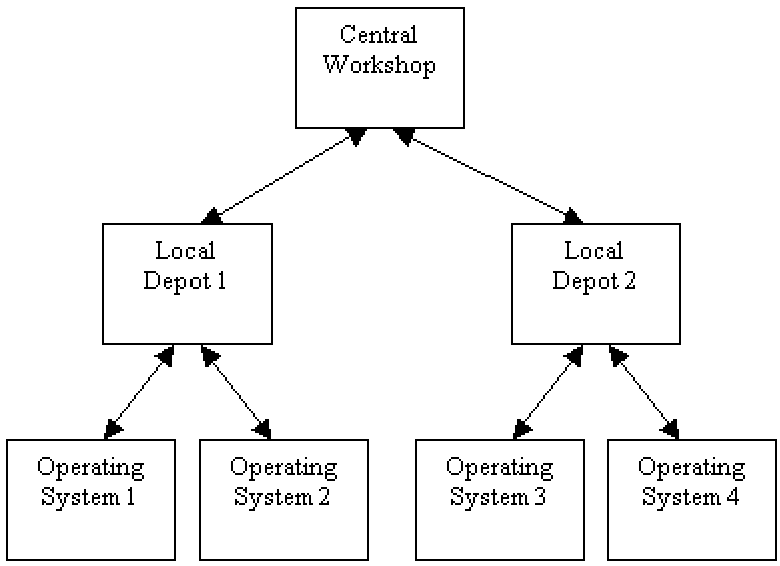

Figure 4.1: Multi-echelon support organisation

Figure 4.1 shows a two-echelon system, where the technical system consists of four operating systems, e.g. four WTs. Two local depots are supplying two operating systems each. Major repairs are done at a central workshop, which sends repaired items to one of the depots. A support organisation can easily be extended to a three- or four-echelon system, with central depots and local stocks at each of the operating systems. Modern support organisations tend to be networks where the physical allocation of spare parts is less significant.

4.2 Optimization theory

Optimization theory refers to mathematical methods and techniques for making optimal decisions and is used for solving problems within many areas and disciplines. The first optimization techniques can be traced back to the 18th century but the major impact in the field came with the term linear programming, coined by George Dantzig in 1947. Linear programming includes methods and theories for solving linear optimization problems, which are very common. Dantzig originally wanted to describe problems concerning the complex U.S. Air Force planning process. A general method for solving the problem was developed, called the Simplex method. With this method and the use of computers, problems including millions of variables could be solved. [4]

An optimization problem can be formulated as an objective function $f(x)$ that is supposed to be minimised (or maximised) given a number of constraints. The problem is linear when $f(x)$ and all the constraints are linear functions of the decision variables. If not, the problem is said to be non-linear. There is also a distinction between continuous and discreet problems, depending on the nature of the decision variables. A linear problem can be formulated as

$$\begin{aligned} &\min f(x) \\ &s.t. \begin{cases} x \leq b \\ x \geq 0, \text{integer} \end{cases} \end{aligned} \tag{4.3}$$

where x is the decision variable, $f(x)$ the objective function and $s.t.$ contains the constraints. This type of problem can be solved with the Simplex method. [4]

4.2.1 Modelling and optimizing spare part stocks

Traditional theory on inventory optimization is mainly concentrated on discardable items, using formulas to find optimal stock levels and reorder points for item by item (known as the *item approach*). One of the first fundamental models was the *Economic Order Quantity* (EOQ) model, often called the Wilson formula, from early 20th century. The Wilson formula uses the mean annual demand for an item, MDY (demands/year), the reorder cost, CR (EUR/order), and the storage cost, CS (EUR/item & year), to calculate the optimal reorder quantity, Q^*. [8]

$$Q^* = \sqrt{\frac{2 \cdot CR \cdot MDY}{CS}} \tag{4.4}$$

When Q is found a reorder point, r, can be calculated, depending on the lead time. It can be noted that the equation (4.4) does not include the item price (which is not needed when calculating EOQ). Within OR many inventory models have been suggested, for example models taking stochastic demand and demand that varies over time into account. These have all been focusing on discardable items. [8] When optimizing support organisations and spare part logistics, repairable items are very important to take into consideration, often dominating the spare part impact on the availability. An item malfunctioning will, if possible, be repaired and not discarded. Repairable items are often more expensive and have longer lead times than discardable items, therefore more important to acquire the optimal quantity for these to the stock. [6]

One of the first models dealing with repairable items was *Multi-Echelon Technique for Recoverable Item Control* (METRIC), developed by Craig Sherbrooke in the middle of the 1960's. [11] It was originally designed for the U.S. Air Force, handling a two-echelon system with military bases supported by one central depot. The METRIC model handled only repairable items and was built around the assumption of independent and identically distributed repair times, with demand being a Poisson process (see section 4.2.2). [6] METRIC theory was later improved and the model extended. For example there was more indentures (i.e. item types; non-repairable etc.) incorporated by Muckstadt in 1973 and the improved Vari-METRIC model, developed by Graves and Sherbrooke in 1985. [1]

One of the most important concepts behind the METRIC model was the use of (expected) *number of backorders* (NBO) to calculate the optimal stock. This technique is used in a lot of optimization software today, for example in OPUS10 which we will use for modelling and analysis. A backorder appears when a system becomes non-operable because of a faulty item and the spare part needed is not in stock (it is under repair or reordered). NBO depends on the stock level and the number of spare parts being in repair at an arbitrary point in time. Given NBO, the expected duration of a backorder can be calculated, that is MWT (for a spare part). With an important result from queuing theory, called *Little's formula*, MWT is given by [1]

$$MWT = \frac{NBO}{DT} \tag{4.5}$$

where DT is the demand rate. Knowing MWT, the availability of the technical system can be calculated with equation (4.1) and (4.2). It is easy to see, since D is a constant, that by minimising NBO, MWT is also minimised. Hence, when minimising NBO we are at the same time maximising the availability, given equation (4.1). NBO is a very useful expression because the NBO value for each item can be calculated and summed to give NBO for the whole system. This is another important concept behind the METRIC model (and models in OPUS10), the way of widen the spare part optimization problem to a system level, instead of solving the problem item by item. Sherbrooke introduced the *system approach* when optimizing the stock, which is superior to item approach. The system approach means that all items are taken into account when optimizing, with the purpose of computing a cost-efficiency curve (C/E curve), e.g. optimal system availability with respect to LSC (see figure 4.2).Trade-offs between item demands and prices are made for the whole system, knowing that optimal stock level for an item depends on stock levels for other items. The system approach also takes into account the different locations (echelons) in the support organisation, allocating the optimal number of items between the depots. [6] Using formulation (4.3), the optimization problem to minimize NBO for a system can be written as

$$\min \sum_{i=1}^{n} NBO_i(s_i)$$
$$s.t. \begin{cases} \sum_{i=1}^{n} P_i \cdot s_i \le b \\ s_i \ge 0, \text{integer} \end{cases} \tag{4.6}$$

where NBO_i is the number of backorders for an item i (where $i = 1, 2, \dots, n$), s_i is the stock level for item i, P is the price of item i and the constant b represents the budget constraint. Every item has a certain demand D (depending on the failure rate and the number of items operating in the system). When using this problem formulation all other support organisation parameters, such as repair times, reorder points and various support costs, are assumed to be fixed. [12] When knowing the demand distribution of an item, $NBO_i(s_i)$ can easily be calculated (see section 4.2.3). This optimization problem is then effectively solved, using *marginal analysis* and *convexity* (see [6] for a more detailed description) to find optimal *convex points* on the C/E curve. With NBO recalculated to system availability the optimal solution could look like the curve in Figure 4.2.

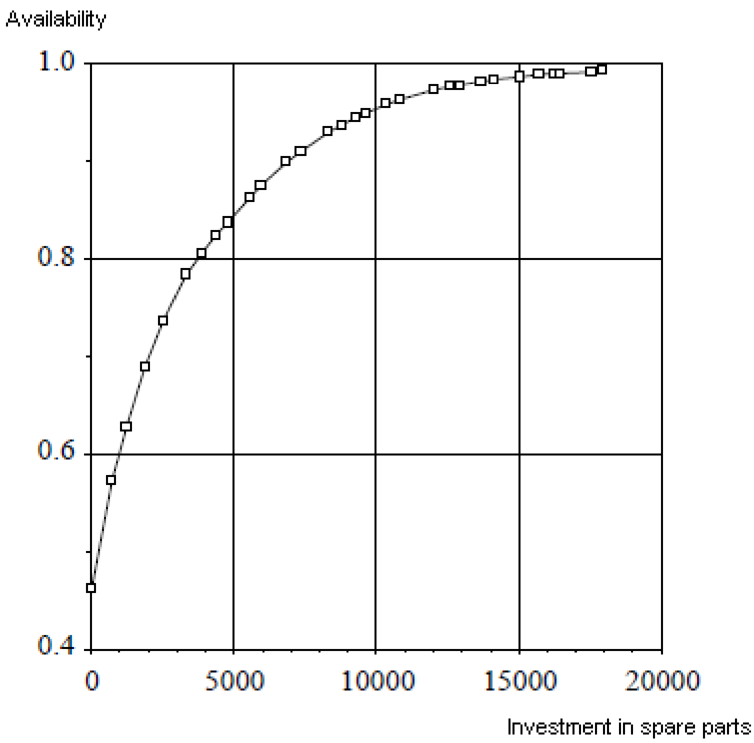

Figure 4.2: Cost-Efficiency Curve

4.2.2 Spare part demand and the Poisson process

The failure rate of an item (or demand rate for a spare part) is an important parameter when modelling and optimizing spare part logistics. If earlier failures have no influence over the probability of a new failure, the time between failures is said to be exponentially distributed. This type of distribution is also called a *Poisson process*. The Poisson process has only one input parameter, DT, which is the average demand during the time period T. The parameter DT represents both the mean and the variance of the distribution. The Poisson probability distribution is given by, see [6],

$$p(n) = \frac{(DT)^n}{n!} e^{-DT} \tag{4.6}$$

where n is an integer (n = 1, 2, 3, …). Consider the following case. We have a wind farm consisting of 50 WTs. Each WT have one generator, which have a certain probability of failing, causing the WT to shut down. The whole system then has a total of 50 generators. If four of these fail on average during a year, there is a mean annual demand of four spare generators. If the demand of the generator is a Poisson process of four per year, calculated with equation (4.6), the number of failures during a year would be distributed with the probabilities as in Figure 4.3.

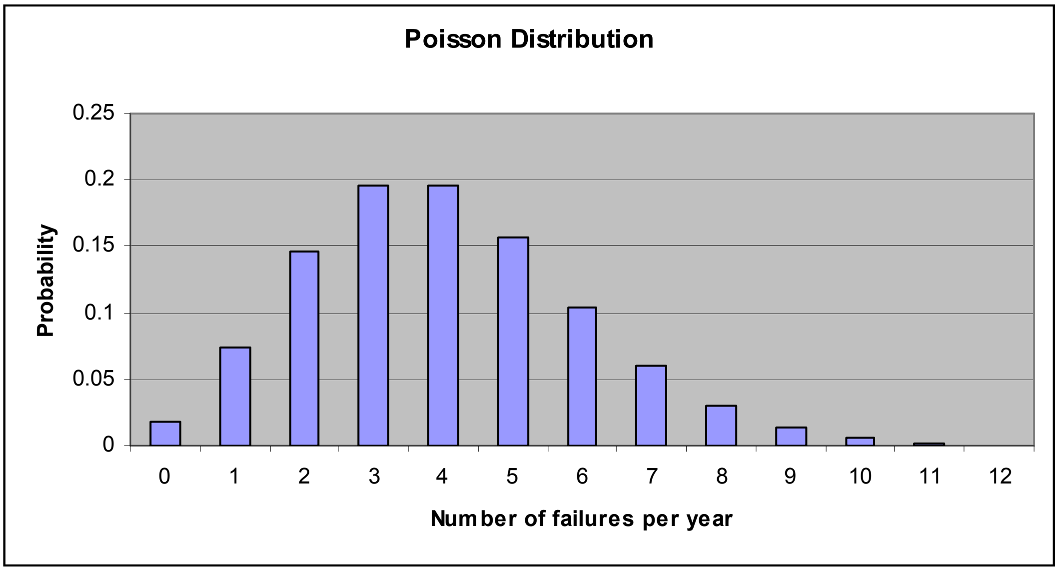

Figure 4.3: Poisson distribution with mean 4

In real life, many technical items have this type of random stochastic behaviour. However, items often experience some sort of wear out with time, including a period of “infant mortality”. [6] This gives the classic “bathtub” curve, with an increased probability of failing at the beginning and at the end of the lifetime and a lower, constant failure rate, in the middle (see Figure 4.4).

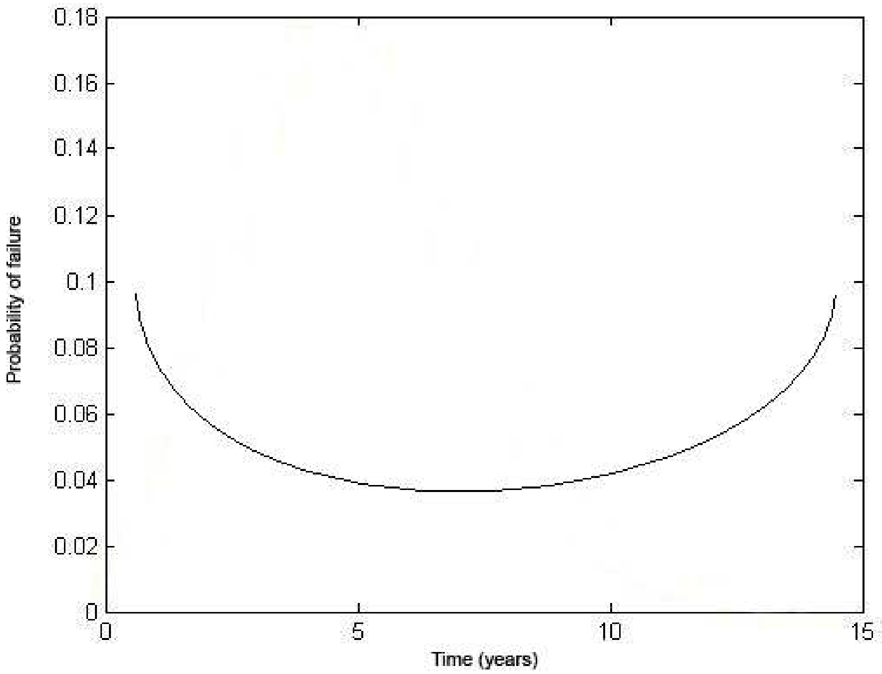

Figure 4.4: The "Bathtub" curve; an example of how the failure rate can vary during the lifetime of an item

For a WT farm with a lot of items in operation in several WTs, the actual accumulated operational time for each individual item may be very different due to different starting dates, failures and replacements. So even if each item failure rate is following the bathtub curve the total demand has an almost constant rate (Poisson distributed). [1] Taking repairable items into consideration, not only is the demand rate important, but also the number of items being repaired or waiting to be repaired in the workshop (of course depending on the failure rate). One major result from early queuing theory, known as *Palm's Theorem*, is very useful for estimating this number. The theorem states that if demand rate for an item is constant, D, and has an average repair time TAT, the steady-state distribution of the number of items in repair (at the workshop or depot) is a Poisson distribution with the mean D*TAT. An important condition is that the repair time for each failed unit is independent, which in many applications should be a reasonable assumption. [6]

4.2.3 Optimization of repairable items

We have in section 4.2.1 described the general idea behind spare part optimization, using the system approach. Most of these theories are applied for repairable items and in this section we will, to some extent, exemplify them. An important term when optimizing stocks for repairable items is the *pipeline*, which is a random variable for the number of items being in repair or re-supplied from a higher echelon-level (see previous section). [6] With the Poisson assumption and using Palm's theorem, NBO for a certain item can be calculated. Another expression, important for calculating NBO, is *risk of shortage* (ROS). ROS is the probability that a spare part is missing in stock when needed, i.e. given a demand. The following example is based on an internal document from Systecon [12], and it will put the theories on optimization of repairable items in a real context.

Example 4.2

We consider a wind farm consisting of 20 WTs. We assume that there are only two repairable items per WT. One is an electric motor (EM) driving the yaw system the other one is a control card (CT), controlling the yaw system. When one of these items fails they are exchanged with an item stored in stock. The exchange takes 4 hours, i.e. MTTR = 4. The faulty EM or CT is sent for reparation and is placed in stock after it is repaired. The EM and CT are in constant operation. The failure rates λ are assumed to be $2 \cdot 10^{-4}$ failures per hour for the EM and $5 \cdot 10^{-5}$ failures per hour for the CT. Using these failure rates the arrival (demand) rate of the items to the repair facility, D, can be calculated. Since there are 20 WT the arrival rates will be:

Electric motor: $D_{EM} = 20 \cdot 2 \cdot 10^{-4} = 4 \cdot 10^{-3}$.
Control card: $D_{CT} = 20 \cdot 5 \cdot 10^{-5} = 1 \cdot 10^{-3}$.

We do also need to state the repair time, TAT, for each item. The repair times are assumed to be independent and are set to

TAT electric motor: $TAT_{EM} = 100$ h
TAT control card: $TAT_{CT} = 100$ h

The final input to our model is the initial item price, P.

Electric motor: $P_{EM} = 7000$
Control card: $P_{CT} = 3000$

If X is the number of items in repair, then the expected value, E[X], is calculated by multiplying D and TAT.

Electric motor: $E[X_{EM}] = D_{EM} \cdot TAT_{EM} = 0.4$
Control card: $E[X_{CT}] = D_{CT} \cdot TAT_{CT} = 0.1$

By calculating NBO and using marginal analysis, the optimal spare part stock can be found. Two important recursion formulas are needed for computing NBO. The first one is used to calculate ROS, denoted $ROS_k(s_k)$, where s_k is the stock level for item k. In this example we have two items, EM and CT. ROS depends on the pipeline, and from equation (4.6) we get $p_k(n)$, which is the probability of n number of items being in repair. Equation (4.8) is used to calculate NBO, denoted $NBO_k(s_k)$, which depends on ROS. [12]

$$ROS_k(s_k + 1) = ROS_k(s_k) - p_k \tag{4.7}$$

$$NBO_k(s_k + 1) = NBO_k(s_k) - ROS_k(s_k + 1) \tag{4.8}$$

NBO and ROS for the two items are calculated and presented in Table 4.1 below.

Table 4.1: Example of NBO and ROS for two items

n	$p_{EM}(n)$	$ROS_{EM}(n)$	$NBO_{EM}(n)$	$p_{CT}(n)$	$ROS_{CT}(n)$	$NBO_{CT}(n)$
0	0.670320	1.000000	0.400000	0.904837	1.000000	0.100000
1	0.268128	0.329680	0.070320	0.090484	0.095163	0.004837
2	0.053626	0.061552	0.008768	0.004525	0.004679	0.000158
3	0.007150	0.007926	0.000842	0.000151	0.000155	0.000003
4	0.007715	0.000776	0.000066	0.000004	0.000004	0.000000
5	0.000057	0.000061	0.000003	0.000000	0.000000	0.000000

Initially the total spare part stock is empty, $s_k = 0$. The expected NBO is $NBO_{EM}(0)+ NBO_{CT}(n) = 0.4+0.1 = 0.5$. With marginal analysis the next item to invest in is found by minimising the quotients $\Delta\ NBO_k(s_k)/P_k$, which implies that $ROS_k(s_k+1)/P_k$ is to be maximised.

$$ROS_{EM}(1) / 7000 = 0.00047 \tag{4.9}$$

$$ROS_{CT}(1) / 3000 = 0.00032 \tag{4.10}$$

Comparing (4.9) and (4.10) it is clear that the maximum value is obtained for EM, hence the first investment should be one EM. The NBO now is 0.5-$NBO_{EM}(0)$ = 0.170320. The procedure is repeated and when knowing NBO, the other measures of effectiveness, MWT, MDT and A can be calculated with equation (4.5), (4.2) and (4.1). The most cost-efficient spare part investments are shown in Table 4.2. In Figure 4.5 is the operational availability plotted with respect to the investment in a so called cost-efficiency curve.

Table 4.2: Summary of the calculated results for Example 4.2

Point	s_{EM}	s_{CT}	Investment	NBO(s)	MWT(s)	MDT(s)	A(s)
1	0	0	0	0,500000	100,0000	104,0000	0,9747
2	1	0	7000	0,170320	34,0640	38,0640	0,9906
3	1	1	10000	0,075157	15,0315	19,0315	0,9953
4	2	1	17000	0,013606	2,7211	6,7211	0,9983
5	2	2	20000	0,008927	1,7853	5,7853	0,9986
6	3	2	27000	0,001000	0,2001	4,2001	0,9900
7	4	2	34000	0,000224	0,0448	4,0448	0,9900
8	4	3	37000	0,000069	0,0139	4,0139	0,9900

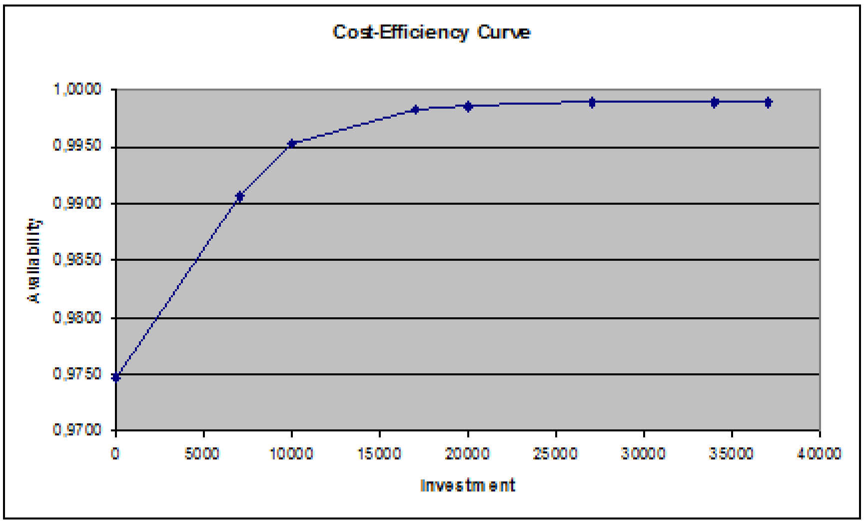

Figure 4.5: Cost-efficiency curve for Example 4.2; basic optimization of repairable items

4.2.4 Optimization of discardable items

When optimizing discardable items the aim is to find an optimal reorder point and reorder size. The reorder size can easily be calculated using the Wilson EOQ formula. A common situation is to give discounts depending on the order size, which complicates the use of the EOQ formula. Example 4.3 below shows how it is possible to handle this type of problem. In the example NBO is not taken into account, only the trade-off between yearly consumption, reorder costs and storage costs are considered.

Example 4.3

Consider a situation where there is an item; let us say a control card, which has a demand rate of four per year. Control cards are ordered when the storage is empty. Order administration cost, including freight, is EUR 400 per order. The price of a control card varies depending on the order size (which can be seen in Table 4.4). To store a card costs 20 percent of the control card price per year. The initial conditions are presented in Table 4.3.

Table 4.3: Initial conditions for Example 4.3

Yearly demand	4
Order cost	EUR 400
Storage cost	20% of item value
Initial price	EUR 1,800
Reorder point	0

If the EOQ formula (4.4) were used, ignoring the discounts, the optimal order quantity, *Q**, would be:

$$Q^* = \sqrt{\frac{2 \cdot 400 \cdot 4}{0.2 \cdot 1800}} = 2.98 \approx 3 \tag{4.12}$$

The total yearly costs for spare parts are to be minimised. The total cost is the sum of all the other costs generated when handling and storing a control card. Table 4.3 show how the total cost is affected by the order size and that there is one optimal point which gives the lowest yearly costs.

Table 4.4: Summary of the calculated results for Example 4.3

Order size	**Discount**	**Discounted price**	**Cost for yearly consumption**	**Order cost**	**Average stock size**	**Yearly storage cost**	**Total yearly cost**
1	**0%**	1,800	7,200	1,600	0.5	180	8,980
2	0%	1,800	7,200	800	1	360	8,360
3	0%	1,800	7,200	533	1.5	540	8,273
4	0%	1,800	7,200	400	2	720	8,320
5	**15%**	1,530	6,120	320	2.5	765	7,205
6	15%	1,530	6,120	267	3	918	7,305
7	15%	1,530	6,120	229	3.5	1,071	7,420
8	15%	1,530	6,120	200	4	1,224	7,544
9	15%	1,530	6,120	178	4.5	1,377	7,675
10	15%	1,530	6,120	160	5	1,530	7,810
11	**25%**	1,350	5,400	145	5.5	1,485	7,030
12	25%	1,350	5,400	133	6	1,620	7,153
20	25%	1,350	5,400	80	10	2,700	8,180
21	**30%**	1,260	5,040	76	10.5	2,646	7,762
22	30%	1,260	5,040	73	11	2,772	7,885
30	30%	1,260	5,040	53	15	3,780	8,873
31	**35%**	1,170	4,680	52	15.5	3,627	8,359
32	35%	1,170	4,680	50	16	3,744	8,474
50	35%	1,170	4,680	32	25	5,850	10,562

In *Table 4.3* it is clear that the cheapest reorder strategy is to order 11 control cards at a time to a total yearly cost of EUR 7,030. This is also illustrated in Figure 4.6 below.

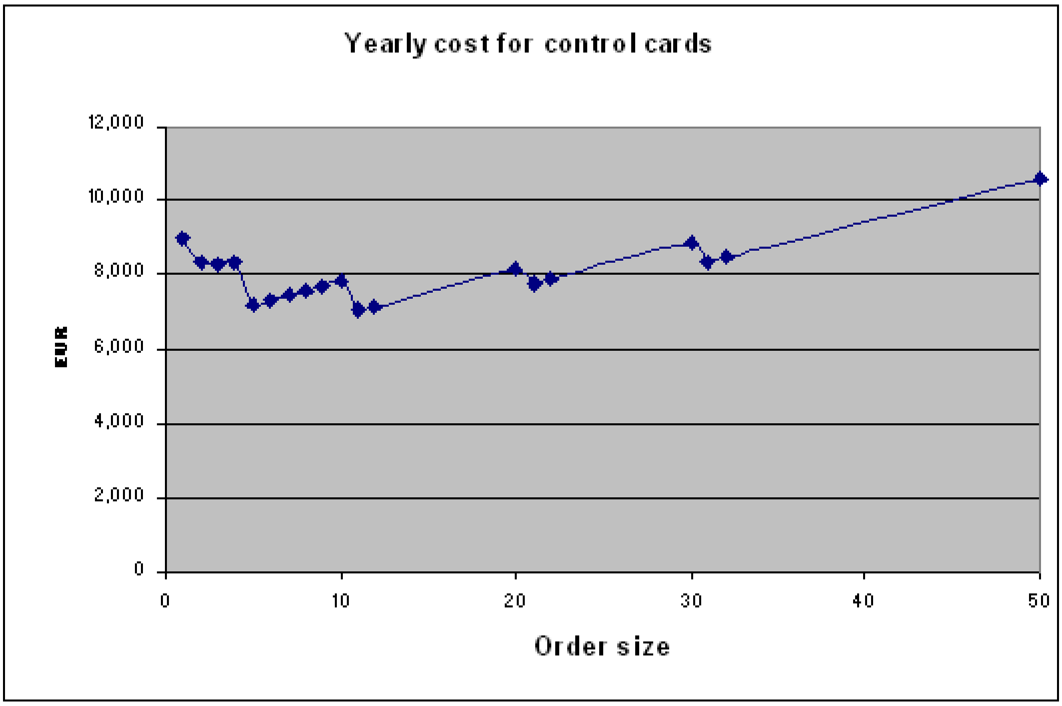

Figure 4.6: Yearly costs depending on order size in Example 4.3

4.3 Sensitivity analysis

Sensitivity analysis can be done to evaluate a mathematical model, and the information from this type of analysis can be used in many ways. The basic idea is to change the value of different model parameters to see how the efficiency of the system is affected. This can give information on how the support organisation should be designed. For example investments in improved performance might be more cost-effective than higher spare part stock levels, such as shorter repair or lead times. The same goes for investment in more reliable (and expensive) equipment, by testing different values on item failure rates. Another way of using sensitivity analysis is to find which parameters that needs to be accurate for the optimal solution to be valid. This is used for what is often referred to as *model validation*. For example, if certain item failure rates are sensitive model parameters, more comprehensive research on these should be done. Sensitivity information can also be used to improve a support organisation model in later stages of the technical system's life cycle. [1] Often more exact data on system parameters can be gathered which perhaps results in different solutions for optimal spare part allocation and stock levels.

For large mathematical models with maybe hundreds of parameters comprehensive sensitivity analysis are needed, which can be very demanding with respect to time and resources. However, when building a model a lot of input data are relatively certain and therefore does not need to be tested for model validation. Hence, an important part of the sensitivity analysis is to predetermine which parameters that are uncertain and has a considerable affect on the results. A simple model for classifying parameters for (and after) sensitivity analysis are shown in Figure 4.7 below.

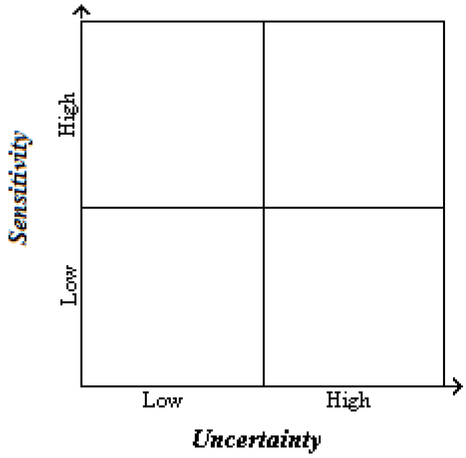

Figure 4.7: Classification model for sensitivity analysis

Parameters can either be classified with high/low uncertainty and high/low sensitivity, were parameters in the upper right group in the figure can be problematic for the model. Parameters with high uncertainty are of main interest when conducting sensitivity analysis, since low uncertainty implies that only small changes are possible, which seldom affect the output result.

4.4 Strategies for spare part logistics

There are various strategies for spare part logistics, many of which have been briefly mentioned earlier in this chapter. To start with, most support organisations for complex technical systems have several echelon levels, as described in section 4.1.4. This means that depots can be used to supply other depots or operational sites. The choice of structure of the support organisation is to be considered as a certain spare part logistics strategy. One strategy is to use a common stock (a spare part pool) for a number of sites, sometimes referred to as *pooling*. This can be useful when different operators have the same type of systems and more or less identical spare parts. This often leads to considerable administration costs, which implies it might be applicable for expensive items only. One reason for this is that centralised reorders and handling requires better computer networks and software. Another strategy then is to have local stocks (depots) at the operating sites, but storing some (perhaps expensive) spare parts in a common depot. [13]

A strategy which is quite common in the wind power industry, especially during the first years of operation, is *consignment stocks*. In section 3.3 we discussed about warranties and service contracts for wind farms. WT manufacturer often handles service and maintenance on a two or five year contact, including spare part logistics. A consignment stock is a stock provided by the supplier (contractor), meaning that the operating company does not own any spare parts of their own, but is supplied when needed. This can of course be profitable in some cases and but sometimes uneconomic. Some advantages are that risk concerning storage and transportation of spare parts are moved from the operator to the supplier, and that storage costs might be lower for a manufacturer. The drawbacks are for example limited competition when acquiring new spare parts and that the risks taken by the supplier normally are charged and paid for by the operator. [13]

The spare part stock is a sort of *safety stock* for the technical system. If lead times and item repair times (TAT) would be zero, no safety stock is needed. Hence, one spare part strategy is to reduce these times and therefore lower storage costs. When finding optimal spare part stocks, sensitivity analysis can be done to investigate the effect of shorter TAT for repairable items and shorter lead time for discardable items. If it is possible to halve some of these parameters it might be a cost-effective solution. [13]

4.5 Economic aspects

There are important economic aspects to consider when optimizing spare part stocks. A support organisation model consists of many different cost parameters, both input and output parameters. Most of the input parameters have already been discussed in this chapter, all related to various support costs. Another important economic parameter, when modelling spare part logistics over a long time horizon, is the *interest rate*, sometimes referred to as *cost of capital*. The interest rate takes into account the value of money over time. Capital tied up in stocks cannot be invested, for example in government bonds or in a bank, thus representing a yearly loss of income (or cost of capital). [4]

Often a term called *present value* is used to relate future costs in terms of the economic value of today. The present value, *PV*, depends on the time horizon, *T*, (in our case the system life length, i.e. the assumed life length of a WT), the interest rate, *i*, and the annual cost, *C*. *PV* is calculated with the following formula [16]

$$PV = C \cdot \frac{(1-(1+i)^{-T})}{i} \tag{4.12}$$

The later part of the product is referred to as the *net present value factor* (NPV). If the present value for a certain time period is known the annual cost can easily be calculated by dividing it with NPV. For models with long time horizons in combination with low interest rates NPV can be a significant cost driver.

Example 4.4

Consider a wind farm with an annual support cost of EUR 10,000. If an operator wants to calculate future costs, the present value formula (4.12) can be used. Let us say the expected lifetime of the WTs are 20 years and the interest rate is set to 7 percent, then *NPV* is:

$$NPV = \frac{(1-(1.07)^{-20})}{0.07} = 10.594 \tag{4.13}$$

and we have:

$$PV = 10000 \cdot NPV = €105{,}940 \tag{4.14}$$

5 Modelling with OPUS10

5.1 Introduction to OPUS10

The Swedish company Systecon AB developed the first version of the spare part optimisation tool OPUS almost 40 years ago. OPUS has changed name in conjunction with major upgrades and is now called OPUS10. OPUS10 is in its 8th version and has been continuously updated to meet demands and requirements from different users and industries working with complex technical systems. The software is mostly used within the defence area, both by authorities and the industry. It has also proven to be effective in other sectors, such as transportation and energy production. OPUS10 uses optimization algorithms to find an optimal storage policy for spare parts, including stock sizes and reordering points. It can be used for initial provisioning, replenishment procurement and reallocation of spare parts. OPUS10 is also a powerful tool to better understand the support organisation and how it affects the performance of the technical system. By using OPUS10 it is possible to identify and eliminate bottlenecks and thereby maximizing the efficiency of the support organization. Many companies have reduced their invested capital in spare parts by as much as 30 percent while maintaining the same or higher operational performance by using OPUS10. [19]

5.2 Input data and structure

The OPUS10 input data is divided among different tables, each describing certain properties of the technical system, the support organisation or the operations. The main data categories are *stations*, *systems* and *items*. Other important data tables for our study are the ones concerning preventive maintenance. There are also some global parameters to consider, affecting the analyses. All these will be described in the sections below.

5.2.1 Stations

The stations in OPUS10 represent the interface of the support organisation, with stores, depots and workshops, located at different sites. Each station type has its own properties

- *Stations where items are stored* (STORE). These stations represent a typical warehouse, used for storage of spare parts.
- *Stations where items are repaired, i.e. workshop* (WS). In a WS spare parts can not be stored, but they can be repaired, within an average TAT, and then put into storage or system.
- *Stations where items can both be stored and repaired* (DEPOT).
- *Operating stations* (OP). In an OP items can neither be stored nor repaired. On an OP systems can be operated and faulty parts can be replaced. In this study a wind farm is represented as an OP where the WTs are the systems.

When building up a support organisation in OPUS10 stations are added and linked to each other. Transportation times for parts on the links between these stations are also given. The transportation time depends not only on the geographical distance, but it is also affected by other conditions and logistical problems. This means that the transportation time should represent the average time from a demand is reported to the supporting station until that demand is fulfilled at the ordering station excluding any waiting times for spares that the supporting station might have. One example can be that items that fail during night are not sent from the supporting station until the next morning which makes the average transportation time longer. This can be seen as the MLDT, discussed in Chapter 4.

Figure 5.1 shows a graphical representation of a simple support organisation. The operational station, OP, is at the bottom and contains the systems (e.g. WTs) in operation. OP is supported by a

STORE, containing spare items for the operating systems. If items from the operating systems need to be repaired they are sent from the OP to the WORKSHOP, via the STORE. MLDT between the stations is written next to the arrow pointing in the direction of transportation. Between the STORE and the OP there is a large difference in transportation time depending on in which direction items (spare parts) are sent.

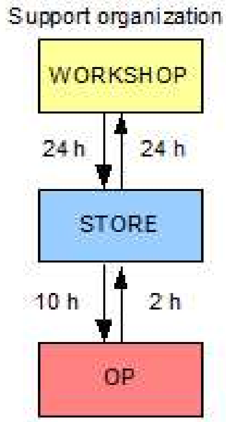

Figure 5.1: The structure of stations in OPUS10

In our report the OP can be an offshore wind farm, consisting of a number of WTs. Due to bad weather it is not always possible to access the WTs by boat. Therefore an average waiting time of 8 hours has to be added to the actual time it takes to sail out to the WTs. This is represented by the 2 hours travelling back from the wind farm (OP). The support structure in Figure 5.1 represents a very simple support organisation. Far more complicated relations between stations are manageable in OPUS10.

5.2.2 Systems

The *system* in OPUS10 refers to the technical system, which the whole support organisation is built to support. A typical technical system modelled in OPUS10 can be an aircraft, or in our case a WT. The system must be connected to a station (often OP) and can be deployed at several positions in a support organisation, which in OPUS10 are referred to as *system deployment*. In order to complete the model, items are connected to the system, or in other words building up the WT or airplane. Input data for systems in OPUS10 is the time to repair the system (MTTR). If a spare part is needed (an item has to be replaced), which is always the case in our analysis, a general MTTR may be given. Optional information on the amount of man-hours needed for the replacement can also be added.

5.2.3 Items

Items are the most data intensive category in OPUS10. The two most important data sets needed are price and failure rate of each item considered for the analysis. The failure rate is given as the number of failures per million hours of operation. It is important to know the quantity of each item there are in each system, in order to be able to calculate the total yearly demand for the spare parts. The items also need to be categorised, specially dividing the repairable items from the discardable ones. The categories for items in OPUS10 are as follows:

- *Line Replaceable Unit* (LRU). LRUs are items that are replaced in the system and then sent to a WS for repair, i.e. they are repairable items. LRUs are stored in a DEPOT or a STORE when they are not used by the system or when in repair.
- *Partly Replaceable Unit (PRU)*. PRUs are items that are replaced in the system and can frequently be repaired but sometimes must be discarded, depending on the type of failure.

- *Shop Replaceable Unit* (SRU). SRUs are items used for repairing an LRU, other SRUs or PRUs, in the workshop. SRUs are repairable in the same way as LRUs.
- *Discardable unit* (DU). DU is, like LRU, an item replaced directly in the system. The difference is a DU can not be repaired, hence it is discarded.
- *Discardable part* (DP). DPs are used to repair an LRU, SRU or a PRU, but can not be repaired.
- ASSY. This type refers to items that has a physical or functional meaning for the system, but can not be replaced when the system is repaired. ASSYs are normally needed only to make the system breakdown structure more readable or logical. They will not have any impact on the calculations or the results.

The item types PRU, SRU and DP are not so common for WTs and will not be used in our models. Therefore no further information about them is presented. For LRUs the repair time (in the workshop), TAT, needs to be given, as well as the repair cost. TAT represents the time between an item arrive at a WS, until it is repaired and sent back to its origin station. For DUs the lead time and reorder cost has to be specified. Depending on the objective of the OPUS10 analysis, the existing stock and reorder quantity of each item can also be given. This is for analysis of an already existing spare part strategy. In section 5.2.2 we mentioned the general MTTR for repairing a system, which will be a default value for replacement of the items. If some specific items take longer to replace, and more man-hours are used, this can also be entered into the OPUS10 model.

5.2.4 Preventive maintenance

Information about the preventive maintenance only affects the spare part optimisation if there are some specific items replaced during this period. If no identified parts are replaced, the preventive maintenance only lowers the total system availability and result in a higher support cost. This information is of course important to include for the model to be more accurate. The input data needed for OPUS10 is the maintenance interval, maintenance time (the number of hours each system is down), man-hours used and cost for each preventive task.

5.2.5 Global parameters

OPUS10 main objective is to calculate an optimal spare part strategy, maximising the system efficiency while minimising the total life support cost. The expected lifetime of the system can be given as an input parameter, which will be the scenario length. When calculating cost over a long time horizon the model often gets more realistic when including cost of capital (as described in Chapter 4). In OPUS10 the annual interest rate is an optional global parameter that can be used for this purpose, resulting in a present value calculation of LSC and other cost elements. Interest rate also plays an important role in the spare part optimization, for example making discardable items “cheaper” to acquire later in the system life-cycle. The cost per hour for maintenance personnel can also be given as a global parameter. In case there is different man-hour cost for different station, this can be detailed. Another useful, optional, input data table is *scale factors*. This can be used to scale other input parameters such as all item failure rates or prices, storage costs or lead times. [17] Scale factors are a very effective way to perform sensitivity analysis.

5.3 OPUS10 Optimization

The optimization in OPUS10 is done with the mathematical techniques described in *Chapter 4, Theoretical background*. This part will instead handle OPUS10 specific characteristics and present how the theory is implemented and used.

5.3.1 Scenario and problem types

There are a lot of different *scenario types* and *problem types*, along with other advanced features regarding how the optimisation is done. These features are for example, *multiple item removal*, *cyclic item demand* (spare parts used during preventive maintenance) and (item) *criticality*, none of which will be used in our analysis. This because of the model assumptions we have made (some described in section *1.4 Delimitations*), for example stating that only one item at a time can be replaced, that item demand is random (Poisson distributed) and that all items included are critical for a system to function. When it comes to scenario and problem types we will describe the ones used in our analysis. [17]

- The *Steady-state scenario* is the standard scenario of OPUS10, which assumes a stationary, non-changing situation. This means that all model parameters are constant over the whole life length.
- The *Initial procurement problem* is probably the most common problem type. This is used for new projects, when spare parts have not yet been acquired. OPUS10 will calculate the optimal number to purchase of each item and at what station they should be stored, calculating a cost-efficiency curve. Furthermore are the reorder points for discardable items calculated and how large quantity.
- *Analysis problem* is used when the cost and effectiveness are to be calculated given a certain assortment and allocation of spare parts, including a reorder strategy. [17]

Depending on the situation different problem types are chosen for optimization of the problem. For replenishment and analysis problems the structure of the support organisation is given. When initial procurement is used, different logistic structures can be tried out, e.g. central or local re-supply of spare parts, and evaluated to determine the best, most cost-efficient strategy.

5.3.2 Prerequisites and assumptions

There are some important prerequisites for the mathematical model in OPUS10, most of which have already been discussed in the in Chapter 4 *Theoretical background*. Here is a short resume:

- *Constant demand rate*. The intensity of the demand for spare parts is assumed to be constant over time. Hence, as the demand rate is a linear function of the failure rate, even the failure rate can not change during the selected period, e.g. item wear-out is not taken into account.
- *Statistically independent items*. Meaning that the demand for one LRU or DU is independent of demands for other LRUs or DUs.
- *Poisson distributed demands*. Constant demand rate implies that the time between consecutive demands of an item will be exponential, in turn implicating that the number of demands during any given period of time will be Poisson distributed.
- *Statistically independent transport and repair times*. Transport/repair times of different items must be independent of each other, as well as consecutive transport/repair times for items of the same type.
- *Constant lead times*. The average lead time for batched item reorder is assumed to be constant over time.
- *Individual handling of items*. Except for the batched reorders items are assumed to be handled individually at all time, when ordered, repaired and transported. However, for certain items exceptions can be made. [17]

These are the standard conditions of the OPUS10 model. As mentioned above, some changes can be done, using some of the advanced features.

5.3.3 Economic model

Using the LSC concept when evaluating system operations is an effective way to ensure that the future costs is not increased in order to save initial money. OPUS10 uses an extensive economic model to handle the costs related to support of a technical system, calculating an estimation of the total LSC. In the model LSC can be broken down into two major cost elements, *capital costs* (CD) and *recurring cost* (CN). CD is calculated per station and can be split into item capital costs (divided in repairable and discardable items) and resource capital cost. CN contains the total lifetime present value of all recurring cost elements included in the OPUS10 model. [17] These are

- Item consumption (CND)
- Reordering costs (CNO)
- Storage costs (CNS)
- Transportation costs (CNT)
- Corrective maintenance costs (CNC)
- Preventive maintenance costs (CNP)

CNC and CNP are useful cost elements, since they represent the proportion of maintenance costs spent on correcting faults and preventing faults respectively. These cost elements include both labour costs and other related costs. CN and all its sub elements are in OPUS10, as stated above, recalculated to present values. The present value, PV, of a recurring cost, RCOST, is calculated with the following formula:

$$PV = RCOST \cdot NPV \cdot NPV0 \tag{5.1}$$

where:

$$NPV = \begin{cases} \dfrac{1-e^{-iT}}{i} & \text{if } i > 0 \\ T & \text{if } i = 0 \end{cases} \tag{5.2}$$

$$NPV0 = e^{-i \cdot T0} \tag{5.3}$$

and:

i	= Interest rate (as a fraction, not in percent)
T	= Scenario length (in years)
$T0$	= Scenario start time (often set to 0)

OPUS10 is, as can be seen from the formulas above, using a so called continuous interest rate, which is slightly different from the classical pro anno interest rate (see section 4.5). [17] For interest rates lower than five percent pro anno the values are almost identical, otherwise the interest rate in OPUS10 has to set a bit lower than the annual interest rate. Furthermore, LSC and all their cost elements can be converted to annual costs. This is done by dividing the values with the *net present value factor*, NPV.

5.3.4 OPUS10 outputs and results

When a complete model of a support organisation is built up in OPUS10 it can be analysed based one of the problem types presented above. There are two types of results that are deduced from an OPUS10 analysis. Some of the results are independent of the optimisations performed by OPUS10 and some that are depending on the optimisation.

The first types of results, independent of the optimisation, are general results connected to some of the model parameter values and how the support organisation was defined. These results can be seen as a summary of the model and its input data. For example, OPUS10 calculates an inherent availability that represents the availability the modelled system would have if there was always a spare part at hand without delay at the system. The inherent availability is therefore only dependent on the times set for replacement/repair actions (MTTR) and of course on the item failure rates given. The failure rates combined with the total number of items in operation in the deployed systems and their operations also generate an annual spare part demand (the mean number of each DU discarded per year and mean number of LRUs repaired per year) and fixed costs associated with item replacements and repairs (CNC), item consumption (CND) and preventive maintenance (CNP).

The second type of results is dependant on the results from the optimisations performed in an OPUS10 and varies between the points on the C/E-curve. The primal result from the optimisation is a C/E-curve (described in Chapter 4) of a MoE with respect to a certain cost (element), e.g. system availability on the y-axis and LSC on the x-axis. The C/E-curve consists of several points, were each point represents a given spare part strategy (with individual stock sizes, reorder points and spare part allocation). [17] Except from the point specific results mentioned above there are hundred more. The most interesting are, except of the previous mentioned, risk of shortage if a spare part is needed (ROS), capital costs from spare part investments, storage costs and reordering costs.

5.4 Using grouped data in OPUS10

Inaccurate data, in combination with the factor that the future is always uncertain, is a complicating factor to nearly all maintenance or spare part calculations. One way to handle uncertainties in the data model is to group data. This gives you a much blunter dataset but it is also more robust. Now the data accuracy boundaries are shifted from concerning the variance of the parameter, to a question if the distribution of the parameter is within the group boundaries. To group data can also be a way to show that failure rate data is not absolute, giving a more accurate picture of collected data. Furthermore, grouping of data have a very small influence on OPUS10 optimisation. The difference is also small in comparison with other uncertainties. [14]

6 Field Studies

6.1 Introduction

In the previous chapter we presented the OPUS10 model and what are the most important parameters to consider. The first objective when building a support organisation model in OPUS10 is to find the spare parts (items) of interest. As mentioned before, different WT types consist of an almost unique set of items, depending on the manufacturer. To get a better understanding of the WTs within Vattenfall's fleet, field studies were conducted at four major sites:

- Bergkvara service station
- Näsudden wind farm
- Klagshamn service station
- Esbjerg service station

The main focus of the field studies where the two largest Vattenfall offshore wind farms, Lillgrund and Horns Rev, operated from Klagshamn and Esbjerg, respectively. Lillgrund wind farm consists of 48 Siemens SWT-2.3-93 and Horns Rev of 80 Vestas V80-2.0. As earlier discovered, there is a lack of public data on WT failures and difficulties on generalising over different WT types. Therefore the field studies were necessary in turn to generate data on WTs suitable for OPUS10 analysis. The information and data gathered via field studies and interviews are compiled and divided into section 6.2 and 6.3, for the Siemens WT and Vestas WT respectively. This chapter will include information on all important data collected for the two WT models and how estimations were done regarding input data for the OPUS10 analysis.

6.2 Siemens SWT-2.3-93

As the acronym implies SWT-2.3-93 has a rated power of 2.3 MW and a rotor diameter of 93 m. There are similar models called SWT-2.3-82/101/107 where the major differences are the rotor diameter of 82 m, 101 m and 107 m. Hereinafter Siemens SWT-2.3-93 will be referred to as *SWT-2.3*. The SWT-2.3 has a hydraulic pitch system controlling the power output from the three bladed rotors, with the blades pitched individually. The blades are produced by Siemens and are made of fibreglass-reinforced epoxy. SWT-2.3 is equipped with a three-stage planetary-helical gearbox produced by Winergy AG. The mechanical break is a hydraulic disc brake located at the high speed shaft exiting the gearbox. At the end of the drive train there is a generator. Production is controlled by a microprocessor-based industrial controller equipped switchgear and protection devices. Siemens have their own converter system, NetConverter®. [20]

6.2.1 SWT-2.3 deployment

At the end of 2007 Vattenfall installed 48 SWT-2.3 at the offshore wind farm Lillgrund, located a few kilometres out in Öresund, just outside of Malmö. The same year two SWT-2.3s were also installed onshore in Lyngsmose and thirteen SWT-2.3s in Nørrekær Enge, Denmark. [23]

Existing fleet of SWT-2.3:

- 48 Lillgrund, offshore, Sweden
- 2 Lyngsmose, onshore, Denmark
- 13 Nørrekær Enge, onshore, Denmark

Vattenfall also has ongoing projects including SWT-2.3. For Sweden Vattenfall have written a contract with Siemens which makes Vattenfall obliged to buy about 100 MW worth of wind power from Siemens. 100 MW corresponds to approximately 44 SWT-2.3 turbines, which will be installed in different locations in the southern parts of Sweden. 18 WTs are already being built at a wind farm outside of Falkenberg. For the remaining 26 SWT-2.3 there are no specific sites set. In Denmark there are 30 SWT-2.3 planned to be built within the next five years, which makes it a total of 74 new SWT-2.3 for Vattenfall. [26]

Upcoming SWT-2.3 projects:

- 18 Falkenberg, onshore, Sweden
- 26 South of Sweden, onshore, Sweden
- 13 Hagesholm, onshore, Denmark
- 4 Dræby, onshore, Denmark
- 4 Blaksmark onshore, Denmark
- 5 Avsumgaard onshore, Denmark
- 4 Ejsing, onshore, Denmark

In the future it is possible that Vattenfall will take care of O&M for all these sites, including spare part management and logistics. The SWT-2.3s at the different locations will most likely use the same type of spare parts. Good coordination between the sites is of high interest.

6.2.2 Support organisation for SWT-2.3

At the moment there are individual support organisations for the Vattenfall wind farms operating with SWT-2.3. There are also contractual differences for the O&M carried out at the wind farms. In this section we will describe the different conditions at the existing sites, together with a possible future support organisation for the 74 SWT-2.3 planned to be built. First the main location of the manufacturer Siemens is presented.

Brande

Brande in Denmark is the main hub for Siemens wind turbine functions. Brande is situated in the middle of Jutland, Denmark. The production facility for SWT-2.3 is situated in here and also the main storage facility for spare parts. Most spare parts ordered to the wind farms come from Brande. This is also were faulty items (LRUs) are sent for repair. [27]

Klagshamn

The main storage for Lillgrund wind farm is located in Klagshamn harbour, a few kilometres south of Malmö. In Klagshamn harbour there is a control room and a depot (owned by Vattenfall), from where Lillgrund is monitored and operated. In the harbour there is a special designed boat that the service technicians use to get to the site, which takes about 30 minutes. Although when looking at the mean logistic delay time (MLDT) between Klagshamn and Lillgrund, many other factors to consider. To start with it takes about an half an hour to load the boat when sailing out and half an hour unloading the service teams to different WTs on the wind farm, adding one hour to MLDT, for a total of 1.5 h. The fact that the service station is staffed 11 hours a day also prolongs the time between a failure occurs until the boat is ready to sail. On an average the station is unmanned 6.5 h per day ($13*0.5 = 6.5$). The probability that a failure occurs during the night is 0.54 ($13/24 = 0.54$). This means that the average waiting time added for faults occurring at night is 3.5 h ($0.54*6.5 = 3.5$). MLDT between Klagshamn harbour and Lillgrund also depends on the weather condition, since it is an offshore wind farm were boats can not go when winds and waves are to strong. Due to the fact that Lillgrund is enclosed in a small sound between Sweden and Denmark, the weather condition at the site is not that harsh, enabling the service boat to sail about 95 percent of the time. As mentioned above, the service station is staffed 11 hours a day. Given the 5 percent chance that they can not sail, this adds an average of 0.55 h ($11*0.05 = 0.55$) to MLDT. Together the transportation and waiting times presented above counts for a total MLDT of 6.09 h between

Klagshamn harbour and Lillgrund. In the model we have rounded this parameter to 6 h. The return sail is not exposed to any delays. Picking up the service staff and sailing back takes about an hour. [27]

The time between the Siemens factory in Brande and the depot in Klagshamn is a bit difficult to estimate. This is the time between an item (LRU) has been repaired in Brande and it is received in Klagshamn. Driving between the sites takes about 4 hours and to coordinate the whole activity we approximated the transportation to take a working day. With the spare part not being ready for use until the next day we have estimated the total MLDT to 24 h.

Denmark Onshore
Vattenfall owns and operates 269 onshore WTs in Denmark, with the major wind farms located on western and northern Jutland. Service and maintenance is divided among four service cars, with two technicians in each car. The service cars are responsible for a certain geographical area, containing around 60-70 WTs each. Lyngsmose is supported by *service car south* and Nørrekær Enge by *service car north*. Close to the WTs there can be a small shed containing some spare items and some spare items are carried in the service car. The service car can not carry too many items for SWT-2.3 since it is also servicing many other WT types. If spare parts needed are loaded in the car we assume the service team can reach a faulty SWT-2.3 within 1 h on average. The onshore service technicians works from 07.00 in the morning until 15.00 in the afternoon, Mondays-Fridays. [29] This means they will be unable to repair a WT failure 76 percent of the time, (128 / 168 = 0.76) resulting in an average waiting time for a service technician of about 9 h (24 * 0.76 / 2 = 9.12). Together with the travelling time the MLDT then will be 10 h. This of course depends on where the spare parts are stored from the beginning. If Vattenfall is to support a number of onshore SWT-2.3 in Denmark it might be reasonable to have a spare part stock for these in one place. For the service cars to get there, picking up the items needed, we add another 1 h to the MLDT, resulting in 12 h. If Klagshamn were to support the Danish onshore SWT-2.3 as well as Lillgrund, with all or just some strategic spare parts, we estimated MLDT as from Brande to Klagshamn, 24 h.

Sweden onshore
For the ongoing SWT-2.3 onshore projects in Sweden, the future organisation around service and maintenance are unknown. Some new spare part storage facilities may be built, small or large. At the moment the depot in Klagshamn is exclusively used for Lillgrund, but a possible scenario in the future is that spare parts for other SWT-2.3 wind farms are stored there as well. If we assume the Swedish onshore organisation within Vattenfall is somewhat structured in the same way as in Denmark, there will be a couple of service teams covering different geographical areas (with or without the use of service cars as a spare part stock). In that case the travelling time (including on and offload of spare parts) from the depot in Klagshamn to one of the sites will be approximately 2 h (for some sites in Skåne it might be a bit shorter). If the service teams work for normal 40 h week (no weekends) there will be the same waiting time as for the Danish onshore service teams, i.e. 9 h. The total MLDT from Klagshamn to the future SWP-2.3 sites then will be 11 h. If local depots are to be modelled in OPUS10, i.e. small storage facilities close to the onshore sites, MLDT is estimated to be 10 h.

In Figure 6.1 are the current and future Vattenfall SWT-2.3 and depots (service stations), described above, shown, including the Siemens factory in Randers.

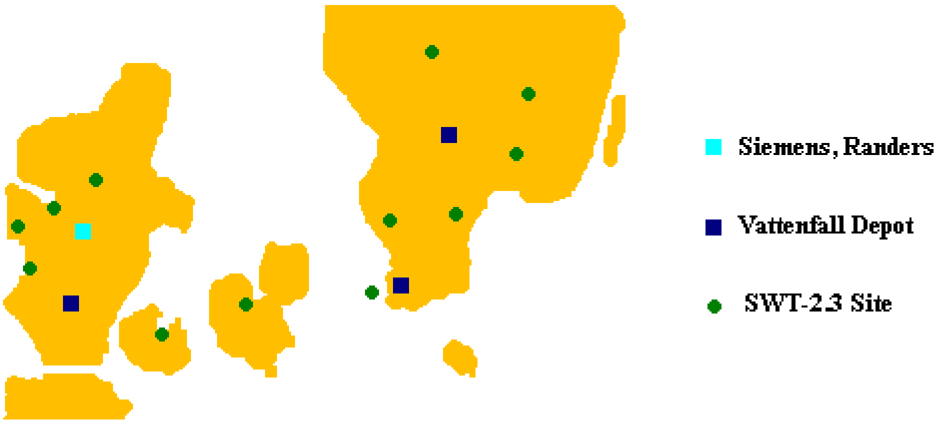

Figure 6.1: Siemens SWT-2.3 and depot deployment

6.2.3 Service and maintenance

The normal procedure when commissioning a wind farm is to let the WT manufacturer take care of O&M the first years. For SWT-2.3 Vattenfall has a service agreement with Siemens for Lillgrund and the onshore farms in Denmark until the end of 2012. A clear strategy at Lillgrund is to involve more Vattenfall service personnel each year. [27] If Vattenfall is to take over O&M and spare part management and logistics they are going to need a strategy for service and maintenance, including a spare part stock policy. Coordination between the different Siemens WT sites may be an option, with for example common or separate storage of spare parts.

At Lillgrund there are twelve service technicians working each day, in teams by two. For most of the maintenance tasks, smaller repairs and replacement of faulty items, one team is needed. The service personnel work seven days a week, eleven hours per day. In the service contract with Siemens there is a clause giving Vattenfall the right to phase in their own personnel in the service teams. Right now there are three Vattenfall employees among the twelve technicians, with three more joining each year until 2012, when Vattenfall has the option to operate Lillgrund by on their own. Vattenfall also has a site coordinator in place that is monitoring all the activities. [27]

Denmark onshore has four service cars handling the maintenance for Vattenfall's 269 WTs operating on Jutland and Fyn. Each car covers a geographical area containing about 70 WTs and the cars are staffed with two technicians each. The WT types maintained are different so there is a broad knowledge needed by the Vattenfall service personnel. When they need help with a WT repair an external technician, often working for the WT manufacturer, is contracted to solve the problem. [29]

When looking at maintenance for the SWT-2.3s planned to be built in southern Sweden, Vattenfall have not created a maintenance plan yet. The new sites will be within close range from the Lillgrund warehouse in Klagshamn, which could be used as a main storage facility for all spare parts if Vattenfall is going to take care of O&M activities for the sites in the future. Another possibility would be to build a new depot(s) at a more strategic place(s) in Sweden. Were to allocate spare parts, how many to acquire and when to reorder new items are questions Vattenfall may have to deal with.

6.2.4 Preventive maintenance

The preventive service of the SWT-2.3 is done once a year, preferably during the summer when the average wind speed is lower. In our model, we have not included any spare parts for this type of service. Items shifted are mostly inexpensive filters. Oil and grease needs to be refilled, but the quantity is detailed in the service manual by the manufacturer. The yearly service represents a cost element in the total LSC though, and also leads to downtime and unavailability for the wind farm. Hence, we approximated the yearly cost and service time for one WT as input data for the OPUS10 analysis. The total item cost for preventive maintenance for one SWT-2.3 is roughly EUR 2500 and the service takes five days. [27] Hence, the WTs are unavailable for 108 h each (5 days and 4 nights). The man-hours needed for each WT are then set to 88 h (2*11*5 = 110), given that one team works at each turbine.

6.2.5 Item Data

The information required when modelling support organisation logistics are item failure rates, prices, types (including repair TAT or lead time) and MTTR (item replacement). To gather this information an interview was conducted with former Vattenfall site manager at Lillgrund and the Vattenfall site technical advisor of today. We limited the research by looking at approximately 40 items. When sorting out items one important criterion was to create a diversity of failure rate and prices. The items are also selected to represent all five WT subsystems. All data collected on SWT-2.3 items are taken from Lillgrund wind farm. Siemens have provided Vattenfall with activity reports from all the months Lillgrund has been in commission, containing information on what type of service that has been done, date and time, spare parts used etc. The reports cover a period from Mars 2008 until September 2010. This material was used to find and select critical items to include in our analysis and also estimate failure rates for these items. Because of the fact that failure rates and other data, such as item prices, are estimates and differ between different WT sites and models, we classified the items in groups instead of giving them unique values. This also because the models and algorithms in OPUS10 are very robust handles rough data well. All collected item data for SWT-2.3 is presented in Appendix C. Below there is a summary of how Appendix C was created.

Item failure
19 of the 26 items included in the study, were chosen from the 19 months activity reports. With 48 WTs at Lillgrund the data material covered approximately 666 000 operating hours for the whole wind farm. A big disadvantage with this data though, is that it is only covering the first two years of operation. Teething troubles with some items might be a problem and result in a higher failure rate than what is correct. In the reports it is stated when an item is replaced by a spare part. From this we calculated a yearly demand for each item, converted to a failure rate for later OPUS10 analysis. For certain items new models have been introduced, replacing the older version. When two different models of the same item have been used we have chosen to ad up the faults, creating common failure rates for the two models. This is acceptable as long as the new model do not have a significantly lower failure rate compared to the old model, but a problem here is that we do not know exactly when the models were changed (maybe not for all WTs at the same time). We have decided to add up since there are too few hours of operation with the newer model creating a weak statistical material. This given the fact that the material we have is already on the edge on what is acceptable. Further more the new model is working at the same position in the WT and therefore under subject to the same stress as the earlier model. A couple of items were also picked out from a Siemens 2.3 MW turbine spare part catalogue (from 2005). We have no information that these components have failed during the first two years Lillgrund has been in commission, but they are expensive and critical for the WTs to function, hence interesting to include in our analysis. Estimated failure rates for those items, as well as main components such as blades, gearboxes, generators and transformers, were based upon previous WT reliability studies, together with information from interviews.

Item Prices
Because Vattenfall do not own any spare parts connected to Lillgrund item prices were difficult to find. Siemens were restrictive to hand out information regarding exact item prices for the SWT-2.3. But with help from the Lillgrund stock manager at the Klagshamn depot, we got some rough estimates on those selected items in stock (chosen from the activity reports). For the large main components (not in stock) we used the same price estimations as for the Vestas WTs, by information

from interviews and documents collected from Esbjerg.

Item types
To classify the items in to repairable and discardable items we used information from the interviews in Esbjerg (concerning Vestas V80) and Näsudden. From the 26 items chosen, satisfying our criterions on price and criticality, 8 were classed as repairable and 18 as discardable. No item with a price under EUR 1000 is classed as repairable, since repairs not might be cost-efficient for cheap items. Mean repair TAT and lead times were estimated based on interviews and information regarding the Vestas V80 spare parts.

Item replacement
The activity reports also gave us an approximation on how long time it takes to replace certain components, i.e. roughly the MTTR. Most small items, mainly electrical, are changed in half a day. Larger mechanical items like motors and pumps are changed in a day or two. Very large items, e.g. a gearbox or smaller items affecting the whole drive train, e.g. drive train bearings are exchanged in approximately one week.

6.3 Vestas V80-2.0 and V90-2.0

Vestas have two different 2.0 MW WTs. The V80-2.0 has a rotor diameter on 80 m and the V90-2.0 has a rotor diameter on 90 m. The different blade lengths require a different setting of the gearbox between the models. This is the only major difference between the two types. The Vestas 2.0 MW series is inconsistent, with small changes and corrections made every year of production. Therefore two Vestas 2.0 MW models produced a couple years apart can have a complete different set of items used. Hereinafter Vestas V80-2.0 and V90-2.0 will be referred to as V80 and V90, or *V80/90* in general. V80/90 have a hydraulic pitch system controlling the power output from the three bladed rotor, blades are pitched individually. The blades are manufactured by Vestas. The mechanical break is a hydraulic disc brake located at the high speed shaft exiting the gearbox. The generator at the end of the drive train is a 4-pole asynchronous generator operating with variable speed. V80/90 has a 3-stage planetary/helical gearbox, but the gear step up is a bit different between the V80 and the V90. Production is controlled by VCS (Vestas Converter System). A unique Vestas solution is that the transformer located in the nacelle of the V80/90, compared to other models where it is placed in the tower. From the nacelle the transformer can be hoist down if it has to be exchanged. [24]

6.3.1 V80/90 deployment

Danish energy company Elsam (merged with Dong Energy 2004) completed the installation of 80 V80 turbines, off the west coast of Jutland, in 2002. The wind farm, called Horns Rev, was the largest in the world at the time, with a total capacity of 160 MW. [21] In 2005 Vattenfall acquired the wind farm which now is owned 60 percent by Vattenfall and 40 percent by Dong Energy. [28] Horns Rev is located offshore about 20 km west of Esbjerg. Esbjerg is situated on the middle of the west coast of Jutland. Just a few kilometres south of Esbjerg Vattenfall owns a wind farm called Tjæreborg Enge. Here Vattenfall is operating two V80, which were put in commission already in 1996. [29]

Existing V80 within Vattenfall are:

- 80 Horns Rev, offshore, Denmark
- 2 Tjæreborg Enge, onshore, Denmark

Vattenfall have a lot of ongoing wind power projects including V80 and V90. The V90 is more common in Sweden and the V80 in Denmark. The difference is that there is lower wind speeds over Sweden compared to Denmark. In Sweden there is a large wind farm being built in Stor-Rotliden in the middle of Norrland, 70 km north-west of Umeå. The foundations are at place and by the summer of 2010 the first WTs will be raised and the wind farm is going to be in commission by the end of 2010. There will be a total of 40 V90 2 MW turbines. At Yttre-Stengrund wind farm, in Kalmarsund, five old NEG Micon turbines operating there will be exchanged to five new V90. The shifting process was planed to be finished in the summer of 2010 but now the project is on hold. Nine more V90s are planned to be built in Östra Herrestad, but this wind farm project is in an early stages [26]. In Denmark there are five V80 planed to be built onshore in Hesselå/Hoager within the next five years. [29]

Upcoming V80/90 projects

- 40 Stor-Rotliden, onshore Sweden
- 9 Östra Herrestad, Simrishamn, onshore, Sweden
- 5 Yttre-Stengrund, offshore, Sweden
- 5 Hesselå/Hoager, onshore, Denmark

6.3.2 Support organisation for V80/90

At the moment the service and maintenance of the current V80s in Denmark are divided in onshore service teams and offshore service teams. How it is going to be organised in the future is at the moment unknown. [29] In our model we will include the following stations in the support organisation: Randers, Horns Rev, Tjæreborg Enge, Östra Herrestad and Yttre Stengrund, and Stor-Rotliden.

Randers
Vestas headquarters is located in Randers on the east cost of Jutland. Vestas have more production sites in Denmark, for example are nacelles produced in Ringkobing, on the west coast of Jutland. We have chosen to use Randers as the main station for repair of all faulty items for V80 and V90. Since there are very few third party dealers, for spare parts and repairs, most items are ordered from Vestas or sent there for repairs. [28] For transportations between Randers and the different WT service stations we have approximated MLDT to 24 h, except between Randers and Stor-Rotliden where it is set to 48 h, because of the very long distance. We have chosen these long transportation times since Vestas is an external part from Vattenfall. As a result of administrative factors it will probably take at least one day on average to send and receive spare parts between the two companies.

Horns Rev
The maintenance staff and storage for Horns Rev is placed in Esbjerg, Denmark where a totally new office and storage was built in the summer of 2009. In the offices, connected to the storage facilities, Vattenfall has its main control room. From the control room in Esbjerg all Vattenfall wind farms in Europe can be monitored and operated. In Esbjerg only small repairs are made. If there is a larger repair needed the part is sent to Randers. The service teams are most commonly transported out to Horns Rev by boat. The 20 km sail out to Horns Rev takes about an hour. Since Horns Rev is situated on open water, compared to Lillgrund, it is only possible to sail out approximately 40 percent of the time. Due to the low accessibility, all the WTs are equipped with a helicopter pad which enables the service personnel to reach the site when the weather is too harsh. One helicopter, with a pilot, is rented for 200 flight hours per year, which may be extended if necessary. So far a bit over 200 flight hours have been used each operating year. [28] MLDT between Esbjerg and Horns Rev were approximated in a similar way as for Klagshamn-Lillgrund. Loading the boat and transportation out to Horns Rev takes two hours. The service station in Esbjerg is staffed 12 hour a day every day, leading to an average waiting time for fault occurring during the night of 6 h (12*0.5 = 6). The probability that a failure occurs during the night is 0.5 (12/24 = 0.5). Therefore 3 h (0.5*6 = 3) are added to the MLDT. For the 60 percent chance that the service teams can not sail out to

Horns Rev, due to bad weather, delays have to be calculated. Assuming that the station is manned 4380 h (365*12 = 4380) per year, the staff can only reach Horns Rev by boat 1752 h (4830*0.4 = 1752) per year. Transportation by helicopter adds 200 h of possible maintenance work, thus Horns Rev is reachable 1952 h per year (1752+200 = 1952). The influence of the helicopter is very marginal, only adding half a percentage point to the total approximated accessibility (1952/4830 = 0.404). The total time added to MLDT is 7 h (0.6*12 = 7.2). Adding up the times presented the logistic delay time between the depot in Esbjerg and Horns Rev is 12 h on average over a year (2+3+7.2 = 12.2). The boat ride back to Esbjerg takes approximately two hours since there are several service teams being picked up. [28]

Tjæreborg Enge and Hesselå/Hoager
Since Tjæreborg Enge and Hesselå/Hoager will be located onshore in Denmark the WTs are supported by a service car. Even though Tjæreborg Enge and the depot in Esbjerg supporting Horns Rev are very close geographically, the service technicians use Randers as there main facility for spares instead of Esbjerg. This is due too the shared owning of Horns Rev between Vattenfall and Dong Energy. Tjæreborg Enge is serviced by one of the Danish service cars, previously mentioned for the Danish onshore SWT-2.3. [29] Today items are sent directly to, and collected from, Vestas (in Randers). In the future we assume that the onshore V80/90s in Denmark will be able to share storage with Horns Rev or have another depot available on Jutland. The service personnel work Mondays to Fridays 7-16. The time for which the service cars are unmanned on nights and weekends is 123 h, (5*15 + 2*24 = 123). Divided into seven days the station is unmanned 17.6 h per day (123/7 = 17.6). This means that the mean 8.8 h is added to MLDT between the service station and the onshore V80. On average there is also a two hour drive from the station to the onshore wind farms in Denmark. Totally there is about 11 h in logistic delay time between a service station and a V80 onshore.

Stor-Rotliden
Stor-Rotliden wind farm will most certainly be supported by a storage facility built close to the wind farm. Since it is onshore there will be now problems with transportations between the service station and the WTs. A wind farm of this size will probably be staffed every day of the week and have working hours similar to Horns Rev and Lillgrund, about a day. As for the other wind farms it will approximately take an hour for the service staff to gather the proper gear and travel out to the failing WT. Under these assumptions the MLDT from the service station to the WTs will be 7 h (1 + 12*0.5 = 7).

Yttre Stengrund and Östra Herrestad
Vattenfall has a service facility in Bergkvara 40 km south of Kalmar. The service facility was set up when Vattenfall built two of their first offshore wind farms, Yttre Stengrund and Utgrunden. The service personnel are transported out to the wind farms by boat. Under normal conditions it takes about 2 hours to load the boat and sail out to Yttre Stengrund. In Kalmarsund there are difficult sea conditions and it is difficult to moor at a WT when wind speeds are exceeding 9 m/s. This means that the service boat only can sail for about 75 percent of the time. Bergkvara service station is staffed 5 days a week, Monday-Friday, 9 hours per day. [25] The MLDT between Bergkvara and Yttre Stengrund is calculated in the same way as for Horns Rev. The mean waiting time for service personnel because of faults occurring during nights and weekends is 8,8 h ([5*15 + 2*24 / 7] / 2 = 8.8). There is also a 2.25 h (0.25*9 = 2.25) waiting time added for the possibility of harsh weather. Summing up the times above, the approximated MLDT between Bergkvara and Yttre-Stengrund is 12 h (2 + 8.8 + 2.25 = 12.05).

There are no station plans for the Östra Herrestad project. One possibility is that Östra Herrestad is supported by the service staff in Bergkvara who is also maintaining the same type of WT at Yttre Stengrund. There is a three hour drive between Bergkvara and Östra Herrestad. Considering this scenario the MLDT between Bergkvara and Östra Herrestad is approximated to 13 h (1 + 8.8 + 3 = 12.8). If Östra Herrestad instead were to be supported by a local Vattenfall station, close to the site, MLDT would be about 10 h (given the same work schedule and transportation time, including loading spare parts, of 1 h).

The current and future Vattenfall V80/90s and depots presented above, including the Vestas HQ in Randers, are shown in Figure 6.2 below.

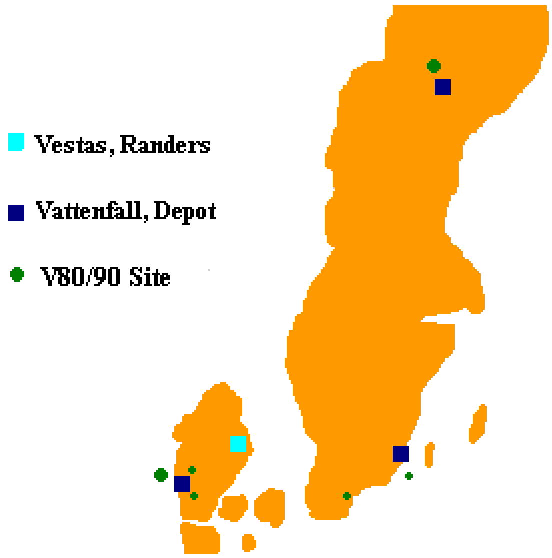

Figure 6.2: Vestas V80/90 and depot deployment

6.3.3 Service and maintenance

As most manufacturer, Vestas sell their WTs with a supplementary service contract. In 2005 Vattenfall procured Horns Rev offshore wind farm from Elsam A/S (now merged with Dong Energy). In 2007 the five-year service contract with Vestas ended and Vattenfall took over O&M for the wind farm and bought the warehouse in Esbjerg from Vestas, including all spare parts. Vattenfall service organisation is financed by both Dong Energy and Vattenfall. For service and maintenance Vattenfall has twelve technicians working full time, six persons in two shift teams, working every other week. Service personnel are also hired from Vestas to support the teams, three persons each week. The shift teams work twelve hours a day, seven days a week. That means if a WT for some reason stops during the night, e.g. because of an item failure, no one is there to reset or repair it. The crew has access to one boat, owned by Vattenfall, to get to the site from Esbjerg, renting another one when the preventive maintenance is done. The stock in Esbjerg is managed by one person, coordinating the Horns Rev service crew and providing them with equipment and spare parts. [28]

Service and maintenance for the two V80 in Tjæreborg Enge, is done by one of Vattenfall's service cars. At the moment, Vattenfall has no clear inventory policy in Denmark on how many of each spare to have in stock or when to reorder. For Horns Rev we have approximated current stock levels and reorder size from the inventory list. The initial stock level is set to the level achieved as the last orders arrived. The order quantity was set to the reorder size.

Bergkvara service station will maintain the five new turbines at Yttre Stengrund. In Bergkvara there are four service technicians supporting seven WTs at Utgrunden wind farm and five WTs at Yttre Stengrund wind farm. At the service station there is a site coordinator handling most item reorders and contracts with external firms. [25] Since Vattenfall already have a service station connected to the site the contract with Vestas will look a bit different.

Stor-Rotliden will be under a service contract the first years of operation. The plan though is to gradually incorporate Vattenfall's own service teams into the work at Stor-Rotliden, which is quite similar to the process taking place at Lillgrund wind farm. [26]

6.3.4 Preventive maintenance

The preventive maintenance for the V80s at Horns Rev is performed twice a year. A larger service are performed during the summer, were for example filters and a number of batteries are replaced. In January a smaller preventive maintenance is done, where some of the service tasks are repeated, like refilling grease. The large service takes three days per V80 and it is performed by a team of two technicians. The price for all items used at the larger service amount to roughly EUR 1500 per WT. A small service is approximated to include about two thirds of the tasks compared to a large service, taking two days and have a cost of EUR 1000. [28]

6.3.5 Item Data

The majority of item data are taken from interviews conducted in Esbjerg and an inventory list for Horns Rev. The V80s installed at Horns Rev were an very early type of V80 and therefore they have gone through some major changes over the years. The latest modification in progress is the exchange of all the pitch cylinders to a stronger and more reliable type. There is also a larger program where all gearboxes are being changed over a few years (a gearbox warranty from Vestas). As the gearboxes are changed the cooling system connected to the gearbox is also exchanged. One problem with the data taken from Horns Rev is that it is hard to generalise for more modern models of V80 and V90, because it is generally difficult to share items for WTs that are produced more than two years apart. [28]

When choosing which items to study closer for the V80s at Horns Rev we received an inventory list for the items in stock in Esbjerg. The inventory list includes information on price and quantity in stock. There is also information on items in stock that was left by Vestas. The list included the amount of individual items that have been used or received at the store. There are about 400 items listed and there is price information on half of them. From the items with price information there were 114 items with a price exceeding EUR 100.

From these 114 items 39 were picked out to be included in our study. A few more critical and expensive items, not included in the storage list, were also added to our study. These are gearboxes, generators, generator bearings and pitch accumulators, which make it a total of 43 items selected for analysis. Appendix B presents a list of all items included and their characteristics. The following parts will explain more closely how Appendix B was created.

Item failure rates

The V80s running on Horns Rev are nine years old. After nine years of operation the early problems are gone and the WTs at Horns Rev should be somewhere in the middle of the so called bath tub curve for the failure distribution. To estimate failure rates for items we have looked in the inventory list, were every item that have been taken out from the storage have been logged. The list we received contained information for 12 months of operation representing approximately 700,800 operating hours for the V80s at Horns Rev. First we calculated the yearly demand by counting the number of each item taken out of the stock. These demand rates were then recalculated to a failure rate corresponding to OPUS10 format.

Item Prices

Information on item price was retrieved from the inventory list. For items not included in the list the price were approximated by the Horns Rev stock manager. Although we had the exact price for most items we grouped these data as well.

Item types
To classify items as repairable or discardable we took help of the service team manager at Horns Rev. Out of the 43 items chosen for analysis, 6 could often be repaired while the rest were discarded after been replaced at the WT. For repairable items we also got estimations on repair times (TAT) and lead times for the discardable items. TAT was about 16 weeks for the gearbox and generator, and 8 weeks for the rest. The standard lead time was 1 week, while blades and transformers were a bit harder to get, with lead times of 8 and 16 hours respectively. [28]

Item replacement
During the information on item replacement times for the items we have chosen to look at, i.e. rough estimates of the MTTR. Most small items, mainly electrical, are changed in half a day. Larger mechanical items like motors and pumps are changed in a day or two. Very large items, e.g. a gearbox or smaller items affecting the whole drive train, e.g. drive train bearings are exchanged in approximately a week. [28]

7 OPUS10 Analysis and Results

7.1 Outline of the analysis

OPUS10 analyses have been performed in one pre-study and on nine cases, including some sensitivity analysis. A fixed scenario including a number of WTs that are supported by a predefined support organisation constitutes a case. Support organisation structure and WT deployment are based on the information presented in Chapter 6. The pre-study and case one to five concerns V80/90 turbines and the results for these analyses are presented in section 7.3. The results from SWT-2.3 cases, six to eight, are presented in section 7.4. The last and ninth case is based on V80 data from Horns Rev the number of WTs operating is varied.

- Pre-study: Horns Rev – Grouped data vs. Exact data

- Case 1: Horns Rev – Optimal stock
- Case 2: Horns Rev – Existing stock analysis
- Case 3: Future V80/90 support organisation – Only local depots
- Case 4: Future V80/90 support organisation – Central depot
- Case 5: Future V80/90 item repairs vs. original data

- Case 6: Lillgrund – Optimal Stock
- Case 7: Future SWT-2.3 support organisation – Only local depots
- Case 8: Future SWT-2.3 support organisation – Central depot

- Case 9: Scaling of a wind power system

The purpose of the pre-study was to ensure that our item classification method were adequate. In the pre-study results from OPUS10 optimization with grouped data and "exact" data (which we had on item prices and failure rates for the V80s at Horns Rev) were compared. We then began by optimizing the spare part stock for Horns Rev only, using the *Initial procurement* problem type. To evaluate the potential of improvement, the results were compared with those from Case 2, where we reviewed the existing Vattenfall spare part stock for Horns Rev. To do this we used the OPUS10 *Analysis* problem type. For the rest of the cases (including the SWT-2.3 cases below) we used *Initial procurement* problem type, since there were no existing stocks to analyse. Case 3 and 4, as well as Case 7 and 8, are future scenarios and the results are compared to evaluate the differences in cost-efficiency for the two support organisation structures. For all cases the OPUS10 *Steady-state* scenario have been used, which means that all model parameters are constant over the whole scenario length (i.e. the WT lifetime).

The *optimal spare part allocation*, given a certain LSC and availability are showed in the C/E-curve calculated by OPUS10. By approximating the revenue for different availabilities, the lifetime profit can be calculated and the *optimal availability* can be found. The most cost-effective spare part strategy giving this availability can then be shown from the OPUS10 results, including allocation, initial acquisition and reordering. For the future support organisation cases we have compared the results to find out how they differ regarding cost-efficiency.

7.2 Assumptions and model conditions

In our OPUS10 models of the support organisations for Vattenfall's Vestas V80/90 and Siemens SWT-2.3 we have used some universal parameters for all scenarios. These model parameters have been used in all cases and can be seen as *basic model conditions*. Three of these parameters are defined as *global parameters* in OPUS10; *interest rate*, *scenario length* and *man-hour cost*. The interest rate and man-hour cost have been set to Vattenfall's standards regarding cost of capital and cost per man-hour. For the scenario length we have used the wind power industry standard for wind turbine operational lifetime. [30]

- Interest rate: 7 percent
- Scenario length: 20 years
- Man-hour cost: EUR 50

The item *reorder cost* and the *storage cost* have also been set as the same value for all of our scenarios. These parameters have been estimated with the help of senior consultants at Vattenfall Power Consultant and Systecon. The storage cost is divided in a fixed cost per item and a cost per item value (a percentage of the value). A cost per item is included in the model to prevent from investing in too many cheap items. It can be seen as a fixed cost for managing each item in stock. The storage cost is specified for each depot in OPUS10 and we have used the same values for all depots modelled. The *repair cost* for repairable items, given as a percentage of the item value, is also the same for all items in both the V80/90 and SWT-2.3 cases.

- Reorder cost (DU): EUR 400
- Repair cost (LRU): 30 percent of item price
- Storage cost per item: EUR 100
- Storage cost per value: 10 percent of item price

A common "rule of thumb" for repair costs is 30 percent of the item price. This is probably a fair estimate for expensive items (with a price exceeding EUR 1000), which all of our LRUs are. We have not included any transportation costs or costs for various resources (such as crane ship for changing main components like gearbox and generator). This has of course affected the total LSC, but these model parameters do not influence the OPUS10 spare part optimization in any way.

7.2.1 Wind turbine profitability

When we are to find the optimal spare part strategy we will look for the most profitable availability, were the revenue are as high as possible compared to the corresponding LSC. For a given availability level, *A*, an approximated lifetime revenue are computed with the formula below.

$$\text{Revenue(A)} = \text{A} \cdot RP \cdot T \cdot c_f \cdot I \cdot NVP \tag{7.1}$$

RP is the rated power (in kW), *T* is 8760 h, c_f is the target capacity factor and *I* the revenue per produced kWh. The capacity factor, according to industry standards, is 0.25 for onshore wind farms and 0.3 for offshore wind farms. [30] In the revenue calculations a capacity factor of 0.3 has been used for all WT locations. We use this approach since our tests showed that the optimal availabilities were not changed when varying the capacity factor between 0.25 and 0.3. The revenue per produced kWh is Vattenfall's approximation, set to 0.09 EUR/kWh. *NPV*, the net present value factor is 10.59 when the time horizon (scenario length) is 20 years and the interest rate is 7 percent. The lifetime profit is then calculated by subtracting LSC for the same availability level, *A* (given by OPUS10). The annual profit and annual support cost is given by dividing with the net present value factor.

$$\text{Profit(A)} = \text{Revenue(A)} - \text{LSC(A)} \tag{7.2}$$

$$\text{Annual Profit} = \frac{\text{Profit}}{\text{NPV}} \tag{7.3}$$

$$\text{Annual Support Costs} = \frac{\text{LSC}}{\text{NPV}} \tag{7.4}$$

7.3 Results from Vestas V80/90 cases

Since Horns Rev was the foundation to our study of Vestas V80 and V90 turbines, the first analysis was focused on the current support organisation for Horns Rev. After the analysis of the current situation at Horns Rev a future support organisation scenario was modelled and optimal spare part strategies calculated. The future scenario includes the existing V80s in Denmark and upcoming V80 and V90 projects in Sweden and Denmark. The spare part input data for these cases are shown in Appendix B.

7.3.1 Pre-study

For Horns Rev we had exact data on both item prices and failure rates, i.e. ungrouped data directly retrieved from the inventory list (from where we got the spare part demand recalculated to failure rates). This exact data is not presented in this thesis due to confidentiality requirements from Vattenfall. As a first OPUS10 analysis we compared the results from optimizing with the ungrouped data and the grouped data (used for the rest of our analysis). The results supported the previous research on the robustness of OPUS10, described in section 5.4. There were very small differences in the results from the two cases. As seen in Figure 7.1 there is only a marginal difference between the two C/E-curves, representing the two cases. Furthermore the results are probably overshadowed by the uncertainties in the data collected, especially regarding item failure rates.

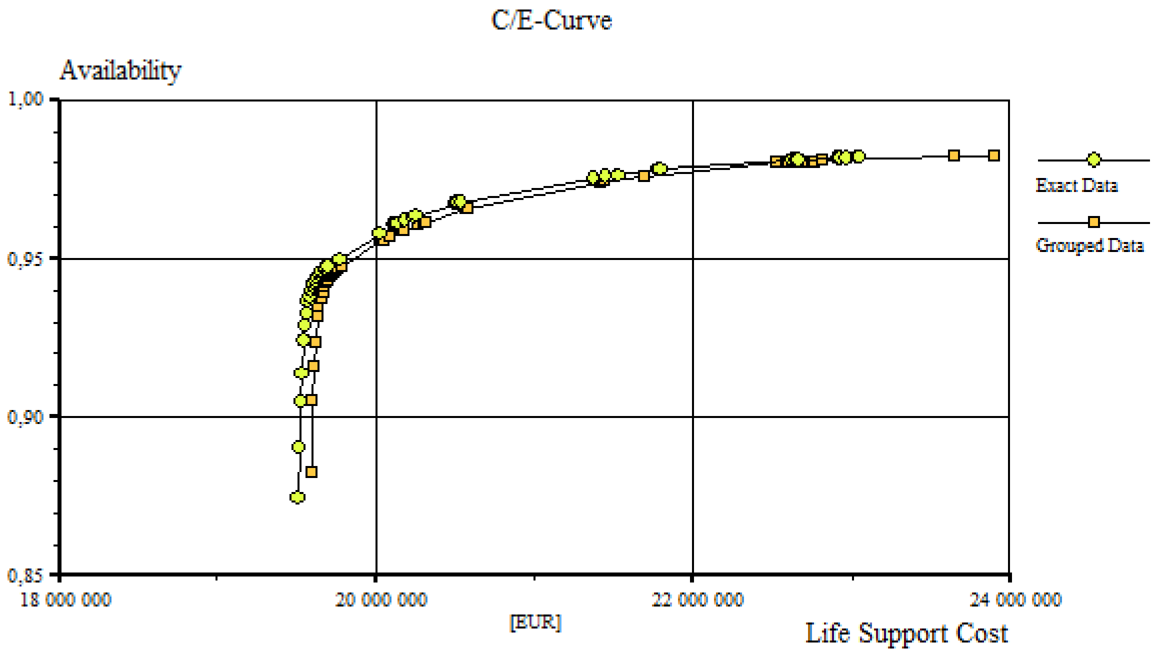

Figure 7.1: C/E-curves for OPUS10 optimization using ungrouped data and grouped data

7.3.2 Horns Rev

For the Horns Rev cases we have used a simple support organisation structure with one workshop in Randers, Denmark, were LRUs are repaired. All spare parts are stored in a depot in Esbjerg, from where all DUs are reordered. The 80 Vestas V80-2.0 are connected to an operating station, Horns Rev. In Figure 7.2 below the structure is shown, including MLDT between the stations.

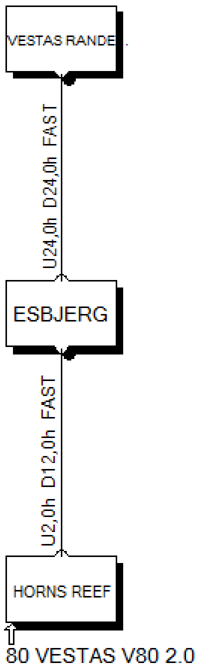

Figure 7.2: Horns Rev support organisation structure (U stands for "up" and D stand for "down")

There are some interesting OPUS10 results not depending on the spare part strategy, but input data on for example item failure rates. The number of LRUs repaired and DUs consumed over a year are shown in Appendix I. WT failures, repair/replacement times (MTTR) and preventive maintenance also results in an *inherent availability* that is independent on the investments in spare parts. With the model used in Case 1 and Case 2 this maximum availability is 98.66 percent.

Case 1 – Baseline optimization

Figure 7.4 shows the C/E-curve for Horns Rev spare part stock computed by OPUS10. By calculating the profits for each value on availability where LSC was given an optimal spare part strategy could be found. Figure 7.3 shows how the profit changes for different availability levels.

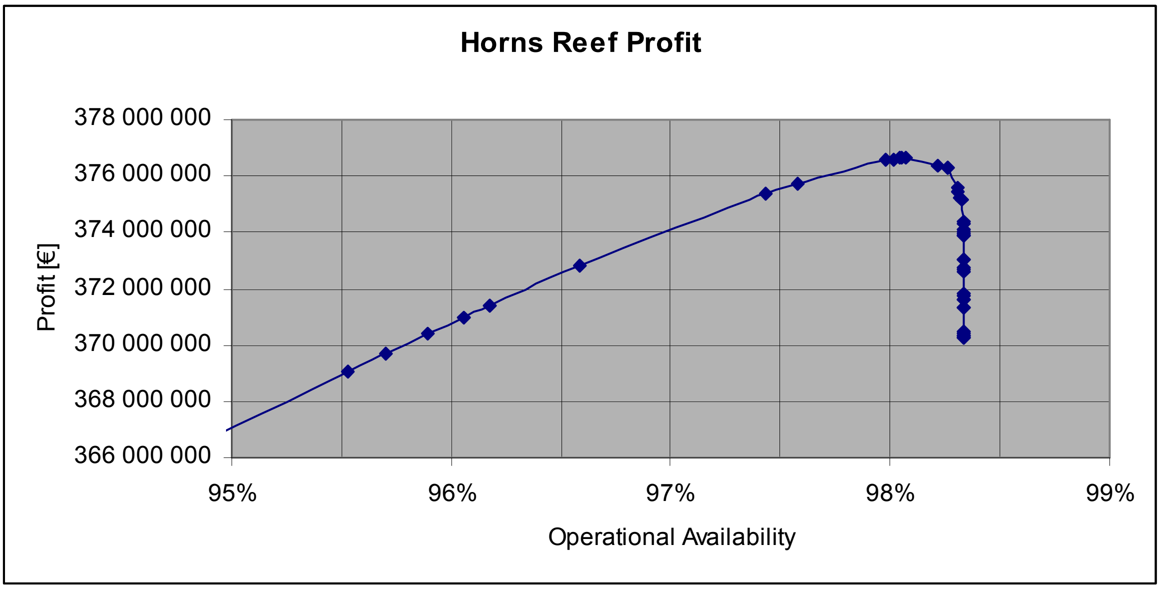

Figure 7.3: Approximated profit for different availabilities at Hors Rev (over 20 years)

The maximum calculated profit was EUR 376.7 million over 20 years, which is achieved with the spare part strategy that generates an operational availability of 98.05 percent. For this optimal strategy the calculated LSC is EUR 22.7 million. For a higher availability levels the profit decreases, because LSC gets too high. The optimal strategy (point) is circumscribed in the C/E-curve figure below. To increase the availability even more it requires investments in additional expensive spare parts, for example in another gearbox. The optimal spare part strategy, including initial investments (optimal stock size) and reorder points for DUs are shown in Appendix D.

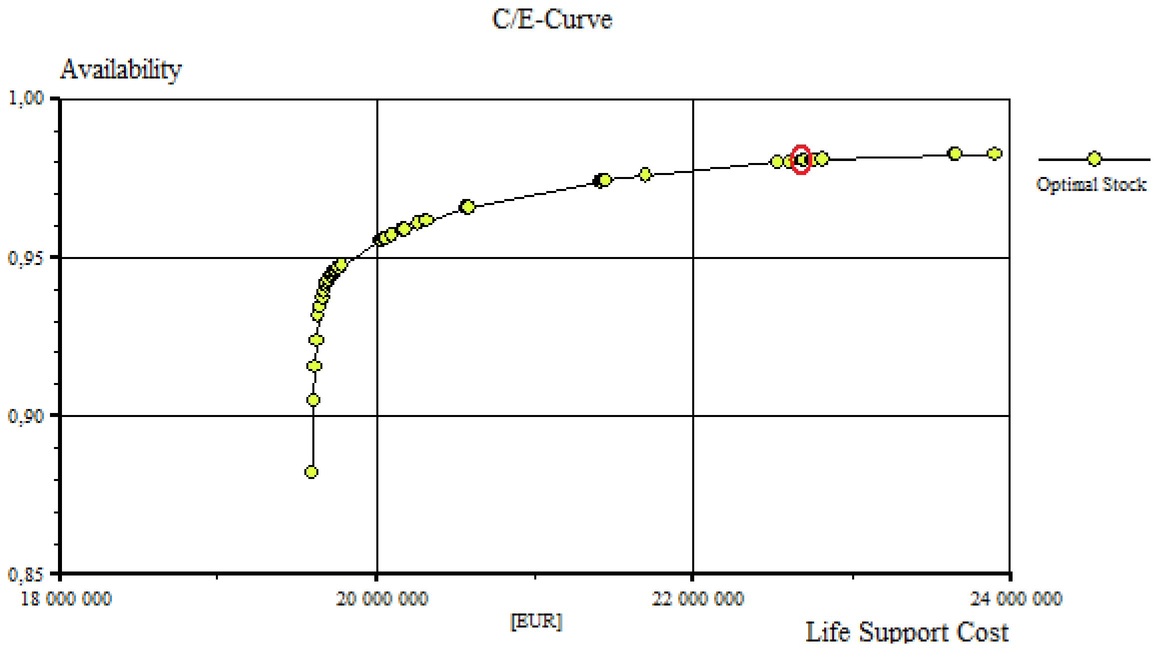

Figure 7.4: OPUS10 C/E-curve; optimal spare part strategy for Horns Rev

Apart from operational availability, other *measure of effectiveness* (MoE) can be of interest when evaluating spare part strategies. Some of these were described in Chapter 4. The C/E-curve can for example show *Risk of shortage* (ROS) with respect to LSC. This is illustrated in Figure 7.5. The most important MoE values for this optimal spare part strategy are presented in Table 7.1.

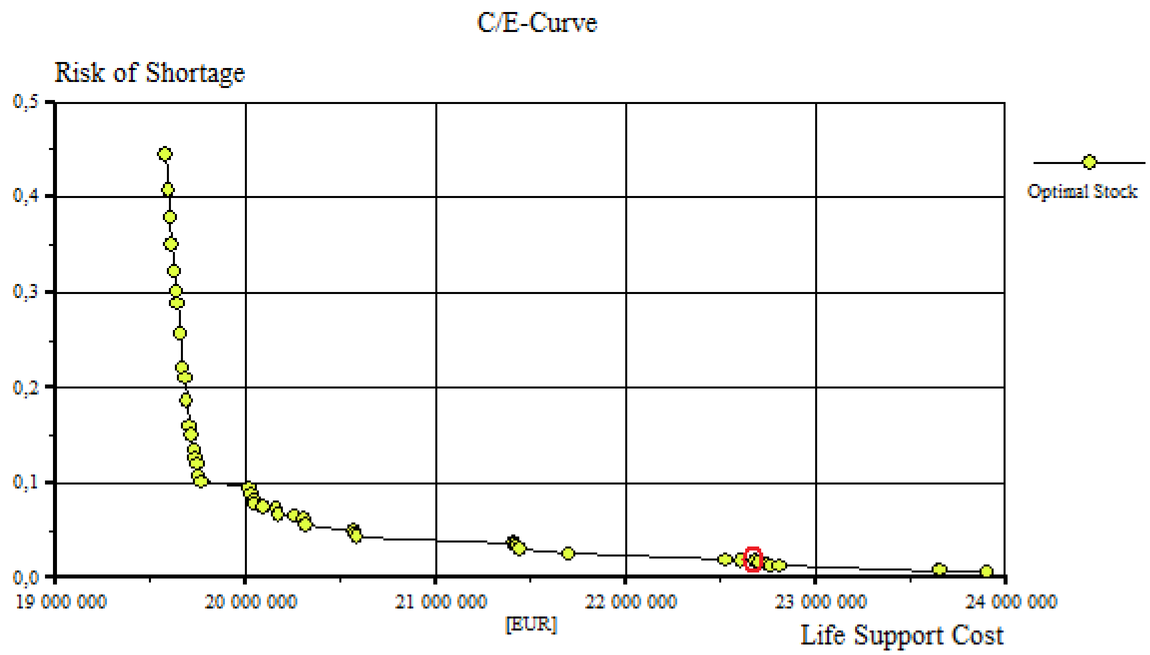

Figure 7.5: Risk of shortage for cost-efficient spare part strategies at Horns Rev

Table 7.1: Measures of effectiveness for optimal spare part strategy for Horns Rev

	Number of system not operational ready (NOR)	***Mean Down Time (MDT)***	***Risk of Shortage (ROS)***	***Mean Waiting Time (MWT)***
Horns Rev Optimal	1.56	39.48	0.016	10.91

The value of NOR means that on average 1.56 WTs at Horns Rev will be down due to corrective or preventive maintenance. The mean downtime is 39.48 h. ROS states that given a demand for a certain spare part there is on average a 1.6 percent probability that the spare is not in stock. If the spare is not in stock the mean waiting time is then 685.7 h. The overall mean waiting time for spare parts (MWT) is 10.91 h.

Case 2 – Analysis of the current spare part strategy

For the analysis of the existing spare part strategy for Horns Rev input data needed were stock sizes (nominal) for all items and reorder points for DUs. These parameters where estimated from the information on the inventory list for Horns Rev. The current stock sizes were presented and by investigating the reorder strategy and if spare parts were recently taken from the stock we approximated the “real” stock sizes. And by looking at the average reorder sizes we got a rough estimation of the reorder points (which often are not that fixed in real life). The existing spare part strategy for Horns Rev, used for the OPUS10 analysis, is shown in Appendix E. All other input data were the same as for case 1, including TAT for LRU and lead time for DU. When running the case in OPUS10 the following C/E-point were calculated, in Figure 7.6 compared with a segment of the C/E-curve from Case 1.

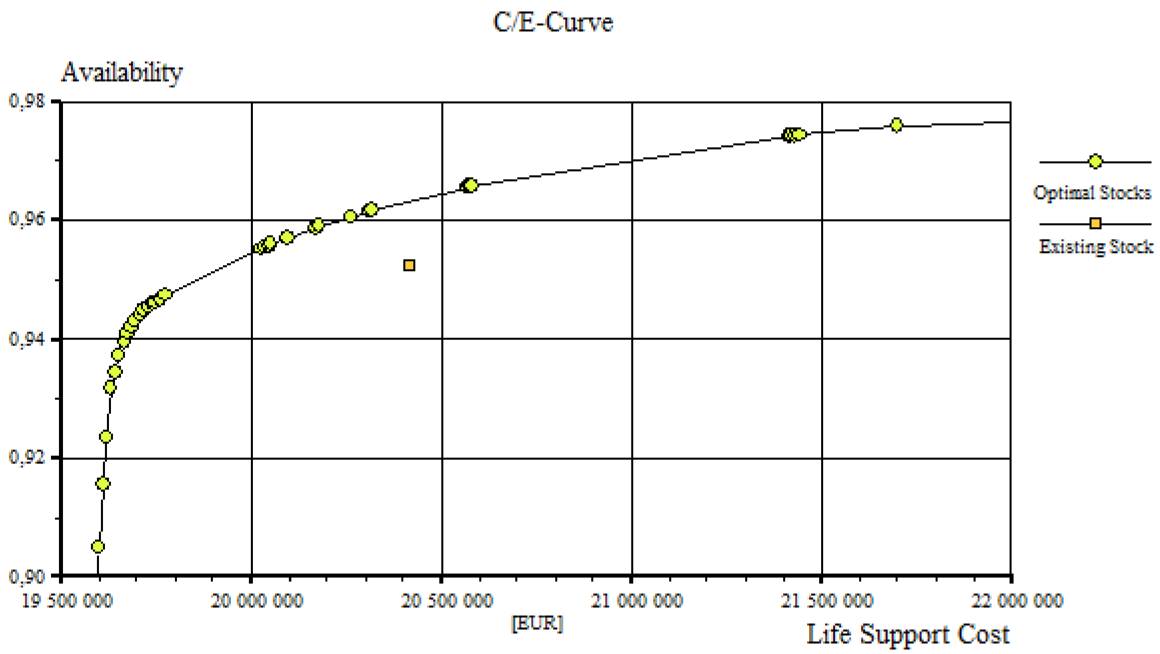

Figure 7.6: The existing spare part strategy for Horns Rev compared with a part of the C/E-curve calculated by OPUS10

The operational availability with the existing strategy is only 95.24 percent, with a calculated LSC of EUR 20.4 million over 20 years. The lifetime profit generated with the existing strategy will be EUR 9.2 million less than with the optimal spare part strategy (a decrease with 2.4 percent). The main economic results from Case 1 and Case 2 are shown in Table 7.2 below, recalculated to annual cost and profit.

Table 7.2: Main economic results from Case 1 and Case 2

	Availability	***Annual Support Cost***	***Annual Profit***	***Annual Production***	***Cost/MWh***	***Profit/MWh***
		M EUR	*M EUR*	*MWh/year*	*EUR*	*EUR*
Optimal strategy	98.05%	2.11	35.00	412 300	5.1	84.9
Existing strategy	95.24%	1.90	34.15	400 500	4.7	85.3
Difference	3%	0.21	0.85	11 800	0.4	-0.4

The key performance indicators (KPI) Cost/MWh and Profit/MWh are lower with the existing strategy. These measurements are in some way describing the cost/profit-efficiency for electricity production. However, with a better strategy a higher operational availability can be achieved and generate more revenue for a minor increase in support costs, hence result in a higher profit. In that sense these KPIs does not give a good indication of the efficiency of a specific spare part strategy.

Moreover, the total annual support costs shown in the table above are to a large extent clouded by costs not affected by the spare part strategy. For example corrective maintenance costs, such as man-hour cost for item replacements and LRU repair costs, and also preventive maintenance costs. These costs represent about 95 percent of the total LSC. Cost elements that from a spare part strategy point of view are interesting, are primarily item investments (capital costs), reorder costs and storage costs. If a point on the C/E-curve with availability around 95.3 percent (another cost-efficient spare part strategy) is chosen, the LSC cost elements can be compared with those for the existing strategy. The results are shown in Figure 7.7, where the cost elements are recalculated to annual support costs. The strategy for this cost-efficient point (20) is shown in Appendix F, and gives an availability of 95.53 percent, slightly higher than the existing strategy.

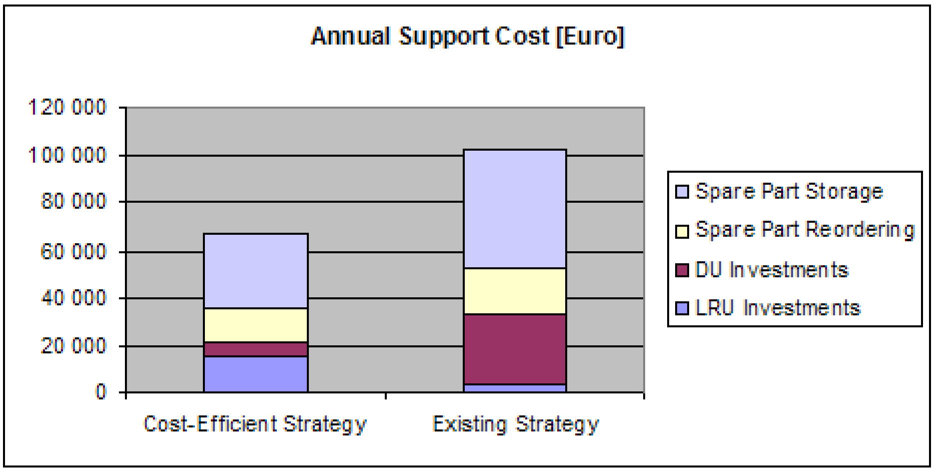

Figure 7.7: Comparison of annual support cost elements for a cost-efficient spare part strategy calculated by OPUS10 (availability 95.53 percent, not the most profitable) and the "existing strategy at Horns Rev

To start with, the higher availability, about 0.3 percentage points above the existing strategy, and a EUR 0.4 million lower LSC gives roughly EUR 1.6 million more in profit over 20 years. By looking at the cost elements in Figure 7.7 we can see that there are major differences between the two strategies. The initial investments in repairable and discardable spare parts differ a lot. The cost-efficient strategy also reduces the reordering costs by almost 30 percent and the storage costs by over 35 percent. To show some of the differences in stock size and reorder point for some specific spare parts, a selection from Appendix E and F are presented in Table 7.3 below.

Table 7.3: Stock size and reorder point for some V80 spare parts with a cost-efficient OPUS10 strategy (availability 95.53 percent, not the most profitable) compared to the existing strategy at Horns Rev

	Cost-efficient strategy		**Existing strategy**	
Spare part	*Stock size*	*Reorder point*	*Stock size*	*Reorder point*
Proportional Valve	3	0	4	2
Encoder	4	0	6	1
Generator Bearing	1	-1	0	-1
Yaw Motor	2	-1	1	0
TRU card	2	0	2	1
Transformer	0	-1	1	0

When the reorder point is set to (-1) it means that new spare parts are not ordered until a backorder occurs, i.e. when an item fails and there is no spare of that item in stock. One major difference between the two reorder strategies is that the OPUS10 strategy does not need any safety stock in order to reach an availability of 95 percent. That is, new spare parts are only ordered when the stock is empty or there is a backorder (this goes for all spare parts, see Appendix F). Together with the lower stock sizes using this strategy the average stock is much lower, resulting in money saved in storage costs. Comparing *generator bearing* and *transformer* in the table above, the two strategies differ from one another. Although transformers have a higher failure rate (group 2) than generator bearings it is more cost-efficient to have one bearing in stock than one transformer. Even though the lead time for a transformer is 8 weeks compared to 1 week for the bearings. This is because of the large difference in price (see Appendix B), resulting in a much higher storage cost for having a transformer in stock.

In Case 2 we modelled the existing stock with no gearboxes or generators. We know that these two items have long TAT and that by adding them to the “existing stock” the availability will increase (as the LSC). Therefore we did some extra analyses of an existing Horns Rev stock, were we added one, two and three gearboxes and generators (of each). The results are shown in Appendix L, were the new points are compared with the C/E curve from Case 1. As expected the operational availability increased a lot which resulted in a higher profit. For the cases with two or three gearboxes and generators the profit were only EUR 1.5 million lower (about 0.6 percent) than for the optimal spare part strategy.

7.3.3 Future V80/90 support organisation

The future Vestas V80/90 cases represent two different support organisation structures, for all the 141 future V80/90. Like the Horns Rev cases all faulty LRUs are assumed to be sent to a Vestas workshop in Randers for repair. In Case 3, operating stations (i.e. V80 and V90 wind farms) are supported by local depots, from where DUs are reordered and LRUs are stored. In Case 4 we instead have a central depot in Esbjerg, reordering new DUs for all V80-V90 operating stations. The central depot is placed in Esbjerg because the vast majority of the Vestas 2 MW WTs are located at Horns Rev. It is also a reasonable scenario since the wind power service station in Esbjerg is Vattenfall's largest and is located relative close to Randers and other Vestas production sites. In our OPUS10 case the central depot is supplying local depots in Stor-Rotliden and Bergkvara, supporting the operating stations. In Case 5 we have changed item types to include more LRUs in the model, mostly to investigate the economic effects of more faulty items being repaired.

The inherent availability for all these cases, given by the item failure rates, MTTR and preventive maintenance is 98.66 percent, the same as for Case 1 and 2 (because this availability is independent of the support organisation and the logistic structure). The average number of LRUs being repaired and DUs reordered over a year is presented in Appendix J (for Case 3 and 4). The numbers are the same in Case 5 but with the new LRUs being repaired instead of reordered. Naturally the increased repair/reorder volumes from Case 1 and 2 are proportional to the extended number of WTs.

Case 3 – Local spare part storage and handling

The support structure used in this OPUS10 case is presented in Figure 7.8 below. The depots are on the second echelon-level. MLDT between the stations are also shown in the figure.

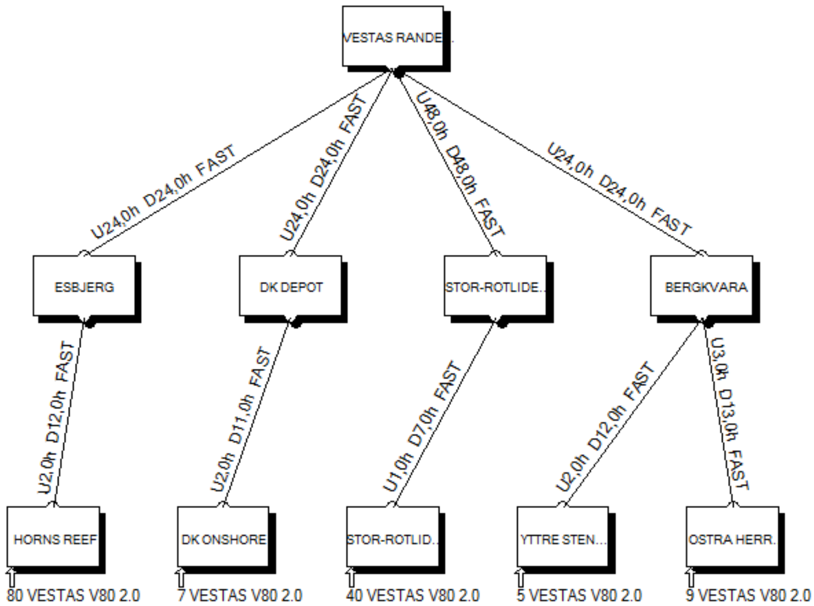

Figure 7.8: V80 and V90 support organisation structure with local depots. (U stands for "up" and D stand for "down")

From the OPUS10 C/E-curve for this case the most profitable spare part strategy where found, with operational availability on 97.78 percent and LSC of EUR 41 million. The optimal spare part allocation is shown in Appendix G (not including reorder points for all the depots). In the optimal solution the large wind farms, Stor-Rotliden and Horns Rev, are prioritised and have an operational availability around 98 percent, while the others are below 97 percent. This is illustrated in Table 7.4 below. The C/E-curve, main results and annual support cost elements for this case are compared with Case 4, in Figure 7.10, Table 7.8 and Figure 7.11, respectively.

Table 7.4: Optimal Availability levels for the operating stations in Case 3

Operating Stations	***No. WTs***	***Availability***
Stor-Rotliden	40	97.98%
Horns Rev	80	98.05%
Östra Herrestad	9	96.76%
Denmark Onshore	7	96.16%
Yttre Stengrund	5	96.11%
Total for all Systems	141	97.78%

Case 4 – Central reordering and spare parts pooling

In this case we have used a model with pooling of spare parts between some of the stations. First of there is a central depot in Esbjerg from where all spare parts are reordered. The Esbjerg stock is supporting both Horns Rev and Danish onshore wind farms, while supplying two depots in Sweden with spare parts when needed. One of the Swedish depots is placed in Stor-Rotliden while the service station in Bergkvara is used to support both Yttre-Stengrund and Östra Herrestad. The support organisation structure is illustrated in Figure 7.9 below, including MLDT between stations.

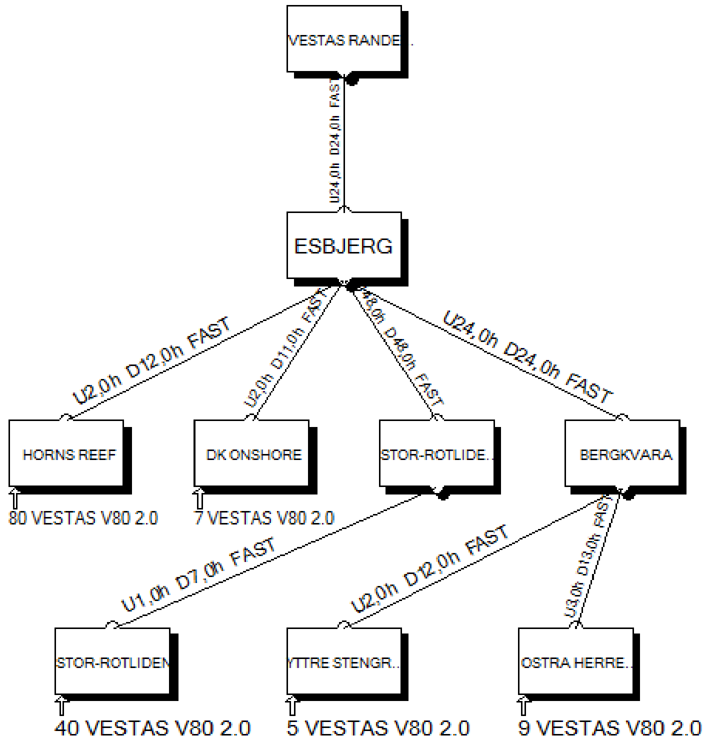

Figure 7.9: V80/90 support organisation structure with a central depot and pooling of spare parts between wind farms. (U stands for "up" in the hierarchy and D stand for "down" in the hierarchy)

The OPUS10 optimization for this support model generated the C/E-curve shown in Figure 7.10 below, compared with the curve from Case 3, with the optimal points circumscribed. It is clear that the strategy used in Case 4, with a central depot including central reordering and pooling of spare parts between WT sites, is better from a cost perspective than local handling only.

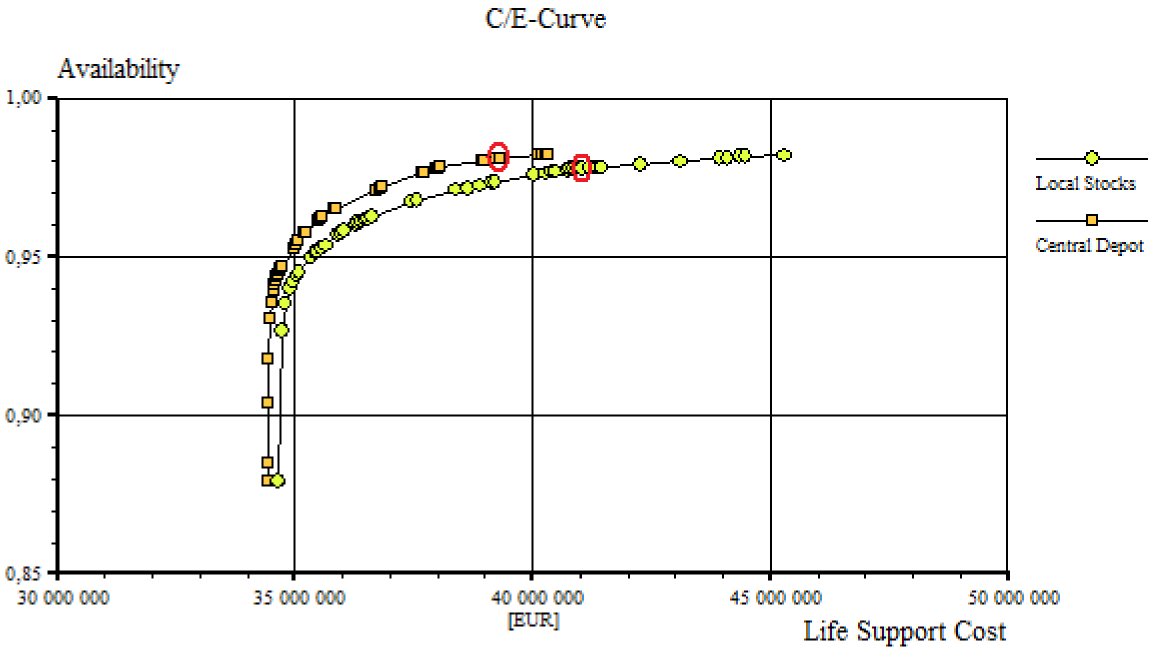

Figure 7.10: OPUS10 C/E-curves for future V80/90 support organisations

The most profitable availability level for this case was 98.12 percent, which resulted in a profit of EUR 666.5 million, about 0.6 percent higher than Case 3. The optimal availability for each station is presented in Table 7.5. Main economic results for the two cases are shown in Table 7.8 below. In Table 7.9 we have compared the LSC cost elements of interest regarding spare part optimization, presented as annual costs. As in Case 1 and 2 the item consumption, corrective maintenance and preventive maintenance costs are the same in both cases.

Table 7.5: Optimal availability levels for Case 4

Operating Stations	***No. WTs***	***Availability***
Stor-Rotliden	40	98.17%
Denmark Onshore	7	98.13%
Horns Rev	80	98.10%
Yttre Stengrund	5	98.05%
Östra Herrestad	9	98.02%
Total for all Systems	141	98.21%

In this case the availabilities for each operating station are almost identical. When wind farms share spare parts, in this model in Esbjerg and Bergkvara, prioritisation is not needed.

Table 7.6: Main economic results from Case 3 and Case 4

	Availability	***Annual Support Cost***	***Annual Profit***	**Annual Production**	**Cost/MWh**	**Profit/MWh**
		M EUR	*M EUR*	*GWh/year*	*EUR*	*EUR*
Only local	97.78%	3.81	61.41	724.7	5.26	912.0
Central depot	98.12%	3.65	61.79	727.1	5.02	914.6
Difference	0.35%	-0.16	0.38	2.6	-0.24	2.6

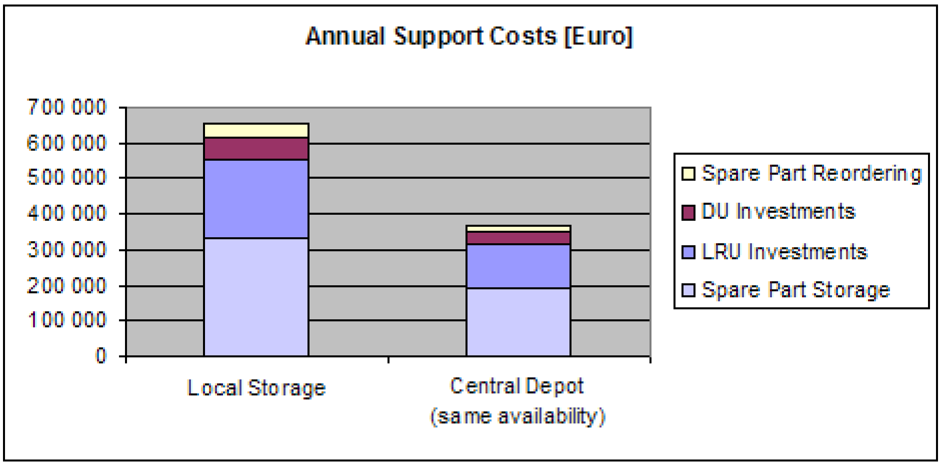

Figure 7.11: Comparison of annual support cost elements for future V80/90 support organisation with only local depots and with central depot

The investments in spare parts, recalculated to an annual capital cost, are 30 percent higher with local stocks. When looking at the annual recurring costs, reordering and storage of spare parts is a lot higher with local stocks, 72 percent and 33 percent respectively. It is clear that pooling spares between the V80/90 wind farms and using a central depot for reordering is a much more cost-efficient support organisation. Overall less spares are needed in the depots with an average total stock size of 212.95 items compared to 336.10 items with local stocks. The optimal strategy in Appendix H also shows that the central depot in Esbjerg is used for storage of strategic and expensive items such as blades, gearboxes and generators. This can be compared with the optimal strategy for Case 3 (see Appendix G), were more of these expensive items are needed, distributed between the largest wind farms (illustrated in Table 7.7).

Table 7.7: Strategic and expensive spares allocation in Case 4 compared to Case 3

	Central depot			**Local depots**				
Spare part (allocation)	*Esbjerg*	*Stor-Rotliden*	*Bergkvara*	*Esbjerg*	*DK Depot*	*Stor-Rotliden*	*Bergkvara*	*OH Depot*
Blade	2	0	0	2	0	1	0	1
Gearbox	3	0	0	2	0	1	0	0
Generator	5	0	0	3	1	2	1	1

As for Case 1 we will present some other MoEs of interest for this Case, apart from the operational availability (Table 7.8). This is done to illustrate the differences when including more WTs and expanding the support organisation.

Table 7.8: Measure of effectiveness for optimal spare part strategy for future V80/90

	Number of system not operational ready (NOR)	***Mean Down Time (MDT)***	***Risk of Shortage (ROS)***	***Mean Waiting Time (MWT)***
Future V80/90 support organisation	2.66	38.06	0.038	20.31

The value of NOR implies that with this many V80/90s 2.66 will on average be down and not operational. MDT is about the same as in Case 1, almost 40 h. ROS have more than doubled resulting in a overall MWT of 20.31 h (which is different for the depots depending on the stock allocation, e.g. MWT in Esbjerg is 8.85 h) compared to 10.91 h in Case 1. The mean waiting time for spare parts, given a shortage, is 534.5 h.

Case 5 – Increased repair capability

This case was done to test the effect of changing item types (LRU/DU). It is obvious that there is a given set of repairable items (or at least partly repairable depending on the failure mode) in a WT. However, in our model only a couple of items are classified as LRU (as a result of information gathered from our field studies), but we have reason to believe more spares could be repaired in the future (when the supply of new items might be lower and demand for spares are higher). When a lot of new WTs and WT parts are in production, the prices of new items are relatively cheap, compared to repairing old items. This is probably why most faulty items are discarded today, independent of the failure mode. [31]

The new item types are shown in Appendix K. We have chosen only to include items which price exceeds EUR 1000, because it is probably not cost-effective to repair less expensive items. The support organisation model used for analysis and comparison is the one from Case 4, with the central depot in Esbjerg. The new C/E-curve generated by OPUS10 is shown in Figure 7.12, together with the original C/E-curve.

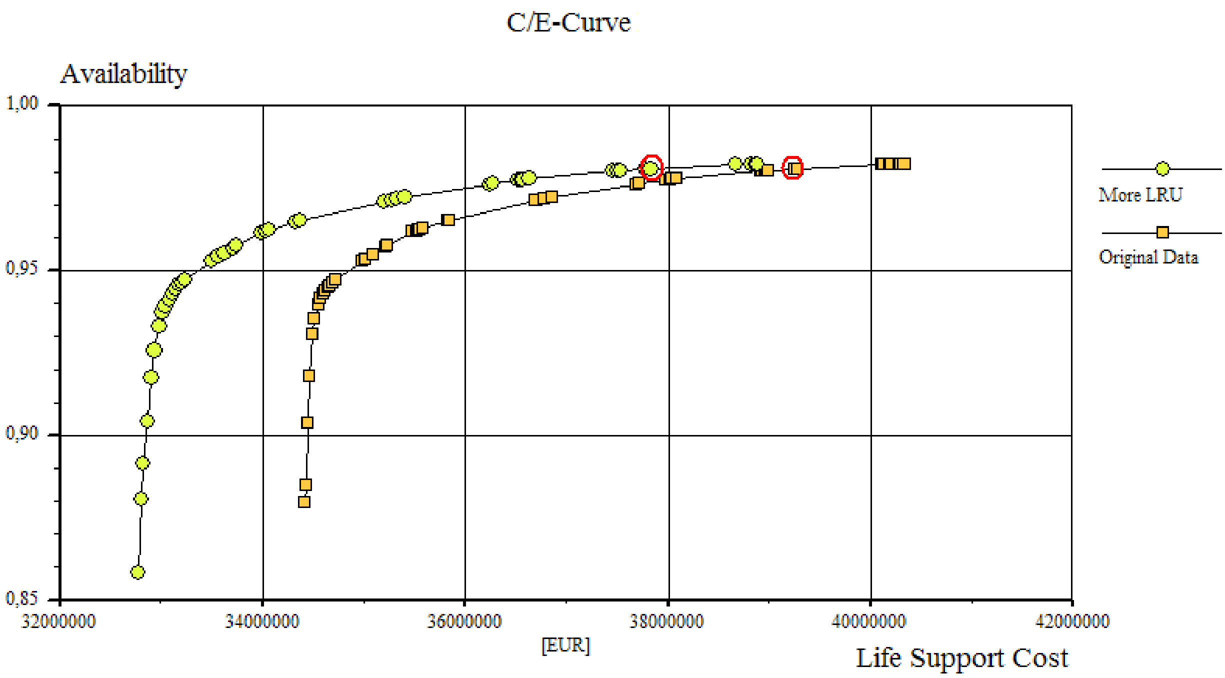

Figure 7.12: OPUS10 C/E-curves; More LRUs vs. original data

The result shows that the optimal spare part strategy with the new model is more cost-efficient than using original data. The most profitable availability is about the same but the LSC is EUR 1.5 million lower. The repair volumes have increased to 167.30 items per year on average compared to 76.27 items per year with the original data setup.

7.3.4 Sensitivity analysis for V80/90 models

Sensitivity analyses have been done primarily to measure the effect uncertain parameters in the model have on the optimal strategy. When applying a spare part strategy generated by OPUS10, with the input data used in our models, it is of interest to calculate the loss of profit if a model parameter is changed, say twice the original value. The sensitivity analyses have exclusively been done on the model used in Case 1.

In Chapter 4 we illustrated a simple classification method for grouping model parameters. The most uncertain parameters that probably also has a very big effect on the result are the item failure rates, because of our method to collect these data and the fact that there are almost no previous research on the subject. One year of data (which we used) is most certainly not enough to get an accurate estimate of the true mean value. However, not all spare parts will have a great impact on the optimal strategy, especially not when calculating the loss of profit. In OPUS10 there is a result table showing a cost-driver index (CDIX) for the items, which is a product of the item price and repair actions per year (failures). Items with a higher value will have a greater impact on the optimization and moreover, on the final profit. Figure 7.13 shows a logarithmic plot of the spare parts grouped by their CDIX.

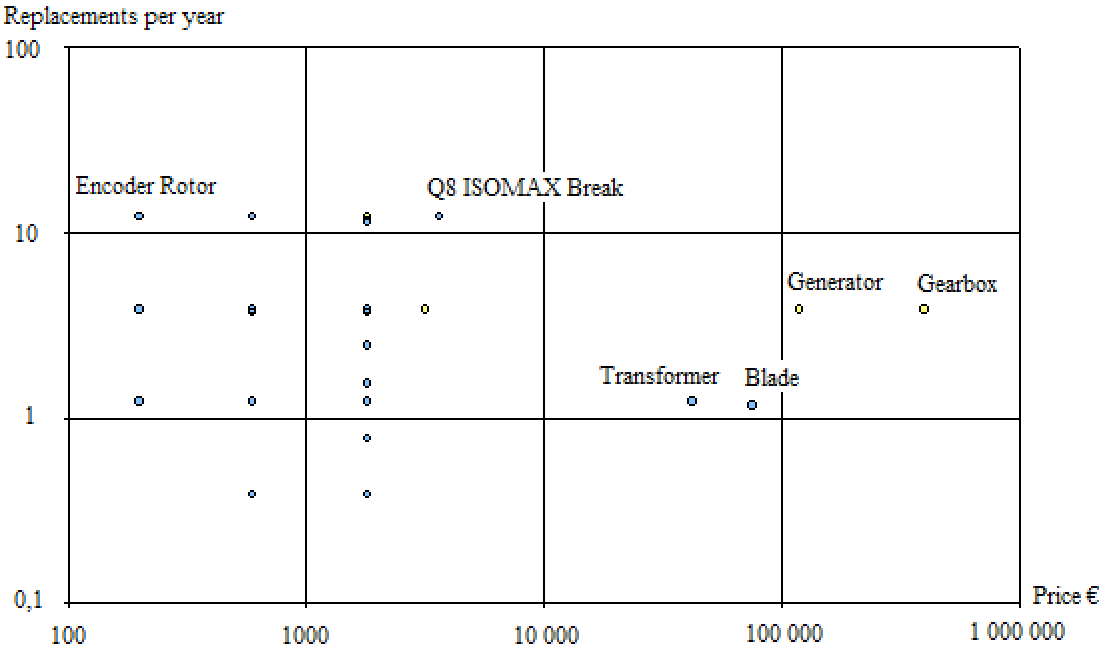

Figure 7.13: Spare part cost-driver plot (for Case 1)

CDIX for all spare parts are shown in Appendix M. The most cost-driving spare parts are the gearbox, generator, blades and transformer, in that order, which are all very expensive. An interesting note is that the Encoder Rotor (for the generator), which is one of the cheapest items, has a relatively high CDIX value, caused by the very high failure rate. We started out the analysis by testing the effect of doubled and halved failure rates for the gearbox and the generator, separately. To calculate the loss of profit we have used the OPUS10 *Analysis* problem type with the optimal spare part strategy (from Case 1) as input data.

Item failure rates

When changing the failure rate of the gearbox to 10.96 (doubled) and to 2.76 (halved) failures per million hours of operation the economic effects by using the original spare part strategy compared to a *new* optimal strategy (considering the new data) is shown in Table 7.9. The same changes have been done for the generator with the results presented in the same table. We also analysed the effect of doubled failure rate for two other items, the transformer and Q8 ISOMAX Break. Halved failure rate for these items had too small effect on the profit and are therefore not presented in the table.

Table 7.9: Results from Sensitivity analysis of the failure rate for some cost-driving spare parts

	Gearbox	***Generator***	***Transformer***	***ISOMAX Break***
Failure rate doubled	*Profit (EUR)*	*Profit (EUR)*	*Profit (EUR)*	*Profit (EUR)*
New optimal strategy	369 174 514	374 488 621	375 757 491	376 984 351

Original strategy	367 676 415	373 442 435	375 581 006	376 982 357
Difference	-1 498 100	-1 046 186	-176 485	-1 994
	0,41%	0,28%	0,05%	0,001%
Failure rate halved				
New optimal strategy	380 498 622	377 787 806	-	-
Original strategy	380 265 555	377 650 884	-	-
Difference	-233 067	-136 922	-	-
	0,06%	0,04%	-	-

The results from these sensitivity analyses showed that the optimal spare part strategy is only sensitive to higher gearbox or generator failure rates, regarding profitability. The loss of profit over 20 years would be 0.41 percent and 0.28 percent, respectively. Other parameter changes resulted in a loss of profit under 0.05 percent, which must be considered as a low effect on the profitability. Failure rates for less cost-driving spare parts would have an even lower effect which means the model is not that sensitive to these parameters.

Another analysis that might be of interest would be to investigate the effect of investing in more reliable spare parts. We know that a decreased failure rate leads to increased operational availability, which affects the profit. If cheap items that fails often were to be changed for more reliable but also more expensive items the profit might increase. We suspect that the “Encoder Rotor” (ER) is such an item. Therefore we compared a scenario where the ER price is tripled (to EUR 600) while the failure rate is halved, with the original Horns Rev case. The new scenario was about 0.02 percent more profitable, which is not much considering the uncertainty in the new parameter values.

Lead times and reorder costs
Another parameter that might be uncertain is the lead time (LT) for DUs. This is especially true since it might change over the WT lifetime. We have used a LT of one week for most items (not blades and transformer which have much longer lead times). However, the mean LT could turn out to be higher and therefore we analysed the effects of changing the standard LT to two weeks and four weeks. The results are shown in Table 7.10 below.

Table 7.10: Results from sensitivity analysis of the lead time for DUs (excluding blade and transformer)

Two weeks lead time	***Profit (EUR)***
New optimal strategy	376 590 662
Original strategy	376 500 205
Difference	90 457
	0,02%
Four weeks lead time	
New optimal strategy	376 503 603
Original strategy	375 681 874
Difference	821 728
	0,22%

The differences in profit over 20 years using the “wrong” spare part strategy are not very big. If LT were to be two weeks instead of one week it would result in a 0.02 percent loss of profit. In the case of LT being four weeks a fairly significant effect can be noted, with a 0.22 percent loss of profit. However, the probability that LT would in fact be that much longer is pretty low.

The reorder cost parameter, in our model set to a fixed value of EUR 400, have also been analysed. We approximated this value to be between EUR 300 and EUR 500 and changed the parameter by 50 percent in both directions. The results showed that it did not affect the profit, with the loss being under 0.01 percent in both cases.

Repair times and costs
Another important parameter that we know is uncertain is the LRU repair time (TAT), especially for items other than gearbox and generator (which we have better information on). In our models we used a fairly long TAT, 16 weeks for gearbox and generator and 8 weeks for the remaining LRUs. We are confident about the special cases of 16 weeks but the standard TAT of 8 weeks could easily turn out to be 4-12 weeks. However, we are somewhat certain that it is not much longer than 3 months. We know from the CDIX values that the gearbox and generator are much more cost-driving than the other LRUs, affecting the output results more. Because of that we have analysed the TAT parameter for all LRUs, were we added and deducted four weeks. The results are presented in the Table 7.11 below.

Table 7.11: Results from sensitivity analysis of the TAT for LRUs

Four weeks longer TAT	***Profit (EUR)***
New optimal strategy	375,995,171
Original strategy	375,717,187
Difference	-277,984
	0.07%
Four weeks shorter TAT	
New optimal strategy	377,231,531
Original strategy	377,206,092
Difference	-25,439
	0.01%

The analysis showed that the model is not that sensitive to changes in the TAT parameters, when measuring the effect by the loss of profit from using the "wrong" spare part strategy. A four weeks longer TAT for all LRUs resulted in a 0.07 percent loss, whereas four weeks shorter TAT resulted in only a 0.01 percent loss.

The LRU repair costs, set to 30 percent of item price, do not affect the OPUS10 optimization but generates a higher LSC. We doubled that cost to 60 percent of the item price and as expected the same spare part strategy were still optimal.

Storage costs
The storage costs are difficult to estimate, hence an uncertain model parameter. We analysed the optimal strategy when storage costs are doubled and halved, i.e. 20 percent of the item price plus EUR 200 per item and 5 percent of the item price plus EUR 50 per item. The results showed no significant loss of profit, under 0.01 percent in both cases.

Economic model parameters
We have previously in this chapter mentioned that the capacity factor for the different wind farms (in our model set to 0.3) is rather uncertain. For the Horns Rev support organisation model we changed that value between 0.25-0.35 and found that the optimal availability level (hence optimal spare part strategy) barely changed at all. The same was for the income parameter (I), set to 0.09 EUR/kWh, which we varied between 0.06-1.2. Minor differences appeared in the optimal strategy,

which only changed at the extreme values.

7.4 Results from Siemens SWT-2.3 cases

In the first Siemens SWT-2.3 case we have optimized the Lillgrund stock only. After that we have included the future Vattenfall SWT-2.3 turbines projected in Sweden and Denmark to model an extended support organisation. The SWT-2.3 spare part data used for the OPUS10 analysis are shown in Appendix C.

7.4.1 Lillgrund

Because Siemens are responsible for all the spare part handling at Klagshamn Vattenfall has no influence or insight of the current stock. Therefore we have no existing stock data to compare with the optimal strategy calculated for Case 6.

Case 6 – Baseline optimization

In this case we have used a simple support organisation model for Lillgrund wind farm. The operating station, consisting of the 48 SWT-2.3, is supported by the depot in Klagshamn, from where DUs are reordered. Faulty LRUs are sent to a Siemens workshop in Brande. This support structure is illustrated in Figure 7.14 below, where MLDT between the stations are shown.

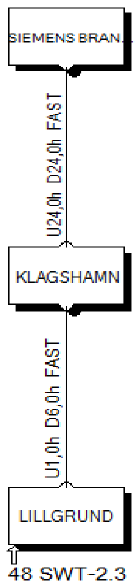

Figure 7.14: Lillgrund support organisation structure (U stands for "up" and D stand for "down")

Optimization with OPUS10 gave the C/E-curve in Figure 7.15, where the most profitable spare part strategy (point 44) is circumscribed.

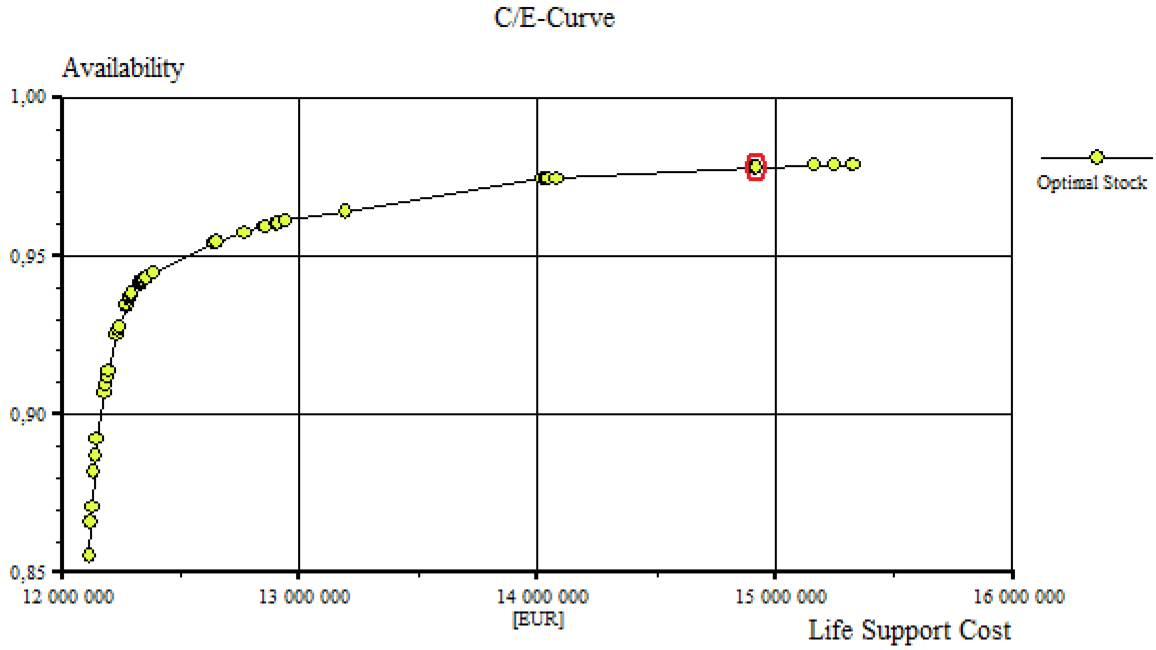

Figure 7.15: C/E-curve for Lillgrund

The most profitable availability level was 97.77 percent with a LSC of EUR 14.9 million. Optimal spare part stock and reordering points is presented in Appendix N and the economic results are shown in Table 7.12 below. The total calculated lifetime profit was EUR 259.9 million.

Table 7.12: Economic results for optimal spare part strategy for Lillgrund

	Availability	***Annual Support Costs***	***Annual Profit***	***Annual Production***	***Cost/MWh***	***Profit/MWh***
		M EUR	*M EUR*	*MWh/year*	*EUR*	*EUR*
Lillgrund Optimal Stock	97.77%	1.4	24.1	283 647	4.88	85.12

The annual profit with this spare part strategy will be EUR 24.1 million, using our formulas, with the support costs being EUR 1.4 million (from the OPUS10 model).

7.4.2 Future SWT-2.3 support organisation

For the future SWT-2.3 support organisation the same structures have been analysed and compared as for the future V80/90. All faulty items are assumed to be sent to the workshop in Brande, as in Case 5. There are three depots in the model, the present service station in Klagshamn and two future depots on Jutland, Denmark, and in south of Sweden (called Depot DK and Depot SWE in the OPUS10 model)

Case 7 – Future SWT-2.3 with local storage

In this case we have three depots supporting all the future SWT-2.3 turbines. The depots will represent a local stock scenario, but in reality there will be pooling of spare parts between the small onshore wind farms in Denmark and Sweden (which we have modelled as two large wind farms consisting of 45 and 44 WTs respectively). The support organisation structure used is shown in Figure 7.16, including MLDT between the stations.

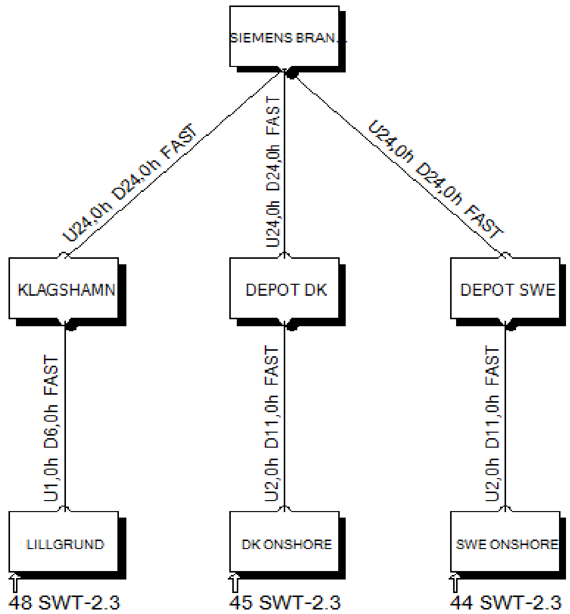

Figure 7.16: Future SWT-2.3 support organisation structure with local stocks (U stands for "up" and D stand for "down")

The results from the spare part optimization with OPUS10 are compared with the results for Case 8 in Figure 7.18 and Table 7.13. The most profitable strategy for Case 7 is shown in Appendix O.

Case 8 – Future SWT-2.3 with spare parts pooling and central reordering

In this case we used the same type of central depot support organisation as in the V80/90 case (4). The central depot, from where all DUs are reordered, is placed in Klagshamn (because that is the operating station with most SWT-2.3). Klagshamn is then supporting Lillgrund and supplying the local depots in Denmark and Sweden with spare parts. The structure is shown in Figure 7.17 below.

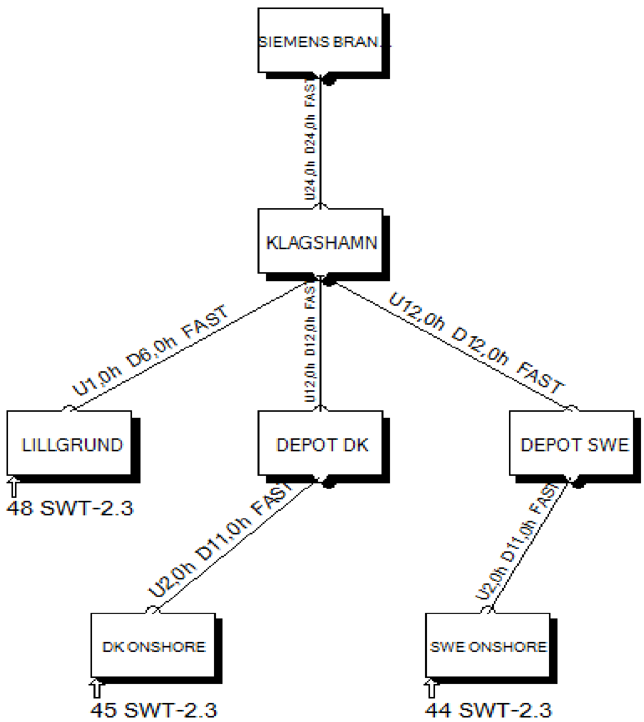

Figure 7.17: Future SWT-2.3 support organisation structure with a central depot (U stands for "up" and D stand for "down")

OPUS10 optimization with this support organisation model resulted in the C/E-curve shown in Figure 7.18, compared with the one from Case 7, with the optimal points circumscribed. The optimal spare part strategy for Case 8 is shown in Appendix P.

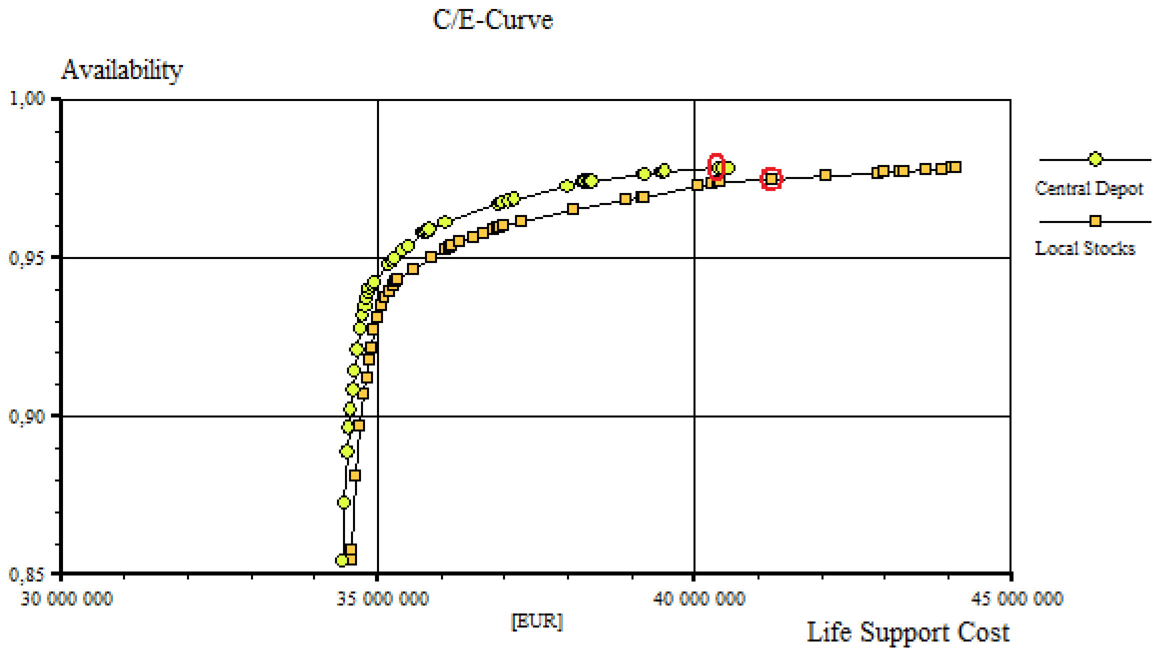

Figure 7.18: OPUS10 C/E-curves for future SWT-2.3 support organisations

The C/E-curves shows that a central depot support organisation is more profitable than supporting the wind farms locally. Economic results fore the two cases are presented in the table below.

Table 7.13: Main economic results for Case 7 and Case 8

	Availability	***Annual Support Costs***	***Annual Profit***	***Annual Production***	***Cost/MWh***	***Profit/MWh***
		M EUR	*M EUR*	*MWh/year*	*EUR*	*EUR*
Only local	97.61%	3.6	69.1	808 270	5.26	85.55
Central depot	97.94%	3.5	69.5	810 996	5.02	85.65
Difference	0.34%	-0.1	0.4	2 726	-0.24	0.10

The use of a central depot resulted in a EUR 0.4 million higher annual profits, which means it is about 0.5 percent more profitable. Thus, the difference is slightly lower than for the future V80/90 in Case 3 and 4.

7.4.3 Sensitivity analysis for SWT-2.3 models

For the SWT-2.3 models we did the sensitivity analysis on Case 8 which represented an extended support organisation model. The same analyses were done as for the V80/90 model, including item failure rates, lead times, TAT, storage costs and economic parameters. The results were very similar to the previous sensitivity analysis, confirming the robustness in the model and the optimal spare part strategy calculated by OPUS10.

7.5 Wind power system scaling

We have analysed different scenarios including a fixed number of WTs. As a last OPUS10 case we wanted to analyse how the number of WTs (of the same type) supported affects the LSC. V80 spare part data is used and the objective is to investigate the support organisation efficiency, concerning spare part logistics, for different sizes of a wind power system, by looking at the LSC/WT.

Case 9 – Scaling of a wind farm

For this case we used the same support organisation structure as for Case 1 and 2, with the same MLDT between the stations. However, the number of systems, i.e. WTs, connected to the OP was changed; 5, 10, 20, 40, 80, 120, 160 and 200 WTs. Because 98 percent in operational availability has been the most profitable level for most cases we used the LSC value of the point on the C/E-curve closest to 98 percent. The LSC was then divided by the number of WTs. The result is shown in Figure 7.19.

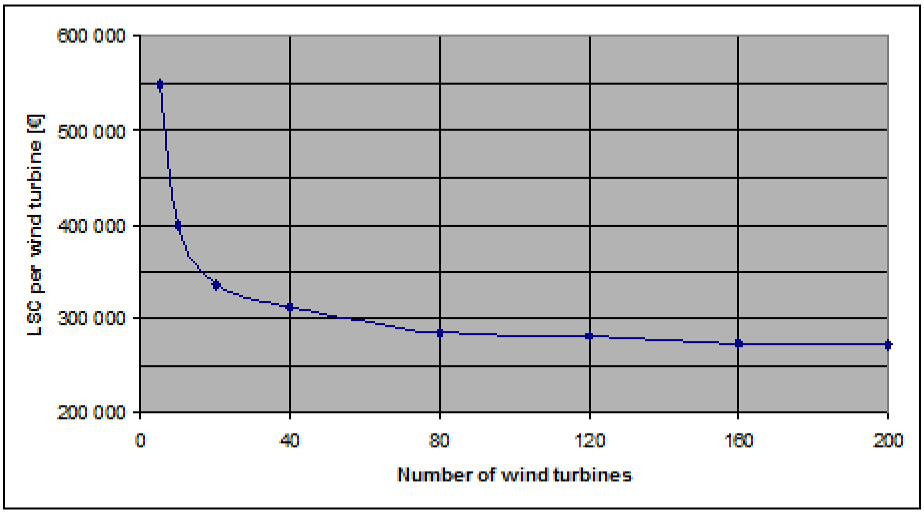

Figure 7.19: Cost-efficiency of spare part logistics depending on the number of wind turbines supported

8 Discussion

8.1 Model parameters and assumptions

All results from the OPUS10 analyses depend a lot on the support organisation model and input data. Hence, we will start this chapter by a discussion around the chosen model and some important parameters. Some item and station data, especially MTTR and MLDT, were to a large extent motivated and discussed in Chapter 6, by information from field studies and interviews. These parameters do not affect the OPUS10 optimization, only availability. This also concern the estimated amount of man-hours needed for certain maintenance tasks, although affecting the LSC instead of the availability. For example do the preventive maintenance parameters only decrease the operational availability and add extra costs to LSC. However, including preventive maintenance in the model creates a more realistic result. It is almost impossible to generate an exact LSC for a wind power system with OPUS10, even if most of the costs mentioned above are modelled correctly. This is due to large administrative costs and other external expenses connected to the operation are very difficult to model. Model parameters that are more important to discuss are the ones affecting the optimization algorithms and thereby the optimal spare part strategies. Item prices and failure rates have a large influence on the optimal spare part strategy. In one sense these parameters are fixed since the support organisation can not easily change them. This is also applicable for repair costs and repair TAT. Important parameters that are dependent on the support organisation are storage costs, reorder costs and repair times. Some of these factors will be discussed below.

Spare part prices

Spare part prices in the Horns Reef cases are known for most spare parts so this parameter must be considered accurate. The prices should also be suitable for the future V80/90 scenarios even though there is a possibility that items are not identical. However, we know that there are big differences in item prices between different WT manufacturers, which make it hard to generalize over other WT models. For the Siemens cases prices are more uncertain but there should be very few items that are not placed in the correct group. For Siemens the largest price uncertainties are for those items that were estimated or assumed to have the same price as a similar V80/90 parts, such as gearboxes, generators, blades and transformers. These are also the most critical and cost-driving spare parts (partly because of the much higher prices) which make validation of these prices even more important. However, the relation between the item prices should be somewhat accurate.

Item failure rates

Knowing the spare part demand is very important when optimizing stocks. Earlier WT reliability studies have only been focused on WT subsystems and not item specific failure rates. Predicting and estimating the real failure rates and distributions are very hard and resource demanding. In our study we have calculated the item failure rates from quite small data sets, but it should be enough to at least place an item in the right failure rate group. In our case the failure rates are supposed to represent the demand that they were deduced from. The failure rates are therefore applicable for Horns Rev and Lillgrund from where the data was collected. For items not included in any inventory list or activity report, mainly large and cost-driving items (e.g. gearbox and generator) we have relied on previous WT reliability studies and information from interviews. These estimates should be considered fairly uncertain but with the use of grouped data the mean value should be placed in the right group. However, most of the previous studies indicated that the gearbox have a higher failure rate than the generator (in our model they are in the same group) which most likely would results in another optimal spare part strategy than the ones we found. Apart from the fact that the gearbox and generator failure rates are uncertain (and have a big effect on the final optimization result) they should maybe not be grouped in the same way as the other item failure rates. To get a better solution the differences in failure rate between these two items have to be modelled.

Item types
For WTs most items are discarded after failing, even some expensive items. Although, the most expensive parts like gearboxes and generators are always repaired, if possible. For these items the repair procedure is quite straight forward. The item is sent to a workshop for repair and is delivered when the task is done. For other mid-price items the process is not quite as clear. These items are sent to the manufacturer when they fail, where they are either repaired or discarded depending on the failure mode. Many WT operators, such as Vattenfall, then gets a “new” item in exchange, for a deduction of the price. In our model LRUs are repaired with a cost of 30 percent of the item price, which is substantially lower than the price deduction given today. As discussed earlier fixed costs are not so important for the OPUS10 optimization therefore this is a minor problem for our study. An interesting step to improve our model could be to include partly repairable units (PRUs) which can describe the dynamics of the failure mode for the WT items.

Reorder and storage costs
The reorder and storage costs will have a big influence on the optimal reorder points and stock sizes for DUs and also for the most profitable quantity of LRUs to invest in. The DU trade-off between having a large stock on hand and having a high reorder frequency depend on the difference between reorder and storage costs. However, these costs are hard to calculate exactly since it is not defined which costs that are connected to storing and reordering of items. Storage includes costs for facilities and personnel, but also risks for spare parts being obsolete or break, which can be difficult to evaluate. There are many hidden costs when reordering spare parts, not obvious when first looking at the reordering process. This can cause organisations to underestimate some of the administrative costs. However, we are confident that the estimates we received from senior consultants are fairly accurate.

Repair TAT and lead times
Workshop repair times vary greatly upon which type of failure an item has suffered. Therefore we used large gaps between the groups to simplify the rating of LRU repair times. For our items there is a small probability that the mean TAT for an item is misplaced. Lead times are also quite certain since the persons interviewed have a great insight in the ordering process. One problem can be that today's lead times are short. When looking on other industries lead times are a bit longer. This could also be the case within the WT industry as the WT market matures.

Revenue model parameters
The revenue model used to calculate the optimal profit and availability level needs some further discussion. An important parameter when calculating the revenue is the capacity factor, which is set to 0.3 in all OPUS10 cases. This was done because the optimal point did not change when lowering this value to 0.25 (if all WT systems were onshore) or raised to 0.35. However, in real life the capacity factor can differ a lot between different sites. If the spare part allocation are to be optimized wind farms with a higher factor then should be prioritised.

8.2 OPUS10 results

The OPUS10 results presented in the previous chapter were divided between the two WT types. An interesting approach when looking at the results from the two WT types would be to compare the characteristics of the two types, e.g. compare LSC per turbine and type. To be able to make such comparisons a much larger study is necessary so that the whole scope of the problem is covered. This study only included a part of the total amount of WT spare parts used, with twice as many items included in the V80/90 material compared to the SWT-2.3 material. Therefore it is impossible to make a fair comparison between the two WT support organisations, and between reliabilities and costs. Hence we have studied the two WT types and their support organisations separately. Our discussion around the OPUS10 results will be concentrated to the differences from the analysis of the current stock policy at Horns Rev and the optimal strategy suggested by OPUS10. Some notations are also made around the Lillgrund optimization. We will then discuss the future scenario results for both SWT-2.3 and V80/90 and compare the different support organisations analysed.

8.2.1 Spare part strategies for Horns Rev and Lillgrund

When the existing spare part strategy at Horns Rev (by our approximations) was compared with an optimal strategy calculated by OPUS10 it showed that the existing strategy was about 2.5 percent less profitable. The most significant differences could be seen when looking at the reorder and storage costs, both reduced by over 30 percent with the optimal stock and reorder strategy. Another interesting aspect were the differences in proportion of item types invested in (LRU representing 70 percent of the spare part capital costs compared to only 11.5 percent with the existing strategy modelled). This is mostly because we modelled the existing strategy with no gearbox or generator (the two most expensive items) in stock. Based on information from interviews we know that there is a desire to have gearboxes in stock in the future and probably also generators. When adding gearboxes and generators (one, two and three of each) to the existing stock we could see that the profit increased a lot. It is obvious that the long TAT for these two, strategic, spare parts generates too much downtime when these are not held in stock. Two or three of each maximised the profit, which then were EUR 1.5 million (0.5 percent) less than if the optimal OPUS10 spare part strategy were used for Horns Rev.

The OPUS10 optimization suggested investments in two gearboxes and three generators, but we know from the sensitivity analysis that two of each might be even better (if the generator failure rate were 30-50 percent lower than the generator failure rate, which previous studies also indicates). On the other hand, if the true value of the gearbox failure rate is 60-100 percent higher than our estimated value, three of each would be optimal. When looking at the results from the Lillgrund optimization it is evident that two gearboxes and two generators is the most cost-effective investment. This result is interesting when comparing with results from the Horns Rev optimization, where the optimal amount of gearboxes and generators were the same, even though there are 32 additional WTs at Horns Rev. *Two-of-each* seems to be a robust investment strategy for a large wind farm. One transformer seems to be optimal for both Lillgrund and Horns Rev, but the blade stock size differs. For Horns Rev two blades are optimal while Lillgrund only needs one blade in stock. Because of the high lead time for blades a new one should be ordered directly when a faulty blade has been replaced.

8.2.2 Future V80/90 and SWT-2.3 support organisations and optimization

The future scenarios modelled were divided into two different support organisation cases. One represented a scenario with local handling and storage of spare parts between the different sites and another where a central depot was used for reordering and pooling of some spare parts. The results showed that the central depot organisation was more cost-efficient for both the V80/90 cases and the SWT-2.3 cases, and resulting in a higher profit. However, the difference in profit was not that large, around 0.5 percent. This is because the revenue is very high compared to the support costs included in our model (a lot of support costs are not taken into account). When looking at LSC the costs for the optimal strategy with a central depot organisation is 4.5 percent lower for V80/90 and 2 percent lower for SWT-2.3. As mentioned in the previous chapter the LSC difference between the two organisation structures are also clouded by fixed annual costs not depending on the spare part strategy. When comparing only the costs that vary, which are spare part investments, reordering and storage, the difference gets larger. For the optimal V80/90 spare part strategy the use of central depot lowered the variable support costs with 25 percent. For the SWT-2.3 central depot case the variable support costs for the optimal spare part strategy were 11.5 percent lower. When we looked at another cost-efficient V80/90 spare part strategy using a central depot, with the same availability as the optimal strategy using local storage, the difference in support costs were much larger. LSC was almost 6 percent lower with the variable support costs being as much as 43 percent lower.

It is obvious from the LSC results that the money saved is only a small proportion of the total support costs; still the central depot organisation must be regarded as the more favourable choice. This is especially true when a range of different wind farm sizes are supported within the same organisation, such as the future V80/90 scenario. The savings being made in storage costs and reorder costs are significant when looking over 20 years. In the SWT-2.3 cases we modelled three WT sites of the same size, which resulted in less improvement when adding a central depot. These three future sites are in reality a number of smaller scattered wind farms which means that the local stock organisation structure already used some sort of regional pooling and reordering of spare parts. If we had modelled all the future SWT-2.3 sites as separate operational stations the difference when adding the central depot would have been much larger, as for the V80/90 scenarios. It can be noted that for the V80/90 central depot case we used the Bergkvara depot for spare part pooling between Yttre Stengrund and Östra Herrestad. If those two wind farms had been modelled with a local depot each the support costs would have been somewhat higher.

8.2.3 Cost-efficiency of WT support and spare part logistics

The results from the future support organisation cases showed that central spare part pooling and handling of spare parts is a better alternative than local storage only. It is obvious that when supporting as many as 140-150 WTs of the same type, especially when scattered between several wind farms of different sizes (as in the V80/90 scenario, where most profit were gained by adding the central depot), coordination and pooling of spare parts is more cost-efficient than having individual support and supply of spare parts for each wind farm. In our last OPUS10 case we investigated the effect of scaling a wind farm (based on data from Horns Rev). The support organisation used in that case (the same as for the Horns Rev cases) could just as well be a depot supporting several wind farms, for example in Denmark and Sweden (onshore), were MLDT between the depot and the sites are 12 h. This is not an unrealistic situation, which can be seen on the MLDT values calculated for Danish and Swedish onshore sites and depots in the future V80/90 and SWT-2.3 cases. The result showed that it was not that cost-efficient to support under 20 WTs of the same type (using the same spare parts). However, the effects are maybe not as drastic as shown in Figure 7.19. This is because it is very expensive for reach an operational availability of 98 percent when supporting a small number of WTs. The most profitable availability level is probably some percentage points lower. Nonetheless, after building 60-80 WTs of the same type there were small improvements in cost-efficiency by increasing the number of WTs within the organisation.

8.3 Model robustness

In our first OPUS10 case we compared the ungrouped Horns Rev data with the grouped data. The results showed small differences between the two models. Together with the previous study on analysis with OPUS10 using grouped data (described in section 5.4) we feel confident about our classifications and grouping of data, since the models appear to be very robust. A bigger problem would be the uncertainties in some of the input data, especially the failure rates. From the sensitivity analysis we found that only the most expensive spare parts, the gearbox and the generator, affected the profit with some significance. This occurred if our estimations of the failure rates were undervalued, i.e. the true value is much higher. Other model parameters that affect the optimal spare part strategy, such as storage costs, lead times and repair TAT can not be classed as sensitive parameters. Hence, further research to improve the model should be to validate and maybe adjust the gearbox and generator failure rates, especially since previous studies indicates that generators should be more reliable (but in our model they have the same failure rate). In Figure 8.1 below are the parameter sensitivity classification model presented in Chapter 4 shown with some of our model parameters grouped.

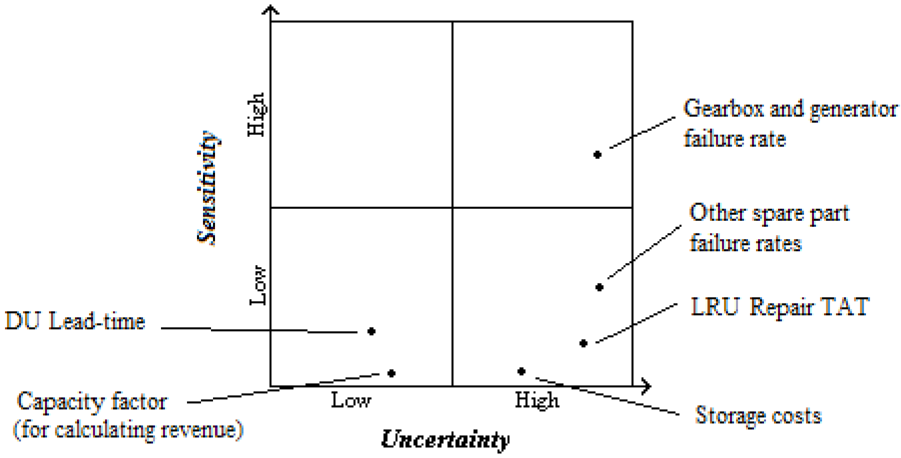

Figure 8.1: Sensitivity of model parameters

Sensitivity information can also be used to evaluate what model improvements are most rewarding in terms of support system efficiency. For example, cheap items that have a high failure rate might cause a lot of downtime, regardless of the safety stock, and thus loss of profit. Investments in more reliable but expensive item types can then be a better strategy, especially if the number of WTs is high. However, the sensitivity analysis on the Vestas V80 Encoder (for the generator rotor) indicated that the increase in profit would not be much if the failure rate were halved for three times the item price. The storage costs for low price and low-medium price items (EUR 200 and EUR 600) in our model does not differ that much, because of the fixed storage handling cost of EUR 100 per item.

8.4 Complicating factors

There are several complicating factors when modelling a WT support organisation. We began this chapter by a discussion around the most important parameters included in the model. However, there are some circumstances not taken into account in our model, which complicates the optimization of spare part stocks. We will discuss three major problems; *influence of the crane ship*, *item upgrades/inconsistent item versions* and *multiple item replacements*.

Crane ship

A crane ship is always needed when large WT items have to be replaced at an offshore wind farm. These ships are very expensive to rent and often have a very long, but unpredictable, lead time (between 1-12 months). As mentioned earlier, fixed costs are not that important for OPUS10 optimizations. The problem is that depending on the lead time of the crane ship and the repair TAT or lead time of the item (large LRU or large DU) the optimal stock size might be overestimated. This is due to the fact that a faulty LRU can be repaired or DU reordered before the crane ship is available at the WT site. This could to some extent be handled by shortening of TAT and lead time for these items, if the lead time of the crane ship could be estimated. Another problem is the tactical decisions behind ordering a crane ship. Because of the high costs associated with renting these large ships, several maintenance tasks/replacements are often awaited and performed at the same time. This would be impossible to model in for example OPUS10. However, it implicates that a number of spare parts (e.g. at least two gearboxes) always should be available for use since so much money is saved by making these multiple replacements. Sometimes other critical items (e.g. gearboxes), that are damaged but have not yet failed, are also replaced at the same time. Another aspect of the crane ship problem is that large spare parts maybe not should be invested in initially. If the crane ship lead time is estimated to be longer than the lead time of the spare part this could be a cost-efficient strategy. However, for LRUs the OPUS10 calculated optimal stock size should be reached within some time and no further investments of that spare part should be made. The problems with crane ships would effectively disappear if a company operating and maintaining offshore WTs invested in such a ship, if possible and cost-efficient.

Inconsistent WT items

A problem when acquiring spare parts for a certain WT model is that some items are being replaced by more reliable versions, especially for new WTs. Software upgrades performed during the first years of operation sometimes also leads to hardware changes. In general WTs are thoroughly upgraded with a few years interval which can make some of the "old" spare parts obsolete. This also makes spare part pooling between WTs, such as in our future V80/90 scenario, difficult. In reality there are probably only a few of the spare parts included in our model that can be used for both the V80s at Horns Rev and the new V90s being built at Stor-Rotliden. At least there is a problem to determine which WT items are identical between different sites.

Multiple item replacements

Another troubling factor, although not that difficult to model, is items that are not replaced one-by-one. Some items can in some way interact so that if one of them fails both needs to be replaced. Items that are installed in pairs must sometimes be replaced by a new pair. This implicates that optimal stock level for a certain spare part must be a multiple of the number of items that are replaced at one single occasion. In OPUS10 this is easy to model if the multiples are known. However, we have not investigated this factor in depth and therefore have assumed that only faulty items are replaced by a spare part. A related factor, also leading to multiple item replacements, is *common cause failure* (CCF). CCF implicates that some item failures are not independent, i.e. there are some probability that items can fail simultaneously (e.g. construction error). This can not be modelled in OPUS10, but failure rates can for example be corrected upwards to get a better estimate of the "real" mean value of the spare part demand. However, when we estimated the failure rates we recalculated them from the (expected) annual demand for each item, which then includes CCF or multiple replacements.

9 Closure

9.1 Conclusions

We have with this thesis contributed with basic modelling of wind power support organisations, including optimization of spare part stocks. It was effectively done with the software tool OPUS10. There are a variety of conclusions that can be drawn from this study, both on how to build such a model and what parameters that are of importance for optimal stocks to be accurate. A lot of this was discussed in the previous chapter. More importantly we have found that fairly large savings can be made by using an optimal spare part strategy, even though the costs related to spare part investments, reordering and storage are only a small proportion of the total LSC.

The most cost-driving WT items, affecting the optimization results the most, are gearboxes and generators. Extra attention has to be given to these items when modelling the spare part logistics, especially regarding failure rate estimates. Together with blades and transformers these spare parts have the largest influence on spare part capital costs and storage costs.

When comparing the existing stock policy at Horns Rev with the optimal strategy calculated by OPUS10 we found that the optimal strategy would result in a large increase of the lifetime profit, even when adding gearboxes and generators to the existing stock. When expanding the wind power system to include more WTs of the same type even bigger profits can be made by coordinating spare part logistics and optimize stocks levels and reorder points. We found that central reordering and pooling of spare parts were clearly more cost-efficient than local storage and handling. The results also showed that at least 60-80 WTs of the same type is needed for spare part supply and storage to be cost-efficient (when operational availability of 98 percent are to be reached).

An important focus for WT operators should be item reparability. Today many items appear to be discarded and during our research we found it difficult to get information on what items that actually can be repaired. When we analysed a future V80/90 scenario with increased item reparability we found that large profits could be made. The larger item volumes to be repaired each year probably also leads to better repair contracts. Finding local workshops would also somewhat reduce waiting times.

There are a lot of complicating factors associated with optimization of WT spare part stocks. One of the most troubling factors is how the extreme lead time of the crane ship affects optimal stock sizes of gearboxes, generators, blades and transformers. This factor is not included in our models but should be taken into consideration when analysing different spare part strategies and the OPUS10 results.

9.2 Further work

During this thesis a lot of problems concerning spare parts optimization have come to light. One of the most troubling aspects is the fact that there are no studies on WT specific item failure rates. This should be of primarily interest for further research.

Another important factor is the reparability of WT items. Defining exactly which WT items that can be repaired needs some further attention, and also which items that are usually being repaired but are sometimes discarded, and at what rate. It would also be interesting to investigate the impact of the crane ship more in depth, and how it affects optimal stock levels and reorder points.

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Appendix A

Item data groups

	Group 1	*Group 2*	*Group 3*	*Group 4*
Price (EUR)	(100-300) 200	(300-1000) 600	(1000-3000) 1800	(>3000) Estimate
Failure rate	(0.3-1.0) 0.55	(1.0-3.0) 1.73	(3.0-10.0) 5.48	(10.0-30.0) 17.32
MTTR (hours)	5	10	72	144
TAT (weeks)	2	8	16	32
Lead time (weeks)	1	8	16	32

Note: Bracked values are the price and failure rate groups used.
For item prices over EUR 3000 a price were estimated.

Appendix B

Vestas V80/90 Spare Part Data

Spare Part	***Price***	***Failure Rate***	***Type***	***MTTR***	***TAT***	***Lead time***
Description	*EUR*	*per 10^6 hours of operation*	*Repairable/ discardable*	*Hours*	*Weeks*	*Weeks*
Blade	75000	0.55	DU	72		16
Proportional Valve	1800	5.48	DU	5		1
Hydraulic Cylinder	1800	1.73	LRU	5	8	
Piston Accumulator	1800	5.48	DU	5		1
Rotating Union	3200	5.48	LRU	5	8	
Encoder	600	1.73	DU	5		1
Gearbox	400000	5.48	LRU	144	16	
Bearing Generator	1800	0.55	DU	72		1
Generator Fan 1	600	0.55	DU	5		1
Generator Fan 2	600	1.73	DU	5		1
Generator	120000	5.48	LRU	10	16	
Encoder Rotor	200	17.32	DU	5		1
Slip Ring Fan	1800	5.48	DU	5		1
Fan	600	0.55	DU	5		1
Motor for Cooling System	600	5.48	DU	5		1
Yaw Gear (right)	1800	1.73	DU	10		1
Yaw Gear (left)	1800	1.73	DU	10		1
Yaw Motor	1800	0.55	DU	5		1
Mechanic Gear for Oil Pump	1800	1.73	DU	5		1
Electric Gear for Oil Pump	1800	17.32	LRU	5	8	
Chopper Module	1800	1.73	DU	5		1
TRU card	600	1.73	DU	5		1
VCP card	1800	5.48	LRU	5	8	
SKIIP 1	1800	17.32	DU	5		1
SKIIP 2	1800	1.73	DU	5		1
EMC Filter	1800	5.48	DU	5		1
Capacitors	200	17.32	DU	5		1
CT 3220 FFFF	600	1.73	DU	5		1
CT 316 VCMS	1800	0.55	DU	5		1
CT 3601	1800	0.55	DU	5		1
CT 3133	600	17.32	DU	5		1
CT 3220 FFFC	1800	1.73	DU	5		1
CT 3218	200	1.73	DU	5		1
CT 3614	600	1.73	DU	5		1
CT 3363	600	1.73	DU	5		1
CT 3153	600	5.48	DU	5		1
CT 279 VOG	200	5.48	DU	5		1
Ultra Sonic Anemometer	1800	17.32	LRU	5	8	
Transformer	42000	1.73	DU	144		8
Phase Compensator Generator	600	17.32	DU	5		1
Q8 Main Switch	3600	17.32	DU	5		1
Q8 Electric Gear	1800	5.48	DU	5		1
Q8 EMC filter	200	17.32	DU	5		1

Note: Q8 is means part of the emergancy system

Appendix C

Siemens SWT-2.3 Spare Part Data

Spare Part	***Price***	***Failure Rate***	***Type***	***MTTR***	***TAT***	***Lead time***
Description	*EUR*	*per 10^6 hours of operation*	*Repairable/ discardable*	*Hours*	*Weeks*	*Weeks*
Blade	75000	0.55	DU	72		16
Proportional Valve	600	0.55	DU	5		1
Blade Block for Hydraulic Pitch	4000	5.48	LRU	10	8	
Solenoid Valve	600	5.48	DU	5		1
Hydraulic Cylinder	1800	0.55	LRU	5	8	
Rotating Union	600	5.48	LRU	5	8	
Brake Disc	600	5.48	DU	10		
Gearbox	400000	5.48	LRU	144	16	
Bearing Generator	1500	0.55	DU	72		1
Yaw Motor	200	1.73	DU	10		1
Yaw Gear	600	5.48	DU	10		1
Piston Accumulator 6L	600	1.73	DU	5		1
Motor for Oil Pump	600	5.48	DU	5		1
Oil Pump	1800	1.73	LRU	5	8	
Piston Accumulator 0,15L	200	5.48	DU	5		1
SMPS 1	600	17.32	DU	5		1
SMPS 2	600	5.48	DU	5		1
Delta Module (SKII Pack)	15000	5.48	LRU	10	8	
Power Supply 240 V/24 V	200	5.48	DU	5		1
Wind Sensor	1800	17.32	LRU	5	8	
Encoder	200	5.48	DU	5		1
I/O-Modul	600	0.55	DU	10		1
Motor 4kW	600	17.32	DU	5		1
Motor 1.8kW	600	5.48	DU	5		1
Generator	120000	5.48	LRU	10	16	
Transformer	42050	1.73	DU	144		8

Appendix D

Horns Rev Optimal Spare Part Strategy

Spare Part	***Type***	***Stock Size***	***Average Stock***	***Reorder Point***	***Reorder Size***
Description	*DU/LRU*				
Blade	DU	2	1.65	1	1
Proportional Valve	DU	4	2.43	0	4
Piston Accumulator	DU	6	3.78	1	5
Encoder	DU	5	3.43	1	4
Bearing Generator	DU	1	0.99	0	1
Generator Fan 1	DU	1	0.99	0	1
Generator Fan 2	DU	2	1.48	0	2
Encoder Rotor	DU	10	5.77	1	9
Slip Ring Fan	DU	4	2.43	0	4
Fan	DU	1	0.99	0	1
Motor for Cooling System	DU	5	3.43	1	4
Yaw Gear (right)	DU	3	1.95	0	3
Yaw Gear (left)	DU	3	1.95	0	3
Yaw Motor	DU	2	1.47	0	2
Mechanic Gear for Oil Pump	DU	2	1.48	0	2
Chopper module	DU	2	1.48	0	2
TRU card	DU	2	1.48	0	2
SKIIP 1	DU	6	3.77	1	5
SKIIP 2	DU	2	1.48	0	2
EMC Filter	DU	4	2.43	0	4
Capacitors	DU	10	5.77	1	9
CT 3220 FFFF	DU	2	1.48	0	2
CT 316 VCMS	DU	1	0.99	0	1
CT 3601	DU	1	0.99	0	1
CT 3133	DU	8	4.77	1	7
CT 3220 FFFC	DU	2	1.48	0	2
CT 3218	DU	3	1.98	0	3
CT 3614	DU	2	1.48	0	2
CT 3363	DU	2	1.48	0	2
CT 3153	DU	5	3.43	1	4
CT 279 VOG	DU	6	3.93	1	5
Transformer	DU	1	0.83	0	1
Phase Compensator Generator	DU	8	4.77	1	7
Q8 Main Switch	DU	5	3.27	1	4
Q8 Electric Gear	DU	4	2.43	0	4
Q8 EMC filter	DU	10	5.77	1	9
Hydraulic Cylinder	LRU	4	3.42	-	-
Rotating Union	LRU	4	3.39	-	-
Gearbox	LRU	2	0.96	-	-
Generator	LRU	3	1.84	-	-
Electric Gear for Oil Pump	LRU	7	5.07	-	-
VCP card	LRU	4	3.39	-	-
Ultra Sonic Anemometer	LRU	7	5.07	-	-
	Total Stock:	168	112.80		

Appendix E

Horns Rev Existing Spare Part Strategy

Spare Part *Description*	***Type*** *DU/LRU*	***Stock Size***	***Average Stock***	***Reorder Point***	***Reorder Size***
Blade	DU	3	1.67	0	3
Proportional Valve	DU	4	3.43	2	2
Piston Accumulator	DU	3	2.28	1	2
Encoder	DU	6	3.93	1	5
Bearing Generator	DU	0	0.00	-1	1
Generator Fan 1	DU	1	0.99	0	1
Generator Fan 2	DU	1	0.98	0	1
Encoder Rotor	DU	9	7.27	5	4
Slip Ring Fan	DU	3	2.93	2	1
Fan	DU	3	2.49	1	2
Motor for Cooling System	DU	6	3.43	0	6
Yaw Gear (right)	DU	4	2.45	0	4
Yaw Gear (left)	DU	4	2.45	0	4
Yaw Motor	DU	1	0.97	0	1
Mechanic Gear for Oil Pump	DU	1	0.98	0	1
Chopper module	DU	1	0.98	0	1
TRU card	DU	2	1.98	1	1
SKIIP 1	DU	23	14.27	5	18
SKIIP 2	DU	3	2.98	2	1
EMC Filter	DU	6	5.43	4	2
Capacitors	DU	7	4.27	1	6
CT 3220 FFFF	DU	3	2.48	1	2
CT 316 VCMS	DU	2	1.49	0	2
CT 3601	DU	2	1.49	0	2
CT 3133	DU	3	1.78	0	3
CT 3220 FFFC	DU	3	2.98	2	1
CT 3218	DU	6	4.48	2	4
CT 3614	DU	3	2.48	1	2
CT 3363	DU	2	1.98	1	1
CT 3153	DU	4	2.93	1	3
CT 279 VOG	DU	4	3.43	2	2
Transformer	DU	1	0.83	0	1
Phase Compensator Generator	DU	9	4.77	0	9
Q8 Main Switch	DU	5	2.77	0	5
Q8 Electric Gear	DU	2	1.43	0	2
Q8 EMC filter	DU	16	10.27	4	12
Hydraulic Cylinder	LRU	1	0.56	-	-
Rotating Union	LRU	2	1.42	-	-
Gearbox	LRU	0	0.00	-	-
Generator	LRU	0	0.00	-	-
Electric Gear for Oil Pump	LRU	8	6.07	-	-
VCP card	LRU	4	3.39	-	-
Ultra Sonic Anemometer	LRU	6	4.07	-	-
	Total Stock:	171	123.13		

Appendix F

Horns Rev Cost-Efficient Strategy (Point 20)

Spare Part	***Type***	***Stock Size***	***Average Stock***	***Reorder Point***	***Reorder Size***
Description	*DU/LRU*				
Blade	DU	0	0,00	-1	1
Proportional Valve	DU	3	1,93	0	3
Piston Accumulator	DU	5	2,78	0	5
Encoder	DU	4	2,43	0	4
Bearing Generator	DU	1	0,49	-1	2
Generator Fan 1	DU	1	0,50	-1	2
Generator Fan 2	DU	2	1,48	0	2
Encoder Rotor	DU	9	4,77	0	9
Slip Ring Fan	DU	3	1,93	0	3
Fan	DU	1	0,50	-1	2
Motor for Cooling System	DU	4	2,43	0	4
Yaw Gear (right)	DU	2	1,45	0	2
Yaw Gear (left)	DU	2	1,45	0	2
Yaw Motor	DU	2	0,98	-1	3
Mechanic Gear for Oil Pump	DU	1	0,49	-1	2
Chopper module	DU	1	0,49	-1	2
TRU card	DU	2	1,48	0	2
SKIIP 1	DU	5	2,77	0	5
SKIIP 2	DU	1	0,49	-1	2
EMC Filter	DU	3	1,93	0	3
Capacitors	DU	9	4,77	0	9
CT 3220 FFFF	DU	2	1,48	0	2
CT 316 VCMS	DU	0	0,00	-1	1
CT 3601	DU	0	0,00	-1	1
CT 3133	DU	7	3,77	0	7
CT 3220 FFFC	DU	1	0,49	-1	2
CT 3218	DU	3	1,98	0	3
CT 3614	DU	2	1,48	0	2
CT 3363	DU	2	1,48	0	2
CT 3153	DU	4	2,43	0	4
CT 279 VOG	DU	5	2,93	0	5
Transformer	DU	0	0,00	-1	1
Phase Compensator Generator	DU	7	3,77	0	7
Q8 Main Switch	DU	4	2,27	0	4
Q8 Electric Gear	DU	3	1,93	0	3
Q8 EMC filter	DU	9	4,77	0	9
Hydraulic Cylinder	LRU	3	2,42	-	-
Rotating Union	LRU	3	2,39	-	-
Gearbox	LRU	0	0,00	-	-
Generator	LRU	1	0,30	-	-
Electric Gear for Oil Pump	LRU	6	4,07	-	-
VCP card	LRU	3	2,39	-	-
Ultra Sonic Anemometer	LRU	6	4,07	-	-
	Total Stock:	132	79,95		

Appendix G

Future V80/90 Supported by Local Depots, Optimal Spare Part Allocation

Spare Part	*Total Stock*	*Average Stock*	*Esbjerg*	*DK Depot*	*Stor-Rotliden*	*Bergkvara*	*OH Depot*
Blade	4	3.45	2		1		1
Proportional Valve	9	6.87	4	1	2	1	1
Piston Accumulator	15	10.61	6	2	4	1	2
Encoder	11	8.38	5	1	3	1	1
Bearing Generator	4	3.98	1	1	1		1
Generator Fan 1	4	3.99	1	1	1		1
Generator Fan 2	7	5.96	2	1	2	1	1
Encoder Rotor	25	15.59	10	3	7	2	3
Slip Ring Fan	9	6.87	4	1	2	1	1
Fan	4	3.99	1	1	1		1
Motor for Cooling System	11	8.37	5	1	3	1	1
Yaw Gear (right)	8	6.42	3	1	2	1	1
Yaw Gear (left)	8	6.42	3	1	2	1	1
Yaw Motor	6	5.45	2	1	1	1	1
Mechanic Gear for Oil Pump	6	5.46	2	1	1	1	1
Chopper module	6	5.46	2	1	1	1	1
TRU card	7	5.96	2	1	2	1	1
SKIIP 1	15	10.59	6	2	4	1	2
SKIIP 2	6	5.46	2	1	1	1	1
EMC Filter	9	6.87	4	1	2	1	1
Capacitors	25	15.59	10	3	7	2	3
CT 3220 FFFF	7	5.96	2	1	2	1	1
CT 316 VCMS	2	1.99	1		1		
CT 3601	2	1.99	1		1		
CT 3133	21	13.59	8	2	6	2	3
CT 3220 FFFC	6	5.46	2	1	1	1	1
CT 3218	8	6.46	3	1	2	1	1
CT 3614	7	5.96	2	1	2	1	1
CT 3363	7	5.96	2	1	2	1	1
CT 3153	11	8.37	5	1	3	1	1
CT 279 VOG	15	10.37	6	2	4	1	2
Transformer	3	2.72	1		1		1
Phase Compensator Generator	21	13.59	8	2	6	2	3
Q8 Main Switch	12	9.09	5	1	4	1	1
Q8 Electric Gear	9	6.87	4	1	2	1	1
Q8 EMC filter	25	15.59	10	3	7	2	3
Hydraulic Cylinder	12	10.97	4	2	3	1	2
Rotating Union	11	9.92	4	1	3	1	2
Gearbox	3	1.51	2		1		
Generator	8	5.96	3	1	2	1	1
Electric Gear for Oil Pump	19	15.57	7	2	5	2	3
VCP card	12	10.91	4	2	3	1	2
Ultra Sonic Anemometer	19	15.57	7	2	5	2	3
Total:	439	336.10					

Appendix H

Future V80/90 Supported by Central Depots, Optimal Spare Part Allocation

Spare Part	Total Stock	Average Stock	Reorder Size	Esbjerg	Stor-Rotliden	Bergkvara
Blade	2	1.40	1	2		
Proportional Valve	7	5.36	4	5	1	1
Piston Accumulator	10	6.57	7	8	1	1
Encoder	8	5.87	5	6	1	1
Bearing Generator	3	2.47	2	2	1	
Generator Fan 1	3	2.49	2	2	1	
Generator Fan 2	5	3.96	3	3	1	1
Encoder Rotor	16	10.55	11	13	2	1
Slip Ring Fan	7	5.36	4	5	1	1
Fan	3	2.49	2	2	1	
Motor for Cooling System	8	5.86	5	6	1	1
Yaw Gear (right)	5	3.91	3	3	1	1
Yaw Gear (left)	5	3.91	3	3	1	1
Yaw Motor	4	2.94	3	3	1	
Mechanic Gear for Oil Pump	3	2.46	2	2	1	
Chopper module	3	2.46	2	2	1	
TRU card	5	3.96	3	3	1	1
SKIIP 1	10	6.55	7	8	1	1
SKIIP 2	3	2.46	2	2	1	
EMC Filter	7	5.36	4	5	1	1
Capacitors	16	10.55	11	13	2	1
CT 3220 FFFF	5	3.96	3	3	1	1
CT 316 VCMS	2	1.99	1	1	1	
CT 3601	2	1.99	1	1	1	
CT 3133	14	9.55	9	11	2	1
CT 3220 FFFC	3	2.46	2	2	1	
CT 3218	6	4.46	4	4	1	1
CT 3614	5	3.96	3	3	1	1
CT 3363	5	3.96	3	3	1	1
CT 3153	8	5.86	5	6	1	1
CT 279 VOG	9	6.36	6	7	1	1
Transformer	2	1.68	1	2		
Phase Compensator Generator	14	9.55	9	11	2	1
Q8 Main Switch	8	5.55	5	6	1	1
Q8 Electric Gear	7	5.36	4	5	1	1
Q8 EMC filter	16	10.55	11	13	2	1
Hydraulic Cylinder	7	5.96	-	5	1	1
Rotating Union	7	5.90	-	5	1	1
Gearbox	3	1.13	-	3		
Generator	5	2.90	-	5		
Electric Gear for Oil Pump	12	8.52	-	10	1	1
VCP card	7	5.90	-	5	1	1
Ultra Sonic Anemometer	12	8.52	-	10	1	1
Total:	292	212.95				

Appendix I

Vestas V80/90 Spare Part Demand, 80 WTs

Spare Part	Mean no of items consumed per year	Repair actions per year
Description	*DUs*	*LRUs*
Blade	1.16	-
Proportional Valve	3.84	-
Piston Accumulator	11.52	-
Encoder	3.64	-
Bearing Generator	0.77	-
Generator Fan 1	0.39	-
Generator Fan 2	1.21	-
Encoder Rotor	12.14	-
Slip Ring Fan	3.84	-
Fan	0.39	-
Motor for Cooling System	3.84	-
Yaw Gear (right)	2.42	-
Yaw Gear (left)	2.42	-
Yaw Motor	1.54	-
Mechanic Gear for Oil Pump	1.21	-
Chopper module	1.21	-
TRU card	1.21	-
SKIIP 1	12.14	-
SKIIP 2	1.21	-
EMC Filter	3.84	-
Capacitors	12.14	-
CT 3220 FFFF	1.21	-
CT 316 VCMS	0.39	-
CT 3601	0.39	-
CT 3133	12.14	-
CT 3220 FFFC	1.21	-
CT 3218	1.21	-
CT 3614	1.21	-
CT 3363	1.21	-
CT 3153	3.84	-
CT 279 VOG	3.84	-
Transformer	1.21	-
Phase Compensator Generator	12.14	-
Q8 Main Switch	12.14	-
Q8 Electric Gear	3.84	-
Q8 EMC filter	12.14	-
Hydraulic Cylinder	-	3.64
Rotating Union	-	3.84
Gearbox	-	3.84
Generator	-	3.84
Electric Gear for Oil Pump	-	12.14
VCP card	-	3.84
Ultra Sonic Anemometer	-	12.14

Appendix J

Vestas V80/90 Spare Part Demand, 141 WTs

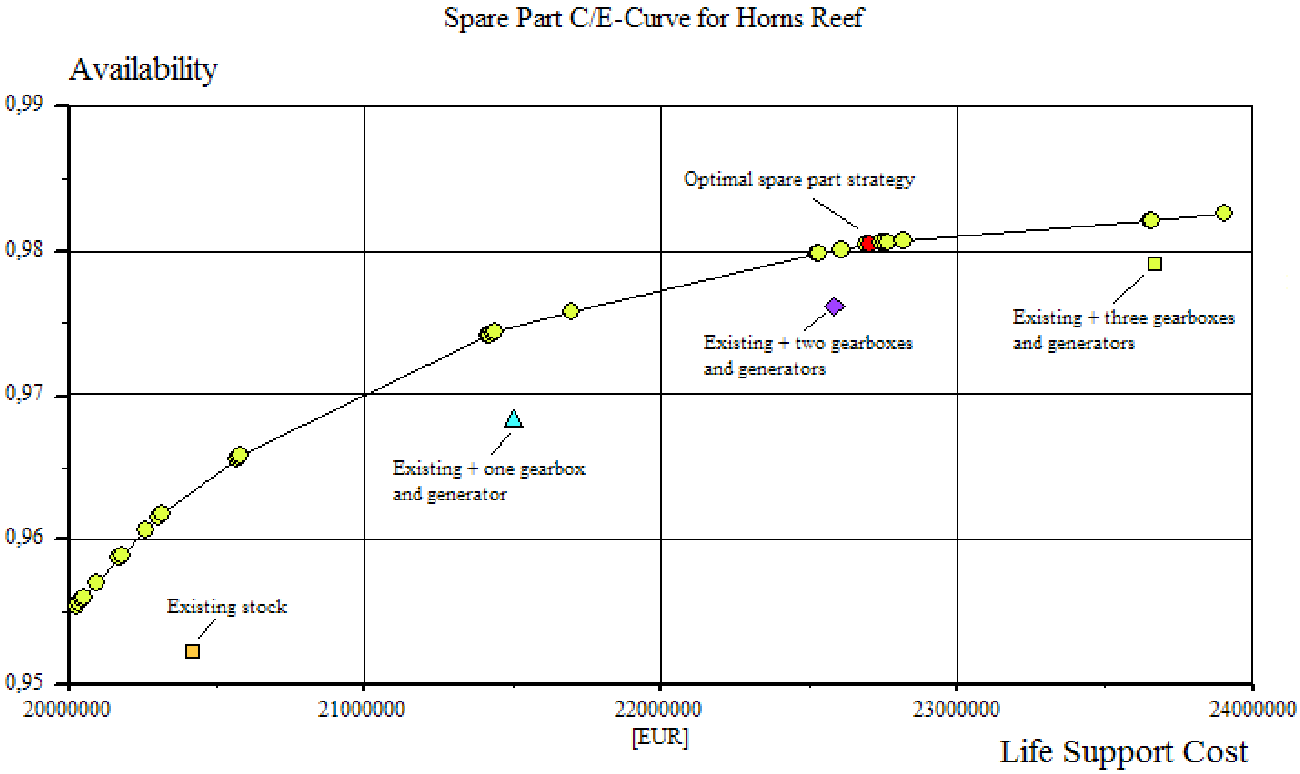
Spare Part	*Mean no of items consumed per year*	*Repair actions per year*
Description	*DUs*	*LRUs*
Blade	2.04	-
Proportional Valve	6.77	-
Piston Accumulator	20.31	-
Encoder	6.41	-
Bearing Generator	1.36	-
Generator Fan 1	0.68	-
Generator Fan 2	2.14	-
Encoder Rotor	21.39	-
Slip Ring Fan	6.77	-
Fan	0.68	-
Motor for Cooling System	6.77	-
Yaw Gear (right)	4.27	-
Yaw Gear (left)	4.27	-
Yaw Motor	2.72	-
Mechanic Gear for Oil Pump	2.14	-
Chopper module	2.14	-
TRU card	2.14	-
SKIIP 1	21.39	-
SKIIP 2	2.14	-
EMC Filter	6.77	-
Capacitors	21.39	-
CT 3220 FFFF	2.14	-
CT 316 VCMS	0.68	-
CT 3601	0.68	-
CT 3133	21.39	-
CT 3220 FFFC	2.14	-
CT 3218	2.14	-
CT 3614	2.14	-
CT 3363	2.14	-
CT 3153	6.77	-
CT 279 VOG	6.77	-
Transformer	2.14	-
Phase Compensator Generator	21.39	-
Q8 Main Switch	21.39	-
Q8 Electric Gear	6.77	-
Q8 EMC filter	21.39	-
Hydraulic Cylinder	-	6.41
Rotating Union	-	6.77
Gearbox	-	6.77
Generator	-	6.77
Electric Gear for Oil Pump	-	21.39
VCP card	-	6.77
Ultra Sonic Anemometer	-	21.39

Appendix K

Vestas V80/90 New Item Types

Spare Part *Description*	***Price*** *EUR*	***Type*** *LRU/DU*
Blade	75000	DU
Piston Accumulator	1800	DU
Encoder	600	DU
Bearing Generator	1800	DU
Generator Fan 1	600	DU
Generator Fan 2	600	DU
Encoder Rotor	200	DU
Fan	600	DU
Motor for Cooling System	600	DU
TRU card	600	DU
EMC Filter	1800	DU
Capacitors	200	DU
CT 3220 FFFF	600	DU
CT 316 VCMS	1800	DU
CT 3601	1800	DU
CT 3133	600	DU
CT 3220 FFFC	1800	DU
CT 3218	200	DU
CT 3614	600	DU
CT 3363	600	DU
CT 3153	600	DU
CT 279 VOG	200	DU
Transformer	42000	DU
Phase Compensator Generator	600	DU
Q8 Main Switch	3600	DU
Q8 EMC filter	200	DU
Proportional Valve	1800	LRU
Hydraulic Cylinder	1800	LRU
Rotating Union	3200	LRU
Gearbox	400000	LRU
Generator	120000	LRU
Slip Ring Fan	1800	LRU
Yaw Gear (right)	1800	LRU
Yaw Gear (left)	1800	LRU
Yaw Motor	1800	LRU
Mechanic Gear for Oil Pump	1800	LRU
Electric Gear for Oil Pump	1800	LRU
Chopper module	1800	LRU
VCP card	1800	LRU
SKIIP 1	1800	LRU
SKIIP 2	1800	LRU
Ultra Sonic Anemometer	1800	LRU
Q8 Electric Gear	1800	LRU

Appendix L



Note: The OPUS10 C/E curve from Case 1 compared with the existing spare part strategy at Horns Rev from Case 2 and additional analysis with one, two and three gearboxes and generators in stock.

Appendix M

Vestas V80/90 Spare Part Cost Driver Index

Spare Part	***CDIX***
Gearbox	1 536 154
Generator	460 846
Blade	86 724
Transformer	50 920
Q8 Main Switch	43 696
Electric Gear for Oil Pump	21 848
SKIIP 1	21 848
Ultra Sonic Anemometer	21 848
Piston Accumulator	20 738
Rotating Union	12 289
CT 3133	7 283
Phase Compensator Generator	7 283
Proportional Valve	6 913
Slip Ring Fan	6 913
VCP card	6 913
EMC Filter	6 913
Q8 Electric Gear	6 913
Hydraulic Cylinder	6 547
Yaw Gear (right)	4 365
Yaw Gear (left)	4 365
Yaw Motor	2 775
Encoder Rotor	2 428
Capacitors	2 428
Q8 EMC filter	2 428
Motor for Cooling System	2 304
CT 3153	2 304
Encoder	2 182
Mechanic Gear for Oil Pump	2 182
Chopper module	2 182
SKIIP 2	2 182
CT 3220 FFFC	2 182
Bearing Generator	1 388
CT 279 VOG	768
Generator Fan 2	727
TRU card	727
CT 3220 FFFF	727
CT 3614	727
CT 3363	727
CT 316 VCMS	694
CT 3601	694
CT 3218	242
Generator Fan 1	231
Fan	231

Appendix N

Lillgrund Optimal Spare Part Strategy

Spare Part	*Type*	*Stock Size*	*Average Stock*	*Reorder Point*	*Reorder Size*
Description	*DU/LRU*				
Blade	DU	1	0.808	0	1
Proportional Valve	DU	1	0.996	0	1
Solenoid Valve	DU	5	3.412	1	4
Brake Disc	DU	4	2.456	0	4
Bearing Generator	DU	1	0.991	0	1
Yaw Motor	DU	7	4.388	1	6
Yaw Gear	DU	10	6.147	2	8
Piston Accumulator 6L	DU	2	1.486	0	2
Motor for Oilpump	DU	4	2.456	0	4
Piston Accumulator 0,15L	DU	4	2.456	0	4
SMPS 1	DU	9	5.221	1	8
SMPS 2	DU	7	4.323	1	6
Power Supply 240 V/24 V	DU	4	2.456	0	4
Encoder	DU	8	4.867	1	7
I/O-Modul	DU	3	1.969	0	3
Motor 4kW	DU	6	3.860	1	5
Motor 1.8kW	DU	4	2.456	0	4
Transformer	DU	1	0.894	0	1
Blade Block for Hydraulic Pitch	LRU	5	3.902	-	-
Hydraulic Cylinder	LRU	2	1.890	-	-
Rotating Union	LRU	4	3.634	-	-
Gearbox	LRU	2	1.324	-	-
Oilpump	LRU	2	1.885	-	-
Delta Module (SKII Pack)	LRU	7	4.804	-	-
Wind Sensor	LRU	6	4.842	-	-
Generator	LRU	2	1.324	-	-
	Total:	111	75.24809084		

Appendix O

Future SWT-2.3 Supported by Local Depots, Optimal Spare Part Strategy

Spare Part	*Total Stock*	*Average Stock*	*Klagshamn*	*SWE Depot*	*DK Depot*
Blade	3	2,45	1	1	1
Proportional Valve	3	2,99	1	1	1
Solenoid Valve	15	10,25	5	5	5
Brake Disc	11	6,87	4	4	3
Bearing Generator	3	2,97	1	1	1
Yaw Motor	21	13,18	7	7	7
Yaw Gear	30	18,49	10	10	10
Piston Accumulator 6L	6	4,46	2	2	2
Motor for Oilpump	11	6,87	4	4	3
Piston Accumulator 0,15L	13	7,87	5	4	4
SMPS 1	27	15,70	9	9	9
SMPS 2	21	13,00	7	7	7
Power Supply 240 V/24 V	13	7,87	5	4	4
Encoder	22	13,62	8	7	7
I/O-Modul	9	5,91	3	3	3
Motor 4kW	18	11,60	6	6	6
Motor 1.8kW	11	6,87	4	4	3
Transformer	3	2,70	1	1	1
Blade Block for Hydraulic Pitch	15	11,86	5	5	5
Hydraulic Cylinder	6	5,69	2	2	2
Rotating Union	11	9,95	4	4	3
Gearbox	4	2,35	2	1	1
Oilpump	6	5,67	2	2	2
Delta Module (SKII Pack)	19	12,74	7	6	6
Wind Sensor	17	13,69	6	6	5
Generator	6	4,06	2	2	2
Total:	324	219,72			

Appendix P

Future SWT-2.3 Supported by Central Depot, Optimal Spare Part Strategy

Spare Part	*Total Stock*	*Average Stock*	*Reorder Size*	*Klagshamn*	*SWE Depot*	*DK Depot*
Blade	2	1,42	1	2		
Proportional Valve	2	1,49	1	2		
Solenoid Valve	10	6,74	4	8	1	1
Brake Disc	8	5,87	4	6	1	1
Bearing Generator	2	1,47	1	2		
Yaw Motor	13	8,17	6	11	1	1
Yaw Gear	19	11,44	8	17	1	1
Piston Accumulator 6L	5	3,96	2	3	1	1
Motor for Oilpump	8	5,87	4	6	1	1
Piston Accumulator 0,15L	9	6,37	4	7	1	1
SMPS 1	17	10,17	8	15	1	1
SMPS 2	14	8,97	6	12	1	1
Power Supply 240 V/24 V	9	6,37	4	7	1	1
Encoder	15	9,10	7	13	1	1
I/O-Modul	7	4,91	3	5	1	1
Motor 4kW	13	8,08	5	11	1	1
Motor 1.8kW	8	5,87	4	6	1	1
Transformer	1	0,96	1	1		
Blade Block for Hydraulic Pitch	11	7,83	-	9	1	1
Hydraulic Cylinder	5	4,68	-	3	1	1
Rotating Union	7	5,94	-	5	1	1
Gearbox	4	2,02	-	4		
Oilpump	5	4,67	-	3	1	1
Delta Module (SKII Pack)	15	8,66	-	13	1	1
Wind Sensor	12	8,66	-	10	1	1
Generator	5	2,96	-	5		
Total:	226	152,642245				