



MSc Graduation Project

**Wind turbine reliability characteristics and
offshore availability assessment**

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ABSTRACT

Since the early 90s, wind energy industry has stepped offshore due to a number of interesting characteristics compared to onshore wind harvesting. At least when initially realized, offshore wind farms were not really different than onshore ones, since the same wind turbine technology with slight modifications was directly applied to the new environment. In these early cases, low water depths and small distance to shore may have justified this option. For future large scale offshore wind farms however, it is doubtful whether simply applying the existing onshore wind turbine technology will lead to the desired outcomes, e.g. high energy yield and revenues. Technical reliability of wind turbines affects the economics of an offshore wind farm since failures increase maintenance costs and decrease operational time, thus energy production.

In the beginning of this report, the most important aspects that drive modern wind turbine design are investigated, followed by a review of different design choices for the various parts of a wind turbine as well as overall wind turbine topologies. A thorough reliability analysis, focused on comparison of the most prominent architectures, is then carried out using failure data from two German databases, LWK-SH and WMEP. Total annual failure rates of 2 to 5 failures per wind turbine per year were observed but no specific topology seemed to clearly stand out in terms of reliability. Most critical components proved to be blades, electrical and electronic systems, as well as hydraulics. Gearboxes, generators, and shafts and bearings are also important not because they fail very frequently, but due to the high associated downtimes. Using a widely used reliability growth model, there seem to be more failures during the first years of operation for most subassemblies.

In order to identify the most important parameters affecting offshore wind farm availability and O&M costs per kWh, several Monte-Carlo simulations were performed using the software tool CONTOFAX. Results showed that availability is not only affected by technical reliability, but also availability of heavy lifting equipment and spare parts, site accessibility, crew and vessel strategy, and distance of the wind farm to shore.

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1. INTRODUCTION

1.1 Offshore wind energy

There is an increased interest about renewable energy sources lately as a result of discussions about the disadvantages of traditional power generation methods. Reduction of greenhouse gases emissions and independency from fossil fuels supplying countries are the main benefits of producing electricity using sustainable sources. Moreover, oil and gas reserves on Earth are not unlimited whereas solar irradiation, and therefore wind which is the result of temperature differences within the earth's atmosphere, are inexhaustible energy sources.

Wind energy is the most widely exploited sustainable source nowadays ([1], see Figure 1) and constantly keeps growing in Europe and worldwide. Installed capacity is increasing year by year and for some countries, like Denmark, Germany, and Spain, wind has an important share amongst the overall electrical power supply. Wind turbine technology is also under constant development and larger machines are introduced in the market with evident cost benefits due to economy of scales. 5 MW wind turbines with a rotor diameter of more than 120 m have been lately manufactured while bigger ones are expected to be developed in the coming years.

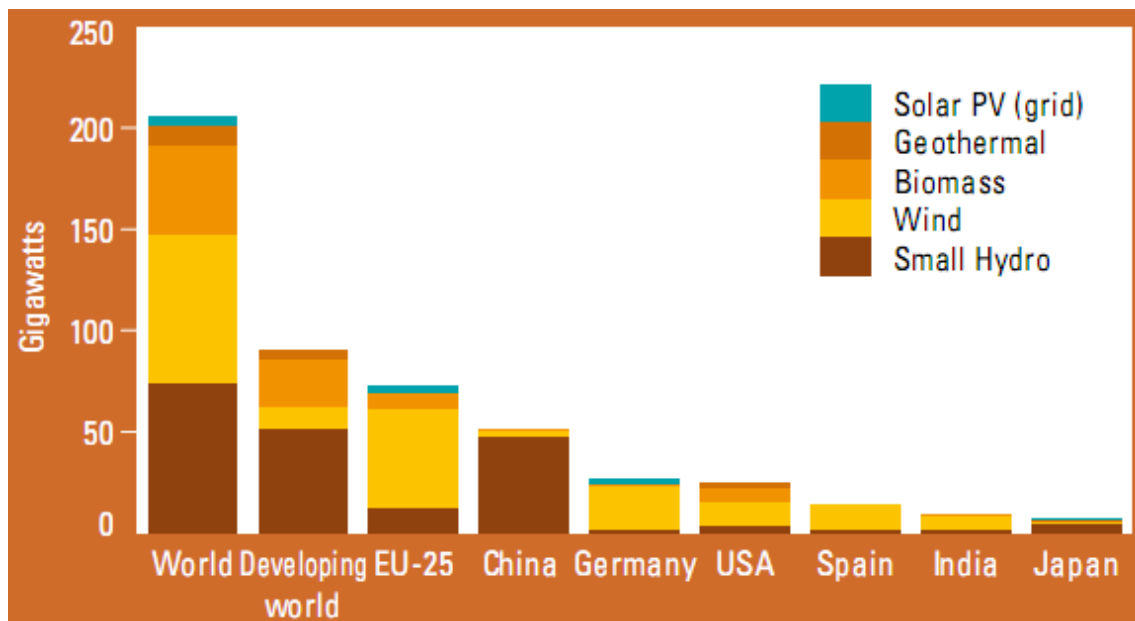


Figure 1. Renewable power capacities in 2007 [1]

Due to lack of space in densely populated areas, aesthetics and noise issues, social acceptance, as well as favourable wind resources, large scale wind power has recently stepped offshore. An offshore wind farm consists of -typically large multi megawatt- wind turbines clustered together in an offshore location some kilometres far from the coast, feeding the local grid on an onshore connection point through cables that are carefully buried under the seabed. Since the early nineties this kind of projects have been realized mainly in Denmark, UK and the Netherlands, countries with advanced wind energy know-how, offshore experience from oil and gas platforms, and favourable characteristics such as shallow waters, strong winds and reliable electrical grids. Nowadays offshore wind farms are gaining increasing interest as an alternative option for electricity generation and various projects are under development (in the Netherlands, Belgium, UK, Denmark, Germany, Spain, and USA). Figure 2 shows the biggest offshore wind farm up to date, which is in operation since 2002. It is located in Horns Rev, 14

1. Introduction

kilometres from the west Danish coast, and consists of 80 Vestas V80-2MW machines at water depths of 6-14 meters.



Figure 2. The 80-unit offshore wind farm in Horns Rev, Denmark

Inevitably there are a lot of challenges that the relatively young offshore wind energy industry has to face and find solutions, mostly because of the special conditions encountered in the marine environment. Extra loads due to waves and currents, water depths, and soil properties of the seabed are just some of the additional parameters that have to be considered during the structural design of an offshore wind turbine. Moreover, due to the saline environment which accelerates unfavourable processes such as corrosion and crack growth, offshore wind turbines require coatings and materials, which are usually more expensive than the ones used onshore. Additionally, difficulties in approaching the site due to weather conditions, distance to shore, and transport means unavailability create problems for the installation and maintenance of offshore wind farms, leading to a significant increase of costs compared to onshore.

At least when initially developed, offshore wind farms were not really different than onshore since the same wind turbine technology with slight modifications was directly applied to the new environment. In these early cases, low water depths and small distance to shore may justify this option. For future large scale offshore wind farms however, it is doubtful whether simply using the existing onshore wind turbine technology will lead to the desired outcomes, e.g. high energy yield and revenues.

1.2 Importance of reliability

A vital factor in the success of -especially offshore- wind energy projects is the technical reliability of wind turbine systems, meaning how often and how severely they fail. Reliability has an impact on the project's revenue because of reduced availability and significant operation and maintenance costs, while it also affects the electrical grid performance, as explained below and visualised in Figure 3.

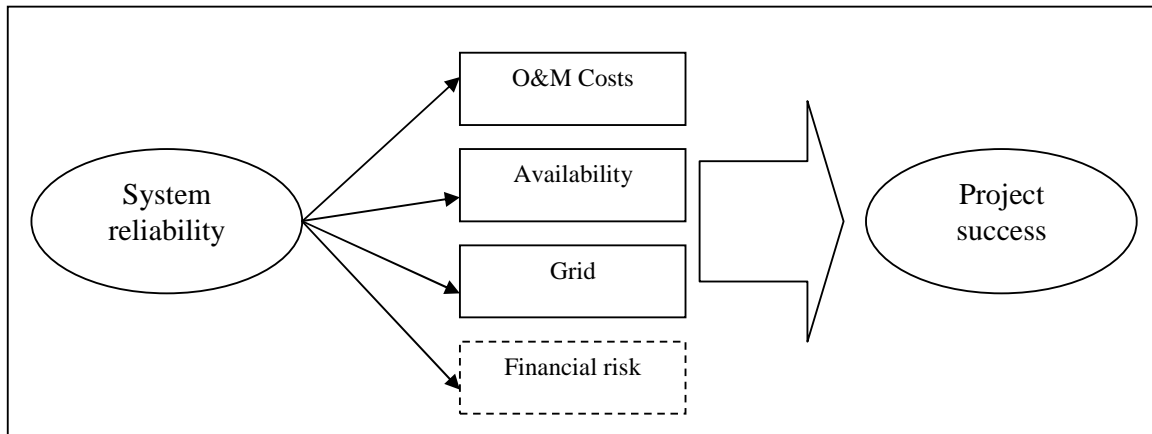


Figure 3. Reliability's influence on the success of a wind energy project

- Availability: Wind turbine (or farm) availability is the percentage of time the system can function properly as it was designed to (a detailed definition follows in section 1.4). Availability is mainly influenced by technical reliability since failures and associated maintenance activities lead to periods of time that the wind turbine is not able to deliver expected power.
- Operation and maintenance costs: These are the expenses necessary for operating and performing maintenance on a wind turbine (or farm), both planned and unplanned. O&M costs strongly affect the cost of wind energy produced electricity; for offshore wind farms they can contribute up to 30% of the total cost [2]. This is mainly because offshore access is much harder than onshore; vessels that are currently used to transport personnel and equipment offshore are expensive and can operate only when the weather is fair. Significant reduction of O&M activities and therefore costs should be reasonably expected if more reliable wind turbines are developed.
- Grid performance: Electrical power produced by offshore wind farms is collected through cables on an onshore point of the network. As part of the electrical grid, wind turbines are requested to function reliably so as to have less severe impact on the power quality of the network. This is more important for networks with high penetration of wind energy systems. In an indirect way, reliability influences the motivation of financial and developer communities to invest on wind power projects, since the increased risk or at least the perception of increased risk for –especially offshore– projects is associated with increased financing fees or interest rates [3]. Investors are not willing to put their money in costly projects with doubtful outcome; they normally demand proven technology so as to reduce risks. The same holds for insurance companies, who hesitate to cover large offshore projects for wind energy exploitation or ask for high premium in order to provide their services.

From another point of view, achieving high availability is also important for manufacturers of wind turbines. Competition in wind turbine business is rather tough today because worldwide there are quite a lot of wind turbine manufacturers, fortunately in a constantly growing market. A proven strategy for a company in order to increase its market share and stand out among its competitors, is to deliver products that exhibit high reliability. This will result in customer satisfaction that eventually facilitates the build up of a good reputation for the company, which is a relative advantage over its competitors.

1.3 Thesis objectives and overview

In the previously described context the main objective of this thesis is to assess the availability of offshore wind farms and suggest how it can be improved by applying certain wind turbine design choices and O&M strategies. In order to reach this main target, the following topics need to be covered as well:

- ✓ review wind turbine topologies that are commonly used or about to be used offshore
- ✓ evaluate the reliability of these topologies by analysing databases containing failures of onshore wind turbines
- ✓ identify the most critical subcomponents of each topology
- ✓ explore factors that affect availability of offshore wind farms.

The first part of the thesis is based on literature and other resources research on wind turbine technology. The analysis begins with identifying the most important aspects that drive modern wind turbine design, followed by a review of different design choices for the various parts of a wind turbine as well as overall wind turbine topologies. Advantages and drawbacks of each system are investigated emphasizing mainly on reliability issues. It should be noted that this part is not intended to be a complete listing of every possible design, but is focused on the most frequently used concepts onshore as well as the ones that seem to be beneficial for offshore applications.

In the second part of the thesis, a detailed study of wind turbine maintenance data from two German sources – LWK-SH and WMEP – is presented. The analysis is focused on four different wind turbine models, each one representing a specific topology but all being similar in terms of size and power output. For various subassembly categories annual failure rates and associated downtimes are obtained by analysing the databases. Additionally, by applying a reliability growth model for repairable systems widely used in other engineering fields, changes of failure rate in time are tracked down. Results from the different topologies are finally compared in order to find possible advantages or disadvantages of each concept in system reliability.

The third part contains availability estimates of offshore wind farms using CONTOFAX [2], which is a software tool based on Monte Carlo simulations. Analysis begins with a case study of a representative modern offshore wind farm which will be used as the baseline. The baseline maintenance strategy represents the most typical maintenance strategy of a common offshore wind farm. Variations of the base case are then simulated so as to find which parameters affect availability and O&M costs of (future) offshore wind farms. Optimization of the O&M strategy is possible by comparing the outcome of all simulated scenarios. At the end of the thesis there is a discussion on the results obtained in all previous parts, and conclusions on reliability and availability issues of current and future offshore wind farms. The last chapter contains some suggestions for research on topics of wind turbine reliability and availability issues.

1.4 Definitions of basic terms

Due to diversity of definitions in reliability relevant literature, it is necessary to clarify the meaning of basic terms which will be frequently encountered in the present document. For the following definitions, sources [4-6] were consulted.

Failure is the inability of a system or part of the system to perform its required function under defined conditions. The system is then in failed state, in contrast with operational (or working) state. The required function of a wind turbine is to convert wind power to electricity

when wind speed is within a certain range. Therefore a failure means that the wind turbine is unable to deliver the expected amount of electrical power for given wind conditions.

Wind turbines are *repairable systems* which means that when a failure occurs, they can be restored into operational condition after any action of repair, other than replacement of the entire system, takes place. Repair actions can be for instance settings adjustment, parts exchange, addition, or removal, software update, lubrication, cleaning. Other examples of repairable systems include vehicles, electrical generators, medical equipment, computers, air conditions, and large household appliances such as refrigerators and washing machines. A *non-repairable system* is a system that is discarded after a failure, either because no repair action can bring it back to properly functioning or, most commonly, because it does not worth to perform repair instead of replacement of the entire system. Light bulbs, keyboards, telephones, desktop fans, pocket calculators are some examples of non-repairable systems. It should be noted that some repairable systems become non-repairable after some time, since technology improvements and automated production processes result in inexpensive products that is cheaper to discard rather than fix when they fail.

Reliability of a system or component is the probability that it performs its required function under stated conditions for a specified period of time.

Failure rate (or failure frequency) of a repairable system or system component is the ratio of the number of failures observed or expected within defined time interval, to this time interval. For wind turbines and their subassemblies, it is usually expressed in number of failures per calendar year.

Mean Time Between Failures (abbreviated as MTBF), usually expressed in hours, is another way to express reliability of repairable systems and denotes the average time between two successive failures. If the failure rate is constant with time, then MTBF is simply the reciprocal of failure rate. *Mean Time To Repair* (abbreviated as MTTR) is the average time required to repair a system and bring it back to operational state after a failure.

In the present document, wind turbine *availability* for a specified time interval (usually one calendar year) expresses the percentage of time a wind turbine is able to function, independently of wind conditions, and excluding grid faults or human interventions such as manual shutdowns. For the complete wind farm, availability is the average of the availability values of all wind turbines for the same period of time. This definition makes clear that availability does not include the amount of time a wind turbine is not operating because wind speed is below cut-in or above cut-out values, but it refers to the time the wind turbine has no kind of failure nor it is under any type of maintenance, scheduled and unscheduled. This amount of time is called *uptime*, while *downtime* refers to hours that a wind turbine is unable to function. The fraction of uptime over the sum of uptime and downtime is usually used to express wind turbine availability. Availability depends on technical reliability, and site accessibility, which are influenced by other parameters, including the chosen maintenance strategy (see Figure 4). *Serviceability* and *maintainability* refer to the ease of scheduled servicing and unscheduled repair respectively, and are usually expressed in average hours required per activity.

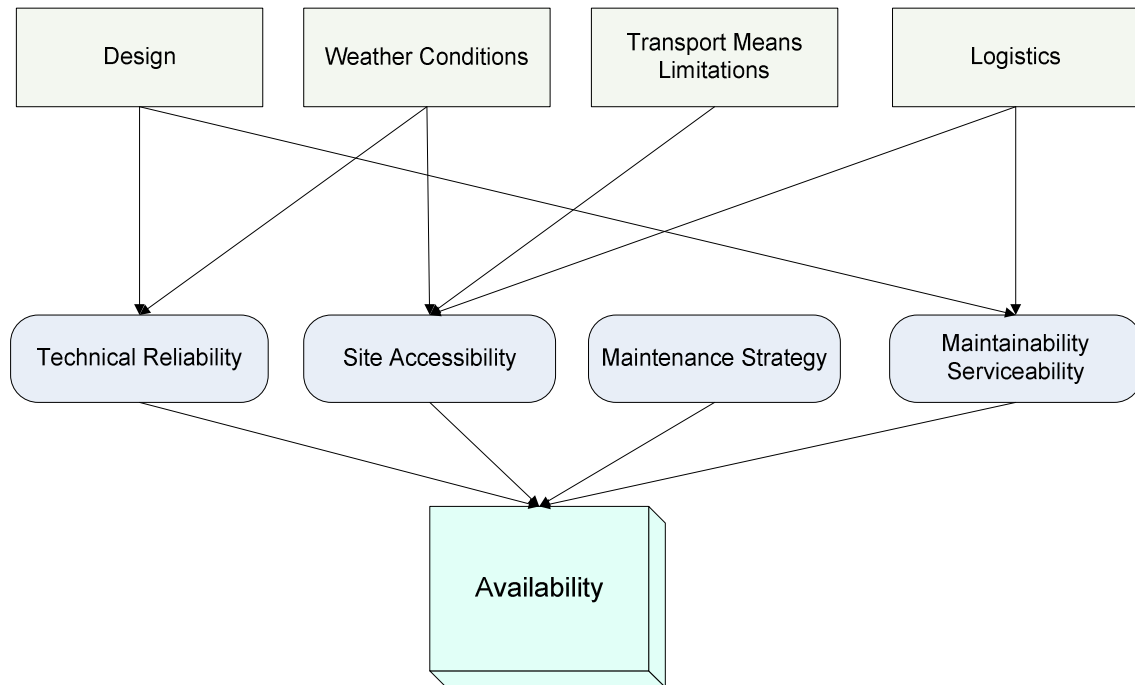


Figure 4. Availability dependencies

The term *maintenance* describes all actions which have as an objective to retain an item in or restore it to, a state in which it can perform the required function. The actions include the combination of all technical and corresponding administrative, managerial, and supervision actions. *Preventive maintenance* includes all actions performed on an item so as to preserve its present operational state, while *corrective maintenance* suggests the actions taken to repair an item and bring it back to function after the occurrence of a failure. Both types can be either scheduled or unscheduled, depending on whether they are planned between regular time periods or not. Maintenance activities that are performed if a certain condition is satisfied are called *condition-based*, in contrast to *maintenance on-demand* which describes actions that are taken immediately after an event such as a failure. It is clear that there are different possibilities on how to perform preventive and corrective maintenance.

Maintenance strategy includes all the chosen tactics and parameters regarding maintenance of a system. In onshore wind farms it is common practice to perform scheduled preventive maintenance twice a year, and unscheduled corrective maintenance on the event of a failure. Usually every 5-7 years, a *major overhaul* takes place which apart from a thorough inspection may also include exchange of large subcomponents.

Especially for offshore wind farms, *accessibility* expresses the amount of time a site can be accessed by the available transport means. Each vessel can operate only within certain wave height and wind speed ranges. Based on meteorological observations, it is possible to estimate the fraction of time that a given site is accessible within a year by a certain type of vessel. Since maintenance actions on a failed machine cannot be performed until the vessel can access the site, accessibility affects downtimes and overall wind farm availability.

2. WIND TURBINE TECHNOLOGY

Before analysing reliability and availability aspects of wind turbines, it is important to clarify functionality of the most important systems incorporated, and explore available design options. Based on what is more probable to be used offshore, common topologies are described at the end of this chapter.

2.1 Structural Breakdown of a modern HAWT

A wind energy converter includes several subassemblies, each one being in charge of specific functions. Figure 5 illustrates name and location of all subassemblies encountered in modern horizontal axis wind turbine (HAWT), while Table 1 summarizes their main functions. Note that these subassemblies can be further broken down into their structural parts, for example the generator consists of a rotor, a stator, slip rings etc.

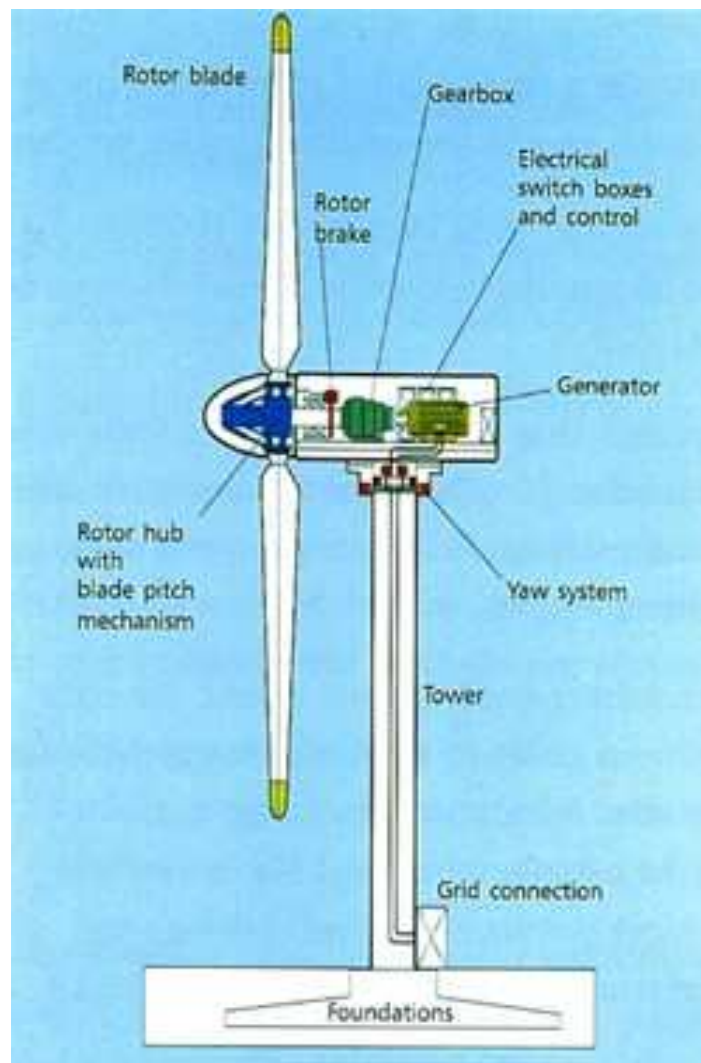


Figure 5. Subassemblies of a modern HAWT

Table 1. Functions of subassemblies

Subassemblies	Functions
Blades	To rotate due to lift force by wind
Hub	For blades attachment
Pitch system	To adjust blade pitch angle to control power output and limit loads, to brake the wind turbine
Yaw system	To orientate the rotor based on wind direction
(Low & high speed) Shafts	To transmit torque
Gearbox	To increase rotational speed
Electrical generator	To convert mechanical torque to electromagnetic torque
Power Electronics Converter	To match generated electricity to grid specifications
Main transformer	To step up voltage level
Sensors	To measure various operational parameters
Control system & PLC	Monitoring, controlling, automation
Braking system	To brake wind turbine
Electrical systems	To connect WT to the grid, to supply power, etc
Tower	Nacelle mounted on top

2.2 Design considerations

Every commercial wind turbine is designed to convert wind power to electricity economically and safely during its technical lifetime. Safety and economics therefore drive wind turbine designs, but this implies several considerations to be taken into account, as summarised in Figure 6. In the following section the most important design drivers are described so as to portray design possibilities and limitations. In this report only drivers directly or indirectly associated with reliability are examined, so for example noise issues or impact on surroundings are not included, although they are taken into consideration during design.

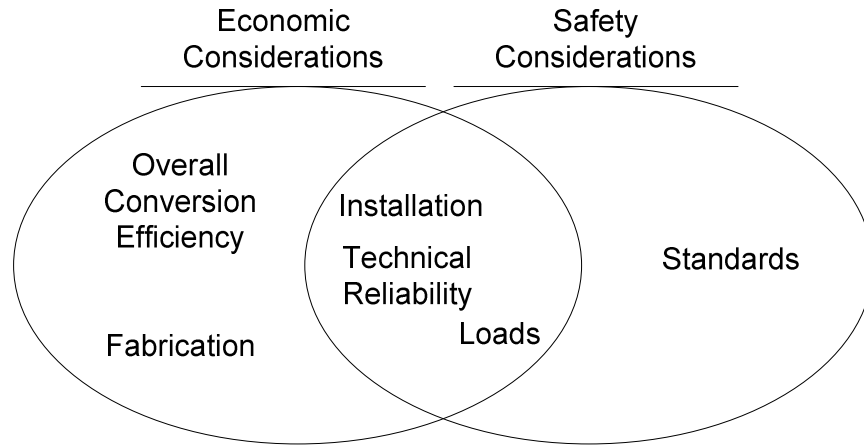


Figure 6. Design considerations

2.2.1 Economic considerations

A fundamental constraint in the process of wind turbine design is economic viability of the final product [7]: the cost per energy produced should eventually be as low as possible, so that the machine will be competitive to other energy conversion systems, both renewable and traditional. The cost of energy depends on various factors, most important of which are listed below; some of them are obvious and others more indirect but of similar significance. These drivers are so important that are taken into account throughout all the design phases, from preliminary to final.

Overall conversion efficiency

All types of energy conversion and transmission include losses. For a wind turbine these can be aerodynamic losses, which blade design aims at minimising, gearbox losses, which come from stepping up the rotational speed, generator losses, such as the iron and copper losses, power electronics conversion losses, due to adjustment of the voltage and electrical frequency level, and electrical losses at the transformer and cabling. In the case of wind farms, array losses due to the wake effect have to be taken into account as well, since they result in energy yield reduction.

Energy production strongly depends on the overall efficiency of the wind turbine, but design does not only target at high efficiency levels, since methods to reduce losses usually require higher manufacturing costs, e.g. advanced power cables. A feasible design should be cost effective and have a reasonable balance between efficiency and production costs.

Furthermore, complex systems which may be used for increasing efficiency should be avoided, since they may reduce overall reliability, be harder to manufacture and/or install.

Fabrication

Total wind turbine manufacturing costs depend on the various (sub-) components' weights, the type of materials chosen, and the fabrication processes used. It is favourable to have low weights mainly for reduction of loads and installation time, but lightweight materials are typically more expensive. Complex designs usually require special manufacturing techniques, which increase the cost of fabrication, thus the overall cost of energy. That is why it is common practice to sacrifice small amounts of efficiency for making components that are easy to manufacture. It is also preferred to use standard off-the-shelf techniques rather than special designs, because such components' delivery times can be quite high, and their

performance is not proven on field. It is even common practice for wind turbine manufacturers to order some parts from external suppliers, but this might cause delays in the production line due to long delivery times, thus increasing costs. Nowadays increasing steel and oil prices give additional rise to manufacturing and transportation costs. The designer should be aware of these issues, since the final product has to be competitive in the market.

Technical reliability

Stand still times due to failures and maintenance works have a negative effect on the performance of a wind turbine, since energy production is a function of the amount of time the machine actually operates. This is more prominent offshore, where downtimes can be quite significant due to inaccessibility of the remote site because of severe weather conditions. It is therefore very important to design wind turbines that operate reliably with as minimum service and repair requirements as possible. In that sense, subcomponents that are sensitive, involve many moving parts, and perform complex functions are sometimes avoided because experience has shown that those characteristics suggest prone to failure products. Moreover, ease of maintenance should be taken into account during the detailed design of subcomponents so as to achieve relatively low repair times, thus reduced downtimes.

Installation

Installing a wind turbine includes transporting all tower sections and nacelle parts on site, preparing the foundations, erecting the tower, lifting the nacelle on top of the tower, and fixing the blades. Due to the increasing size of modern wind turbines, transportation and installation costs can be quite significant and give rise to the overall cost of energy. This is more prominent offshore where special vessels with limited accessibility are required. In order to facilitate transportation and installation procedures, compact or modular designs with reduced weights and sizes are generally preferred. For very large wind turbines, the designer should also be aware of the limitations currently available machinery and transportation means have.

2.2.2 Safety considerations

A wind turbine deals with huge forces caused by the wind and its own rotational movement; it should therefore be designed for safe operation under all possible situations during its technical lifetime. Commercial wind turbines acquire certificates from independent renewed institutes, which prove that they are designed following the principles of accepted standards (e.g IEC-61400 series).

Loads

Reducing loading is crucial for the safety and integrity of the wind turbine and many design choices are based on that constraint. For all its lifetime, a wind turbine must withstand any loads possible to be encountered during any operational state: standstill, starting, producing power, shutting down. Moreover, it should be able to survive any possible ultimate loads caused by extreme weather conditions such as very high mean wind speed, even if they rarely occur. Finally, for a specific amount of time, which is basically the machine's lifetime, usually 20 or 25 years, the wind turbine must also hold up to cumulative, fatigue-induced damage, which comes from periodic, transient, and stochastic loads [7].

Standards

Based on research and experience, various standards have been developed in order to certify safe operation of wind turbines through their lifetime. These standards describe acceptable design procedures, explicitly defined load cases, which cover almost every possible event, normal and extreme, while they also contain requirements for braking the wind turbine under any circumstance. Most standards are quite conservative so as to ensure high level of safety of the wind turbine. The IEC-61400 developed by the International Electrotechnical Commission is a series of standards covering almost every aspect of wind turbine design. For large multi megawatt wind turbines there is not yet enough experience gained and the know-how, design codes, and tools are actually upscaled versions of the ones used for medium class machines.

2.3 Design options

For anything that makes up a wind turbine there are more than one possible technologies to choose from. The following overview of most important design choices is not an extensive catalogue of everything available or attempted in the past, but rather a list of the most dominant options in the wind energy market at present. In the design procedure, every choice depends on the previous step's choice, and specifies the possible options for the next step. At any point, there can be alterations and improvements of the initial design till the final production design is established.

2.3.1 Number of blades

Any number of blades is theoretically possible, but a high number of blades leads to more material use and therefore increased weight. Most modern wind turbines have three blades, some two, and even one bladed machines have been realized in the past (Monopteros, Germany, and Riva Calzoni, Italy).

Three bladed rotors exhibit the following advantages when compared to similar one and two bladed rotors: highest efficiency, smooth dynamic behavior due to the weight distribution being more balanced over the swept area, lower aerodynamic noise levels, and reduced visual impact because their rotation looks smoother.

Two blades have weight and cost advantages, since less material is used to construct them, and are generally easier to install. A major drawback however is that teetered hinges are needed so as to balance gyroscopic loads when yawing. The moment of inertia is higher when the blades are aligned horizontally than vertically. In order to reduce large cyclic loads during yawing teetered hinges are required for two or one bladed rotors [8].

The advantages of one bladed rotors are that they can run at a relatively high tip speed ratio, resulting in lower drive train loads, be possibly cheaper, more reliable, and easier to install. They also offer a unique parking technique: the blade is placed pointing down to the ground and the rotor is yawed downwind. However they are not an attracting option for designers, because they exhibit important drawbacks: lower efficiency as a result of high tip losses; no weight reduction compared to a 2-bladed rotor, since a counterweight is required to balance the single blade; very complex dynamics; high noise levels as a result of high tip speed ratio for optimal energy capture; visibility problems, since one blade seems like rotating unsmoothly.

2.3.2 Rotor orientation

There are basically two possible ways to orientate the rotor, either upwind or downwind of the tower (see Figure 7). In upwind rotors, an active yaw system is used to adjust the rotor position with respect to wind. The blades should be made rather inflexible and have some distance from the tower so as to avoid collision. The main advantages of a downwind rotor

are that the wind turbine is passively oriented to the prevailing wind direction without the need of an active yaw system, and that the blades can be made more flexible, leading to cost reduction. Moreover, it is possible to reduce root flap bending moments in a downwind configuration by taking advantage of centrifugal forces. This is because the blades are normally coned downwind, so centrifugal moments counteract moments due to thrust [7]. However, downwind rotors experience an alternating load due to the periodical passing of each blade through the disturbed wind field of the tower wake, resulting in increased fatigue damage, additional aerodynamic noise, as well as reduced power output. This disadvantage explains why the vast majority of modern wind turbines have upwind rotors. A way to minimize the impact of the tower shadow effect in wind turbines with downwind rotors is the usage of lattice instead of tubular tower designs.

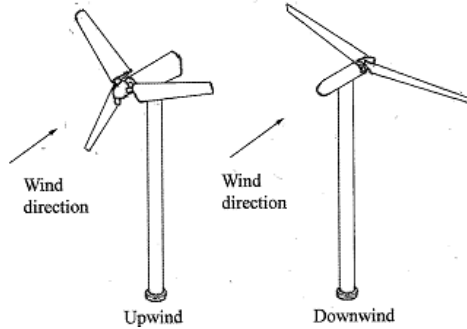


Figure 7. Possible rotor configurations [7]

2.3.3 Power regulation

A control system is necessary so that the wind turbine operates within certain ranges of rotational speed, torque, thrust, and eventually power. Pitch and stall regulation are most commonly used for this purpose, although other techniques are possible like yawing the rotor out of the wind or utilizing aerodynamic surfaces attached on the blades, such as flaps or ailerons. Yaw control has the disadvantage that the hub is subjected to large gyroscopic loads when yawing, and that is why this method is applied mainly in small wind turbines. Aerodynamic surfaces are not so spread mainly because of the complexity they introduce to the aerodynamic blade design. In this section, advantages and disadvantages of possible stall and pitch control philosophies are described and summarized in Table 2.

Table 2. Comparison of most common pitch and stall control systems

Control system	ROTOR SPEED	advantages	Disadvantages				
Pitch (Pitching to feather)	Fixed / Limited variable	High energy yield Loads reduction Pitch for braking Control accuracy Constant power output above	<table border="1"> <tr> <td>Pitch mechanism required</td> <td>Fast pitching required for dealing with gusts</td> </tr> <tr> <td>Power electronics convert</td> <td>Power fluctuations</td> </tr> </table>	Pitch mechanism required	Fast pitching required for dealing with gusts	Power electronics convert	Power fluctuations
Pitch mechanism required	Fast pitching required for dealing with gusts						
Power electronics convert	Power fluctuations						

2. Wind Turbine Technology

	Variable	Due to power electronic converter, different types of generators can be used	Optimum power control Reduced noise levels	er required (variable speed)
(Passive) Stall	(Dual) Fixed	Rigid blades Less maintenance Direct coupling to grid Easy construction		Loads by high thrust Braking system other than blade pitching Noise issues Limited power control
Active stall (Pitching to stall)	(Dual) Fixed	Pitch for braking Better power control than passive stall Constant power output above rated Slower pitch mechanism can be used		Pitch mechanism required High thrust forces Less accurate control

The blades of stall regulated wind turbines are firmly attached to the hub, so the pitch angle is fixed. They are designed so as to take advantage of the intrinsic stall effect which occurs after a certain angle of attack: as the wind speed and angle of attack increase, the flow becomes more and more stalled, the lift force is decreasing and the drag force is increasing. The rotor efficiency drops and this results in limiting the power output. The main advantage of stall control is that there are less moving parts since a blade pitch system is not required, although it can sometimes be present for braking purposes only. On the other hand, the wind turbine is subjected to more severe blade and tower loads due to low vibration damping of the stalled blades [9]. Moreover, the power output of stall regulated wind turbines is a bit lower than that of pitch regulated, mainly because the lift decreases for high wind speeds above rated, where the flow on the blade is into the deep stall region.

In pitch regulated wind turbines, the blades (or part of them) can turn about their long axis by means of an active actuation system, which is usually an electric motor or hydraulic system. The optimal pitch angle is determined according to measured conditions and power output. There are basically two techniques of pitching the blades, one is positive blade pitch control (pitching to feather or simply pitch control) and the other is negative pitch control (pitching to stall or active stall control). In the former type, power is limited by pitching the blades so as to reduce the angle of attack and therefore the lift force. In the active stall type, the angle of attack is increased by decreasing the blade pitch angle towards the stall region where lift becomes lower and drag higher. Pitching to feather control is more accurate and thrust forces are lower than active stall. However, the pitch actuator system for active stall can be much slower than in the case of pitching to feather, allowing simpler designs.

Both pitch and stall philosophies can be used with either fixed or variable speed operation. Most pitch regulated wind turbines operate at variable rotational speed before they reach rated power output because this allows better power controlling, reduction of loads, and the use of a

slower pitch mechanism than in the case of constant speed. Variable speed operation in the range of roughly 60% to 110% of the rated speed [10] is possible by using either a slip ring induction generator together with a partial power converter or a synchronous generator with a full power converter, which is more expensive. Most stall regulated wind turbines rotate at a speed which is kept constant through the generator's direct connection to the grid. Using two generators with different nominal power or a pole changing generator with two stator windings, operation at two fixed speeds is possible, which has advantages in noise levels and energy yield. Limited variable stall controlled wind turbines have been also realized by using variable resistance generator, which permits small speed variations –in the order of $\pm 10\%$ of the rated speed– thus relieving loads.

A pitch system usually consists of an electrical motor and some gears that transmit torque to a rod that crosses the blade. Individual pitching of each blade is possible with the same or different per blade pitch rate. Hydraulic systems can also be used, but are not generally preferred for being sensitive. The whole operation is monitored and controlled by a special computer (Programmable Logic Controller unit abbreviated as PLC) which gathers and evaluates all information that come from various sensors and measuring instruments of the wind turbine. Operation and monitoring can be done remotely, for example from an office located at the closest port in the case of an offshore wind farm.

2.3.4 Drive train

While common electrical generators rotate at 1500 RPM (for grid frequency of 50 Hz), rotor speed is typically in the order of some tenths of RPM. In order to use a standard off-the-shelf generator in a wind turbine, it is required to increase the rotational speed to the level of generator speed; this is done by means of gears. A basic drive train setup consists of: a low speed shaft which transmits the rotor torque to the gearbox; a gearbox where the rotational speed is stepped up according to generator requirements; a high speed shaft which transfers torque to the generator; support bearings and couplings. These are usually implemented either in a modular or an integrated structure. Some examples of the different arrangements of the drive train are given in Figure 8. The main advantages of fully or partially integrated structures are compactness of the nacelle and reduction of weight since the bed frame is not required, as well as easier assemblage. However, maintenance becomes harder and sometimes the whole nacelle has to be taken out for major repairs or replacement of parts. Moreover, in the modular drive train, loads caused by wind gusts can be partially absorbed.

Usually conversion of rotational speed takes place in multiple stages, such as 3. The preferred gears are combined spur-planetary type because of their compactness and therefore lower volume.

In drive train design it is critical to make realistic estimations of the large and varying loads that the various components experience during the wind turbine's lifetime. Operational experience however has shown that especially gearboxes wear more often than expected, implying inadequate design due to insufficient load estimations. Moreover, gearbox losses are quite significant especially during operation below rated rotational speed.

The direct drive concept has been introduced in order to eliminate the gearbox, which is achieved by coupling the rotor directly with a generator that operates at low rotational speeds (more information about direct driven generators is given in the section about electrical generators). Most commonly a shaft connects the rotor directly with the generator, but some manufacturers (Zephyros [12] -now owned by Harakosan- , Directwind, DarwinD) use no shaft but only a single bearing, where on one side the hub is mounted and on the other the generator rotor; this concept's apparent advantage is the reduction of rotating parts and nacelle's weight.

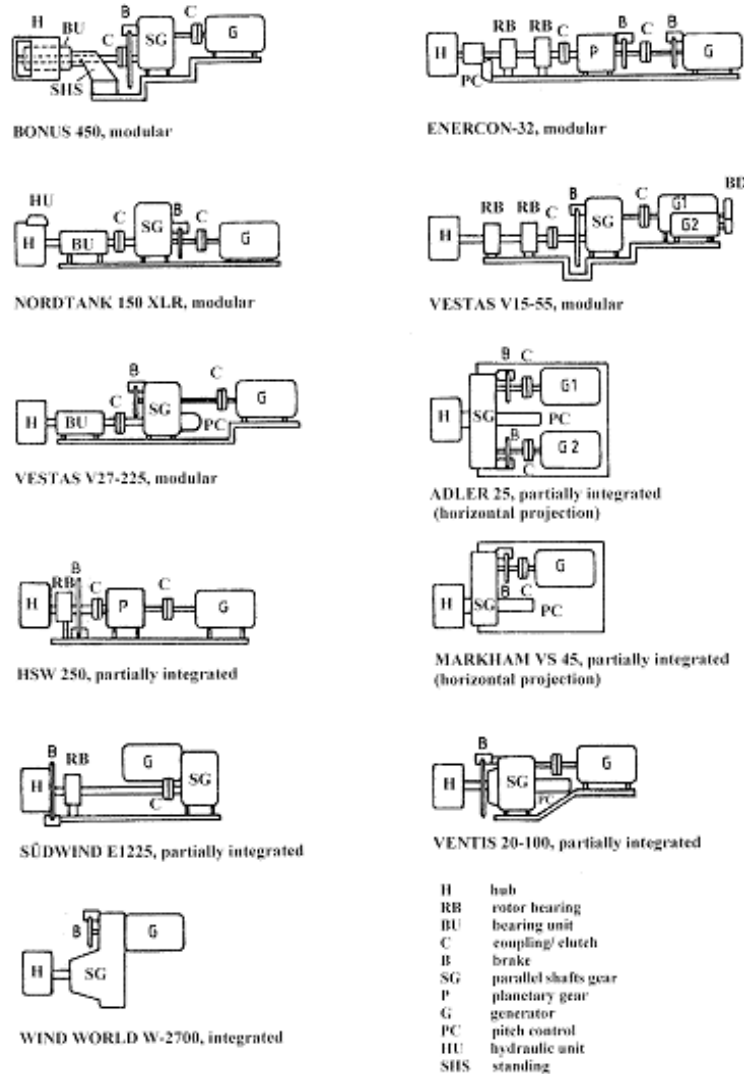


Figure 8. Various drive train structures [11]

2.3.5 Electrical generator

Generator is an electrical machine which converts mechanical energy to electricity, e.g. mechanical torque to electromagnetic torque. There are two types of generators depending on the synchronous speed, synchronous and induction (asynchronous) generators. The choice of the electrical generator depends and influences other design choices such as rotational speed, drive train design, connection to the grid, and type of power regulation. Advantages and disadvantages of most common generator systems are summarized in Table 3; more detailed comparison can be found in [10] and [13].

Standard squirrel cage induction generators are used in wind turbines, because they are relatively cheap and can be directly connected to the grid without the need of conversion by means of power electronics. A gearbox is required for stepping up the low shaft rotational speed to the operational speed of the generator, in the order of 1500 RPM, which is kept fixed due to direct grid connection; this implies fixed ($\pm 1\%$) rotational speed for the rotor as well. It is most common to use this type of generator with stall or active stall controlling.

For fixed speed wind turbines, it is preferred to have two generator speed possibilities in order to reduce noise levels and yield more power from wind speeds below rated. One way to achieve this is to use two generators, a small one for wind speeds up to rated and a large one for wind speeds above rated. In accordance with the generator, the rotor has a low and a high fixed rotational speed. Another option is to use a pole changing generator which has two stator windings with different number of poles, allowing operation in two speed levels. Still, variable speed in the order of $\pm 30\%$ of rated is desirable because of lower noise levels below rated wind speed and higher energy yield, which is achieved by maintaining the tip speed ratio constant at its optimum value. For variable rotor speed operation, a typical squirrel cage induction generator would require power electronic converters with rating 100% of the rated generator power, which are quite expensive and exhibit high losses. It is possible to use smaller power electronics converters with ratings of about 25-35% of the rated generator power by means of a doubly-fed induction generator, which has its wound rotor connected to the converter, while its stator is directly connected to the grid. However this system cannot deal with a grid fault and the wind turbine has to be disconnected until the fault is cleared in order to protect the converter. This seriously affects the power quality of electrical grids with significant penetration of wind power. Additionally, doubly-fed induction generators are more expensive than standard squirrel cage induction generators and require slip rings with brushes, which are sensitive and need regular maintenance. Vestas achieved elimination of brushes, slip rings and external resistors by using optical fibre communications on a wound rotor induction generator with electronically controllable resistance of the rotor windings (OptiSlip[®] patented technique). This allows speed variations in the range of $\pm 10\%$ of rated speed. The main drawbacks that this generator type introduces to the wind turbine are increased loading and noise levels compared to variable speed machines, as a result of smaller speed variation.

As already mentioned in the drive train section, special generators can be directly driven by the rotor without the need for a gearbox. Low speed operation requires a large number of pole pairs and that is why direct drive generators are much larger and heavier than standard ones. Moreover, since they are synchronous machines, a means of exciting the rotor field is needed. Electrical excitation has been initially preferred over permanent magnets (PM) because it was cheaper; however, as prices of permanent magnets drop, PM generators become an attractive option because they are lighter and cheaper, since less active material is needed, have no brushes, and exhibit higher energy yield due to absence of excitation losses [13]. There are however some drawbacks for PM, such as high prices of the materials used, and degradation of their magnetic field with time.

Table 3. Comparison of possible electrical generator systems

GENERATOR TYPE	advantages	Disadvantages
Squirrel cage induction generator	Standard off-the-shelf technology Robust (e.g. no brushes) Simple Cheap Direct Grid Connection	Only $\pm 1\%$ speed variation (thus increased noise and mechanical loads) Lower energy yield Grid voltage and frequency control not possible

2. Wind Turbine Technology

Wound rotor induction generator with Opti-Slip®	No brushes Direct Grid Connection	Limited speed variations ($\pm 10\%$ of rated) Losses in the controllable rotor resistance
Doubly fed (wound rotor) induction generator	Variable speed variation Partially rated power electronic converters Standard off-the-shelf technology	Brushes that require regular maintenance
(Electromagnets or Permanent Magnets) Synchronous generator	Variable speed variation Low rotational speed (no gearbox) Voltage and frequency control as a result of full power conversion	Large and heavy (not for PM) Expensive (specially PM) Not standard technology Fully rated power electronic converters Generally complex electrical system Brushes that require regular maintenance (not for PM)

In all direct drive generator designs, full power has to be converted by means of power electronic converters so as to match the grid requirements. Although costs and power losses are higher, full power conversion results in better power quality because of voltage and frequency control, which can also be used for supporting the grid during grid faults. After choosing the type of generator, a designer has to determine its dimensions and output voltage level. Sizing aims at reducing generator's volume and using as least material as possible. Voltage level is usually in accordance with industrial standard levels, for example 690, 960, 3000 and so on Volts. Low values are more appropriate for small and medium class wind turbines, since they require expensive cables and have more copper losses. High voltage levels result in thick insulation around the generator's wires, and should be used only for large wind turbines or when distance to grid connection point justifies it (e.g. remote offshore wind farms).

In most cases the generator output voltage level will be lower than the grid voltage, so a step-up transformer is needed to match grid requirements. It is a standard industrial device so the choices are the same like any other field where transformers are used. For example, there are wet (oil-filled) and dry transformers available which have different internal cooling system. Transformers are usually placed either in the interior of the tower or in a cabinet located close to the wind turbine.

2.3.6 Braking systems

Manufacturers have to make sure that their wind turbine is able to stop operation under any condition at any time, for example extreme weather conditions, grid failure, component malfunction, rotor overspeed, or maintenance activities taking place in the nacelle. For this purpose two braking mechanisms which must be able to function independently are implemented. Aerodynamic braking is typically used as the main braking system and it can be implemented by pitching 90 degrees along its longitudinal axis either full span or part of the blade. Full blade pitching is used for braking pitch and active stall controlled wind turbines,

since they already have pitch mechanism. In passive stall wind turbines only the tip of the blade can vary its pitch angle (tip brake). Yawing out of the wind is also an option for braking, but exhibits important disadvantages like high gyroscopic loads. Mechanical brakes, like disk brakes and clutches in the drive train, hydraulically or electrically driven, are used as secondary fail safe breaking systems. These are activated when the main braking system is not enough, which occurs rather rarely, or together with the primary brake when technicians perform maintenance activities inside the wind turbine.

2.3.7 Tower structures

Wind speed increases with increasing height as a result of the wind shear effect, while turbulence intensity slightly reduces due to lack of obstacles far from the ground. Those favourable conditions together with noise restriction issues justify the fact that wind turbine towers are generally very high, in the order of 100 m above ground level for multi-megawatt onshore machines. Offshore towers can be made a bit smaller because noise is not an issue, and surface roughness, therefore wind shear effect, is reduced compared to onshore. There are mainly two tower types to choose from, either lattice or tubular; the former are made using welded steel profiles and the latter can be either steel or steel-concrete constructions. Lattice towers are cheaper and reduce the tower effect, which is important for downwind wind turbines. However tubular towers are more commonly used mainly because they offer space for devices such as the transformer and allow easier access to the nacelle for maintenance activities through a ladder and/or a built-in elevator. The tower accounts from 10 to 20% of wind turbine's manufacturing costs ([7] [11],) and has to withstand under any condition for 20 or more years, so the main drivers in tower design are costs and safety. Based on the required dynamic behaviour and stiffness of the tower its optimal dimensions can be determined so that it is made of as less material as possible.

2.4 Common topologies

Feasible combinations of the various design options lead to different wind turbine topologies. In this thesis only horizontal axis wind turbines will be examined, since vertical axis machines are not yet widely encountered in offshore applications and are not likely to be implemented. Moreover, focus will be given on HAWT topologies that have been extensively used onshore and are most probable to be transferred offshore, if not already. It should be noted that variations of the basic topology may exist, e.g. permanent magnets vs electromagnets for a direct-drive wind turbine. Similarities and differences of the topologies described in this section can be found in Table 4.

Fixed speed with induction generator, stall control (Danish concept)

The rotor is rotating with a nearly fixed speed of tens RPM at any wind speed. There is a low speed shaft connected to gearbox and a high speed shaft connected to the electrical generator. The gearbox steps up the speed to 1500 or 1800 RPM, which is needed by the generator in order to convert mechanical energy to electricity. The induction generator is directly coupled to the grid with no power electronic converters. Power regulation at wind speeds above rated is achieved by means of passive stall control, so the blades are fixed to the hub and do not pitch. Safety systems used in this concept are mechanical disk brakes sometimes combined with aerodynamic brakes (blade tip brakes).

Some manufacturers use 2 stages of rotational speeds, the low for wind speeds below rated and the high for wind speeds equal and above rated. This requires either two electrical generators of different nominal power or a switchable poles generator, as described in the electrical generators part.

2. Wind Turbine Technology

Manufacturers that developed or adopted the Danish concept include Vestas, Bonus, Nordex, Micon and Made. A large portion of currently installed wind turbines is of that type, but this tends to decrease as newer models are typically variable speed machines with full span blade pitching.

(Limited) Variable speed with induction generator, pitch control

Depending on the incoming wind speed, the rotor is allowed to vary its speed within certain limits. Blades are -usually individually- pitched to feather according to wind speed and direction so as to minimize loads and harvest more power. Pitching is also used to brake the rotor when needed and a secondary braking system, such as a disk brake, was present in early designs until individual blade pitching proved failsafe. A multi stage gearbox steps up the rotational speed of the low speed shaft to the nominal rotational speed of the induction generator. Voltage and frequency are adjusted to desired levels by means of power electronic converters, which are either fully rated by using any generator, or partially rated by means of a doubly fed induction generator.

Pitch controlled variable speed wind turbines with doubly fed induction generator manufacturers that produce this type of wind turbines include General Electric, Siemens, and late Vestas.

Variable speed with synchronous generator, direct-driven, pitch control

In this concept there is no gearbox present and therefore special low speed electrically excited or permanent magnets synchronous generators are utilized. A blade pitch system is used for limiting power as in the previous concept and the rotational speed is allowed to vary within $\pm 30\%$ of the rated. Fully rated power electronic converters are used before connection to the grid so as to adjust the voltage and frequency levels according to the network specifications. Enercon from Germany is the biggest manufacturer of direct-drive wind turbines, implementing this concept since the early 90s and now having up to 6 MW versions. Lately more companies are beginning to adopt this concept, but prefer permanent magnets instead of electrical excitation for the synchronous generator, since they allow smaller and lighter designs.

Table 4. Features' comparison of common HAWT topologies

	<p style="text-align: center;">"DANISH CON CEPT "</p>	<p style="text-align: center;">LIMITED VARI ABLE SPEE D + PITC H CONT ROL + INDU CTIO N GENE RATO</p>	<p style="text-align: center;">VARIABLE SPEED + PITCH CONTROL + DOUBLY FED INDUCTIO N GENERAT OR</p>	<p style="text-align: center;">VARIABLE SPEED + PITCH CONTROL + SYNCHRON OUS GENERATO R</p>
--	--	--	---	--

		R		
Rotational Speed	Fixed $\pm 1\%$ (possibly 2-stage)	Variable $\pm 10\%$	Variable $\pm 30\%$	Variable $\pm 30\%$
Gearbox	Yes			No
Generator	Squirrel cage induction (possibly 2 units or 1 with switchable poles)	Induction with variable rotor resistance	Wound rotor doubly fed induction	Multipole synchronous
Power regulation	(Active) Stall	Active blade pitching		
Grid connection by	-		Partially rated Power Electronic Converters	Fully rated Power Electronic Converters

3. DATA ANALYSIS

3.1 Data sources

In order to perform reliability analysis of a system, it is fundamental to find available sources containing failure information of this system. Failure databases are a result of monitoring and recording products' performance, either in the laboratory or operational field. These activities are executed by companies, independent institutions, research centres, etc. Companies generally keep track of failures so as to estimate their products' reliability and maintenance requirements. As in any other industry, these data are intended for internal use and treated as confidential, since competitors can potentially benefit if this information is shared.

Especially for wind turbines, a number of failure data sources have been published, found summarized in Table 5

Table 5. Wind turbine failure databases

SOURCE	LOCATION	TIME SPAN	NUMBER OF REPORTING WTS	POWER RATINGS
Lynette [14]	USA	1981-1986	unspecified	Max Average 100 kW
EPRI [15]	USA	1986-1987	290	40-600 kW
EUROWIN [16]	Europe	1986-1989	Up to 3500	Max Average 160 kW
WindStats [17]	Germany Denmark	1994-2007	Up to ~4500 Up to ~2500	100kW-3MW
VTT [18]	Finland	1998-2006	Up to 98	Max Average 900 kW
ELFORSK [19]	Sweden	1997-2007	Up to ~770	Most <1 MW
Felanalys [20]	Sweden	1997-2005	Up to 786	Most <1 MW
LWK-SH [21]	Germany	1993-2006	Up to ~650	Max Average 700 kW
WMEP [22]	Germany	1989-2006	~1500	Most <1 MW

In order to select which ones to analyse, the following important criteria were taken into account:

- Type of available information. For any dataset there should be information for at least the type, location, operational period, age, and number of monitored wind turbines. Moreover, the data should be organised per subcomponent, clearly defining what is included in every subcomponent category. The resulting downtime is also important information, since it allows to determine which failures are more severe in terms of hours that the wind turbine is not able to operate.

- Amount of data. There should be a reasonable amount of data both in terms of covered time period and size of monitored populations.
- Reliability of data. Failure databases are useful when they come from reliable sources and have been developed using scientific methods of data collection.
- Access to data. At least for academic research it is generally easier to get access to databases that are published by institutions rather than by companies.

From the previous data sources, Lynette, EPRI and EUROWIN were not selected for containing old and small wind turbines. WindStats Newsletter has the disadvantage that data are aggregated, so it is not possible to identify failures per specific model and consequently topology. The Finish VTT database has a small number of wind turbines, and the same holds for the first years of the Swedish databases. Eventually the German WMEP and LWK-SH were selected for further analysis because:

- Data are similarly organised so it is possible to make comparisons.
- They both provide information per specific wind turbine model and almost the same models are covered by both.
- At least for the mid power class, both databases contain records for a large number of wind turbines.
- LWK-SH contains wind turbines installed only on the coastline of the Northern region of Germany (Schleswig-Holstein); although WMEP covers all country, it is possible to have segregated data per location, like mainland, coastline and region with mountains.
- Both databases come from trusted independent institutions. Especially WMEP is very reliable source since wind farm operators that participated in the programme were obliged to hand in their data so as to get subsidies.
- Both were accessible by the author. The Wind Energy Research group of TU Delft has all the LWK-SH annual reports; WMEP database was kindly provided by ISET.

3.1.1 Praxisergebnisse Schleswig-Holstein (LWK-SH)

The Chamber of Agriculture “Landwirtschaftskammer Schleswig-Holstein” (LWK-SH) gathers information of wind farms installed in the northernmost part of Germany, Schleswig-Holstein. Every year since 1994 data about wind turbines’ installations, performance and availability are published in a booklet under the name Praxisergebnisse [21] (in English translated as Practical experience results), which can be ordered at a low cost through LWK-SH website [23].

In this source, the data are presented both per power class, which includes aggregated data from different wind turbines of similar ratings, and per individual wind turbine model. In both categories, each dataset begins with the

Compilation of downtimes for wind turbines

WIND TURBINE MODEL			
For the period:	Month.Year	-	Month.Year
Number of WTs:	XX		
Average age at the end of Year	XX	Months	
	Number of	Number of	Percentage

3. Data Analysis

Stop reason			
Maintenance		XX	XX
Grid failure/loss		XX	XX
Storm		XX	XX
Icing		XX	XX
Disconnections	Total	XX	XX
	Average per WT	XX	XX
Lightning		XX	XX
Blade		XX	XX
Rotor Brake		XX	XX
Pitch Mechanism		XX	XX
Brake		XX	XX
Shaft/Bearings		XX	XX
Gearbox		XX	XX
Generator		XX	XX
Hydraulics		XX	XX
Yaw System		XX	XX
Anemometry		XX	XX
Electronics		XX	XX
Electric		XX	XX
Inverter		XX	XX
Sensors		XX	XX
Other		XX	XX
<i>Failures</i>	Total	XX	XX
	Average per WT	XX	XX
<i>Stand still</i>	Total	XX	XX
	Average per WT	XX	XX
<i>Annual availability</i>	Average per WT		%
			XX

Figure 9. LWK-SH form for presenting data (English translation)

time period the data refer to, the number of wind turbines reported, and their average age. Then the number of events that led to standstill and the amount of downtimes are presented for each stop reason, e.g. preventive maintenance, grid failures, storm, icing, and failures. The latter are subdivided into 16 categories, lightning and 15 categories for different wind turbine components: Blades, Rotor Brake, Pitch Mechanism, Brake, Shaft & Bearings, Gearbox, Generator, Hydraulics, Yaw System, Anemometry, Electronics, Electric, Inverter, Sensors, Other. An example page of the 1996 edition of Praxisergebnisse is given in Appendix A (Figure 28), while an English translation of the form is shown in Figure 9. It should be noted

that in the annual reports it is not clarified which subcomponents each category includes, something which has to be taken into account during analysis.

LWK-SH includes wind turbines with power ratings from 20 kW to 3 MW. The larger appear in the latest versions of the database since multi-megawatt wind turbines were introduced in the late 90's-early '00s. As a result, most information is available for wind turbines in the so called mid power class, with power ratings ranging from 500 to about 750 kW; included machines from this class are Micon M1500, Tacke TW600, Enercon E40, Vestas V39, V44 and V47, AN Bonus 450 and 600, GET 41, and Nordtank NTK 500.

3.1.2 Wissenschaftlichen Mess und Evaluierungsprogramms (WMEP)

Scientific Measurement and Evaluation Programme (WMEP) is part of the "250MW wind" funding programme, an incentive of the German Federal Government to fund electricity produced by wind turbines across Germany. It first began as a 100 MW programme in 1989, was expanded to 250 MW in 1991, and reached 350MW by 2006. All funded plants had to deliver operational information to the parallel running WMEP monitoring programme for at least 10 years. Even after that period, some operators kept providing data on a voluntary basis for up to 5 more years.

Institut für Solare Energieversorgungstechnik (ISET) in Kassel handles and processes the WMEP database. Every year standardized evaluations are made public in the form of a yearly report ("Wind Energy Report Germany" [24]) and since early 1997 some results are available on the internet [25] as well. Scientific articles, which assess the reliability of wind turbines using WMEP data, are listed in the references ([26], [27], [28], [29], [30]).

The WMEP database consists of up to 15 years operational data (1989-2006) from approximately 1500 wind turbines of various sizes and technologies. The report that participants in the WMEP programme were requested to fill in is shown in Appendix A (Figure 29). All reports were gathered into logbooks, from which data are retrieved according to desired form using SQL computer language. The main areas monitored are the following [22]:

- Weather conditions (wind speed and direction)
- Wind turbine performance (contribution to supply, annual energy yield)
- Reliability (failures and associated reasons, consequences, downtimes)
- Economics (costs for operation and maintenance, cost of energy)

Table 6. WMEP failure categories and subcategories

Category	SubCategories included
total HUB	Hub Body Pitch Mechanism Pitch Bearings
total BLADES	Blade Bolts Blade shell Aerodynamic Brakes
total GENERATOR	Generator Windings Brushes Generator Bearings

3. Data Analysis

total ELECTRIC	Inverter Switches Cables / Connections	Fuses
total SENSORS	Anemometer / wind vane Vibration Switch Temperature Antenna Oil Pressure Switch Power Sensors Revolutions Counter	
total CONTROL SYSTEM	Electronic Control Unit Measurement cables / connections	Relay
total GEARBOX	Gearbox Bearings Gear-Wheels Gear Shaft Gearbox Sealing	
total MECHANICAL BRAKES	Brake Disc Brake Pads Brake Shoe	
total DRIVE TRAIN	Rotor bearings Drive Shafts Couplings	
total HYDRAULIC SYSTEM	Hydraulic Pump Motor Valves Hydraulic pipes / Hoses	Pump
total YAW SYSTEM	Yaw Bearing Yaw Motor Yaw Gear / Pinion	
total STRUCTURAL PARTS / HOUSING	Foundation Tower / Tower Bolts Nacelle Frame Nacelle Cover Ladder - Tower	

WMEP database has slightly different failure categories than LWK-SH, but it is more clearly defined which systems are included since they are further split into subcategories (see Table 6). For every category there is an additional subcategory not shown in the table, labelled “unspecified”. This includes failures which are not covered by available subcategories, so operators marked only the major failure category and no specific subcategory, when filling in the WMEP report (Figure 29).

3.2 Technical description of selected wind turbines

In order to assess reliability of the common wind turbine topologies, representative models that have similar size and appear in both databases have been selected: Micon M1500; Tacke TW600; Enercon E-40; Vestas V39, V42, V44, V47. Each of the selected wind turbines represents one of the different topologies presented in the previous chapter; Table 7 shows the topology corresponding to each model. They are all horizontal-axis machines with 3-bladed upwind rotor and active yaw system; per model specific description will be presented in this section and Table 8 summarizes the most important characteristics of each model. It should be mentioned that these wind turbines were commercially successful back in the 90s, and a large number of them are still in operation throughout Northern Europe and USA.

Table 7. Topology of selected wind turbines

MICON M 1 5 0 0	FIXED ROTATIONAL SPEED (2 STAGES), PASSIVE STALL CONTROLLED, INDUCTION GENERATOR
Tacke T W 6 0 0	Fixed rotational speed (2 stages), active stall controlled, induction generator
Enercon E- 4 0	Variable rotational speed, pitch controlled, direct driven synchronous generator, power electronic converter
Vestas V 3 9/ V 4 x	Limited variable rotational speed, pitch controlled, variable slip induction generator

Micon M1500

MICON A/S (or MICON Energy Systems) was a Danish company active from 1982 to 1997, when it merged with Nordtank to form NEG-Micon; in 2003 Vestas acquired NEG-Micon. Most Micon machines were implementations of the Danish concept with power ratings from 100 kW up to 750 kW.

Micon M1500, introduced back in 1994, is a representative wind turbine of the Danish concept. This machine was quite successful in the mid class and a lot of units were installed in the mid 90s especially throughout Germany. 500 and 600 kW versions were available for low and high wind speed sites respectively. Each version has two fixed speed levels and the possible rotational speed variation is in the order of $\pm 1\%$ of rated. M1500-500 incorporates a 125/500kW induction generator with switchable poles, and M1500-600 a 150/600kW generator of the same technology. A 3 stage gearbox is used with a ratio of 1 to 56-60. Passive stall technique is limiting power output over rated wind speed, so the three blades are firmly attached to the hub; however, pitching of the blade tips is possible and used as secondary braking. The main braking system is hydraulic disc brakes on the high speed shaft.

Tacke TW500 & TW600

Tacke KG, a German company previously involved in production of industrial clutches and gears capable of withstanding high stress levels, began developing wind turbines in 1984 [31].

3. Data Analysis

Tacke Windtechnik GmbH manufactured wind turbines of less than 1,5 MW using the fixed speed, passive stall, induction generator concept; actually for the latest 1,5MW model, Tacke switched to pitch control, variable speed, doubly-fed induction generator technology. In 1997 Enron bought Tacke due to bankruptcy but in 2003 General Electric acquired the wind division of Enron.

TW600 was introduced in 1995 as an upscaled model of TW500 from 500kW to 600kW. The TW600e version incorporated the Danish concept; 3-bladed upwind rotor, passive stall power control, two fixed speed stages, induction generator with switchable poles (200/600kW), 3-stage combined spur-planetary gearbox, and hydraulically actuated disk brakes. TW600a uses active stall power control by means of pitchable blades that additionally function as primary braking system. Rotor diameter ranges from 43 to 46 meters depending on the IEC wind class of the site. There was also a CWM (Cold Weather Modified) version of the Tacke TW600 slightly adapted for cold environments.

Enercon E-40

The German company Enercon [32], established in 1984, was one of the first manufacturers that applied the direct drive concept back in 1992, when they introduced E-40/500kW. Since then Enercon has been successfully producing gearless wind turbines ranging from 500 kW up to 6 MW nominal power, and has installed more than 12.000 units worldwide.





Two versions of the gearless Enercon E-40 were developed: E-40/5.40 with 40 m rotor diameter and a 500 kW multipole synchronous generator; E-40/6.44 with 44 m rotor diameter and a 600 kW multipole synchronous generator. They both incorporate pitch system for power control and braking. Full rated power electronics converters are used for adjusting voltage and frequency levels to grid requirements.

Vestas V39, V42, V44, V47

Vestas Wind Systems A/S [33] is a Danish company designing and manufacturing wind turbines since 1979 and currently being the leader of the market worldwide. Early Vestas machines followed the Danish concept, but since the late 80s they switched from fixed to (limited) variable speed and from stall to pitch control (OptiTip® patented pitch regulation mechanism).

Fixed speed Vestas V39-500 kW introduced in 1992, featured the OptiTip® technology which is actually active pitch control. Later on, Vestas developed the variable slip generator, which allowed speed variations in the order of $\pm 10\%$ of rated speed (OptiSlip® technology). Depending on the blade length, V39, V42 and V44 600 kW versions were produced using this generator. Model V47-660 kW featured a variable slip 660 kW induction generator for wind speeds above rated and a secondary simple 200 kW induction generator for wind speeds below rated.

Table 8. Features of selected wind turbines

	 Micon M1500		 TACKE Windtechnik TW600		 ENERCON E-40		 Vestas V39/V42/V44/V47		
Version	M1500-500	M1500-600	TW600e	TW600a	E-40/5.40	E-40/6.44	V39	V39/4x	V47

3. Data Analysis

					40	44			
Nominal Power [kW]	125/500	150/600	200/600	150/600	500	600	500	600	200/660
Rotor diameter [m]	43	43	46		40	44	39	39/42/44	47
Speed	Dual Fixed		Dual Fixed		Variable		Fixed	Limited variable	
Generator type	Induction generator with switchable poles		Induction generator with switchable poles		Electrically excited multipole synchronous generator		Induction generator	Induction variable slip induction	1 variable slip induction 1 induction
Gearbox type	3-stage combined planetary spur		3-stage spur	3-stage combined planetary spur	-		Planetary gears / parallel shafts		1 stage planetary + 2 stages parallel
Power regulation	Passive Stall		Passive Stall	Active Stall	Pitch		Pitch		

3. Data Analysis

t o n					
Main B r a k e	Hydraulic disk brake on high-speed shaft	Hydraulic disk brake	Blade pitch	Individual blade pitch	Blade pitch
Secondary B r a k e	Blade tip brakes	Hydraulic disk brake	Hydraulic disk brake		Hydraulic disk brake
Grid c o n n e c t i o n				Fully rated power electronic converters	

In LWK-SH and WMEP databases there was no distinction possible between various versions of the same model, so for example Tacke TW600a and TW600e data are grouped together although they incorporate different power regulation methods. Data for Vestas V39, V42, V44, and V47 were obtained aggregated from the WMEP database, while LWK-SH includes separate data for Vestas V39, V44 and V47.

3.3 Reliability analysis of selected wind turbines

3.3.1 Amount of data

For the selected wind turbines, LWK-SH and WMEP have a relatively large amount of data for more than 10 years. Table 9 lists in detail the average number of wind turbines and time span of data per database and wind turbine model. The number of wind turbines that report every year varies because either new installations are included, or there are wind farm operators who did not hand in data. WMEP offers data separated per location of wind turbines, namely mainland, low mountain regions, and coastline. Since LWK-SH includes wind turbines from the coastline of Germany, it was decided to perform separated analysis for WMEP coastline data so as to make comparisons with LWK-SH.

Table 9. Amount of data in LWK and WMEP for each WT model

		Micon M1500	Tacke TW600	Enercon E-40	Vestas V39	Vestas V47
LWK	Years of operation	11	12	13	13	7
	Average number of WTs	40	34,25	43,2	38,5	18,7

WMEP	Years of operation	11	11	12	12
	Average number of WTs	8,7	42,1	69,1	39
WMEP Coast	Years of operation	-	11	11	12
	Average number of WTs	-	29	40	15

As it is already mentioned, data from different versions of the same wind turbine model are not separately reported in both LWK-SH and WMEP. For example Tacke TW600e and TW600a are collectively presented under the name TW600, although they incorporate different power regulation philosophy, passive and active stall respectively. However, especially for WMEP it was possible to identify how many machines of each version were included throughout the duration of the monitoring programme, not per year of operation. This information, presented in Table 10, reveals that:

- the majority of the Micon M1500 wind turbines are the 600/150kW version
- almost all Enercon E-40 's are 500 kW versions
- there are about half Tacke TW500's in the Tacke TW500-600 category
- almost all Vestas models in the V39/V4x category are V39's

Table 10. Number of wind turbines per version for complete WMEP

Model category	Micon M1500		Enercon E-40		Tacke TW500-600		Vestas V39/V4x			
	500/125	600/150	500	600	500	600	V39	V42	V44	V47
Version	500/125	600/150	500	600	500	600	V39	V42	V44	V47
Number of WTs	2	8	86	2	23	25	42	4	3	2
Percentage of Total	20,0%	80,0%	97,7%	2,3%	47,9%	52,1%	91,3%	8,7%	6,5%	4,3%
Total	10		88		48		46			

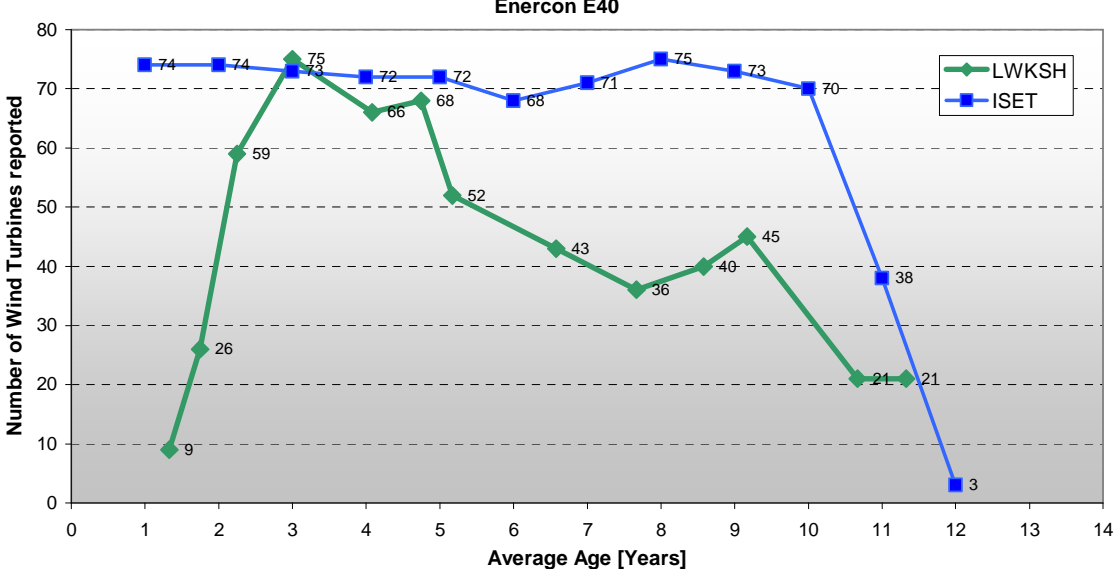
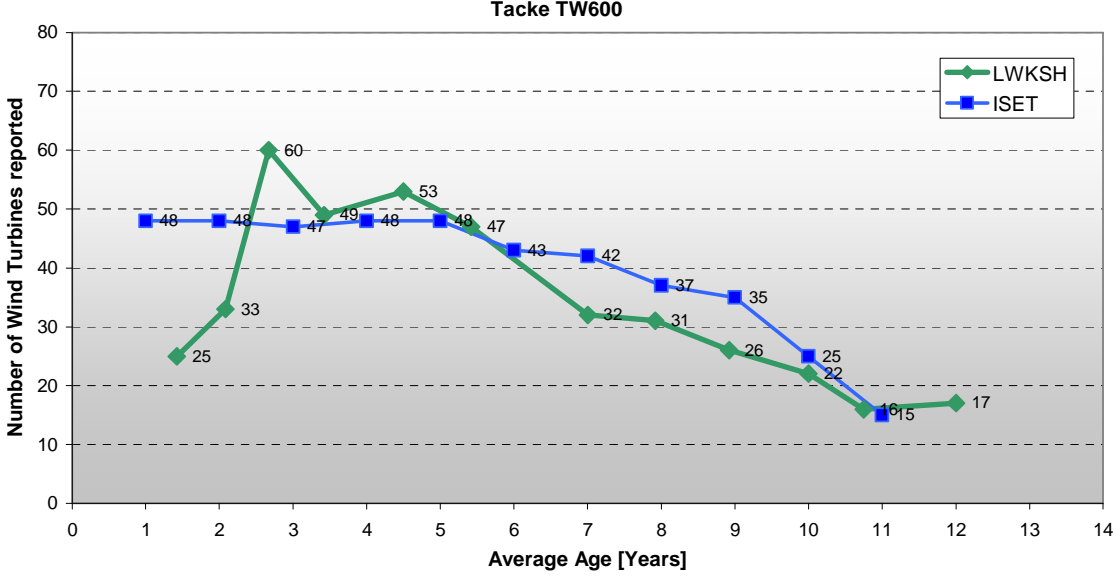
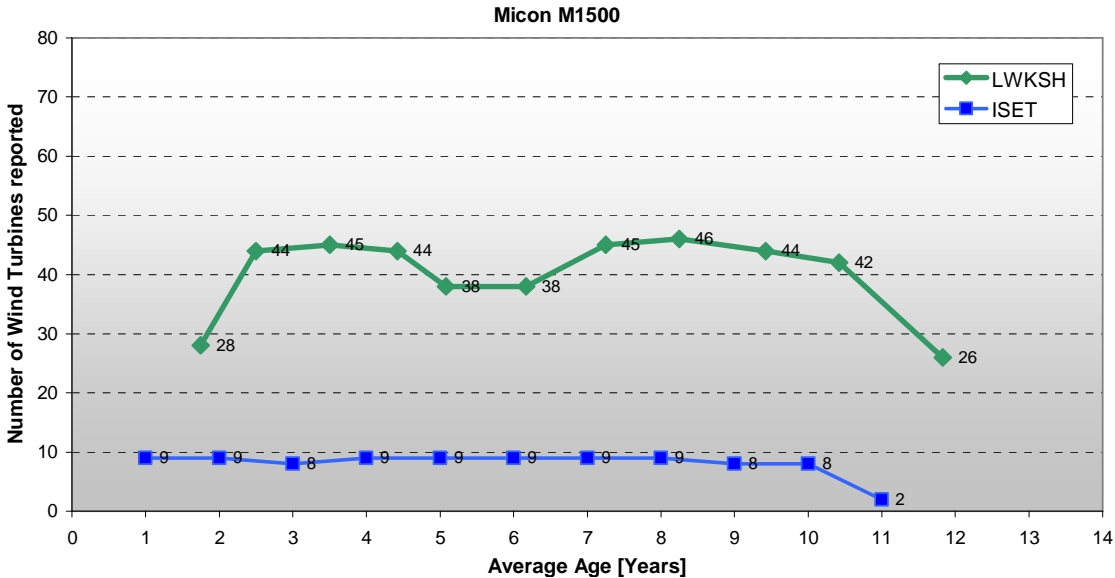
The exact number of wind turbines versus their average age (or years of operation) are graphically presented per model and database in Figure 10. WMEP coastline is not included in the graphs because the number of wind turbines is the same every year and equal to the average values found in Table 9. For every year of operation, the average age of monitored wind turbines in LWK-SH is given on the x-axis of the following graphs; for WMEP this information was not available, so it was assumed that the average age is the same as the year of operation, although these periods might be different up to about six months.

From these graphs the following remarks should be taken into account:

- Almost for every year there are at least 10 wind turbines reporting in both databases. In some cases, e.g. for Micon M1500 and Vestas V39, LWK-SH contains larger amount of wind turbines than WMEP.
- Especially in WMEP, the number of wind turbines does not vary significantly. This is prominent especially during the first 10 years of operation due to the fact that participants were obliged to deliver data for this period in order to get funds from the "250MW wind" programme of the German government. After this period, the number of reporting wind turbines drops significantly; for that reason, data after the 10th year will not be used in the following analyses.

3. Data Analysis

- In LWK-SH, the amount of data for Vestas V44 and Vestas V47, in terms of number of wind turbines and years of operation, is limited compared to the other machines. WMEP has grouped data for Vestas V39, V42, V44, and V47, but since the number of V42, V44, and V47 machines for the complete WMEP programme is small (see Table 10), the WMEP Vestas V39/V4x group will be compared to Vestas V39 from LWK-SH. Therefore, Vestas V44 and V47 data from LWK-SH will not be used in the upcoming analysis.



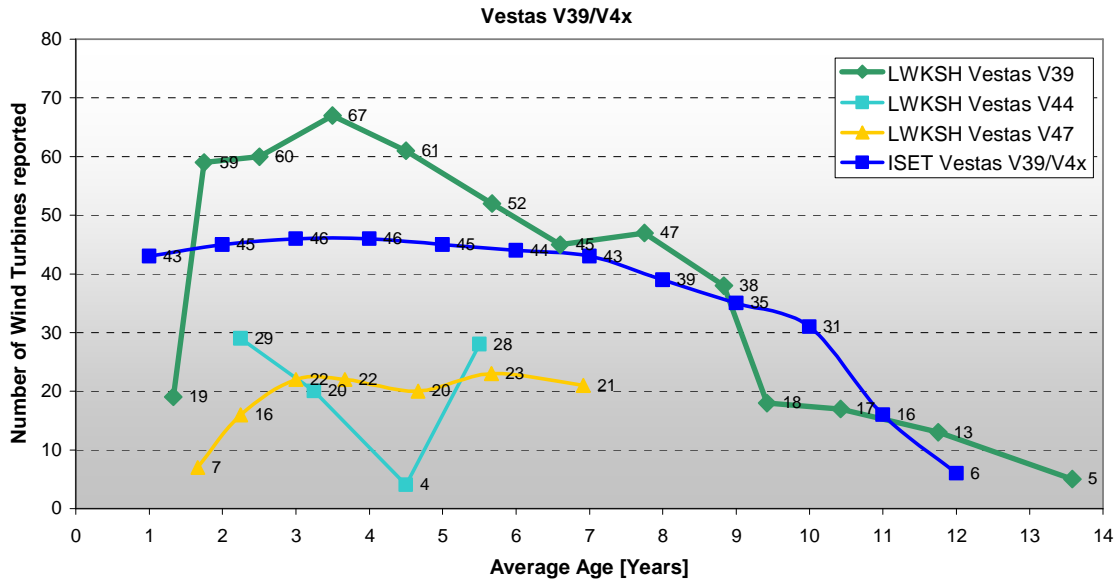


Figure 10. Number of wind turbines vs average age in LWK-SH and WMEP

3.3.2 Annual failure rates & downtimes

In order to assess reliability of different topologies and subassemblies, the average failure frequency or rate will be used. This is defined as the ratio of the number of failures occurring during a time interval over the number of monitored wind turbines times this interval. As it will be explained later in the reliability growth section, this is the same as the failure rate estimation of the Homogenous Poisson Process model, according to which failures occur randomly with no increasing or decreasing trend in time. Although any time scale can be used, failure rate is commonly expressed in number of failures per wind turbine per calendar year; in that case it is called *annual failure rate* and can be calculated using the following equation:

$$f = \frac{\sum_{i=1}^I N_i}{\sum_{i=1}^I X_i \cdot T_i} \quad (\text{Equation 1})$$

- f **Annual failure rate**
- N_i **Number of failures occurred during the time interval T_i**
- X_i **Number of wind turbines reported for the time interval T_i**
- T_i **Time intervals (I in total of 1 year each one)**

While annual failure rates are useful in order to estimate how many failures requiring unscheduled visits occur in a year, they do not provide any information on how severe a certain failure is. In order to quantify the severity of failures, the amount of time a wind turbine stands still (or *downtime*) will be used because downtimes are given in LWK-SH. WMEP programme logged this information as well, but since it was not available to the author, only LWK-SH downtimes are included in this analysis. Note that downtime does not only reflect the severity of failure but also the followed corrective maintenance strategy and the serviceability of each manufacturer, since it is the total time spent for diagnosing,

gathering repair equipment and spare parts, accessing the site when weather conditions allow, and repairing the wind turbine, as can be seen in Figure 11. Diagnosing time is zero in case of a failure that can be identified remotely; accessing the site is not issue onshore, but offshore it may be quite high since waiting time for favourable weather conditions is included.

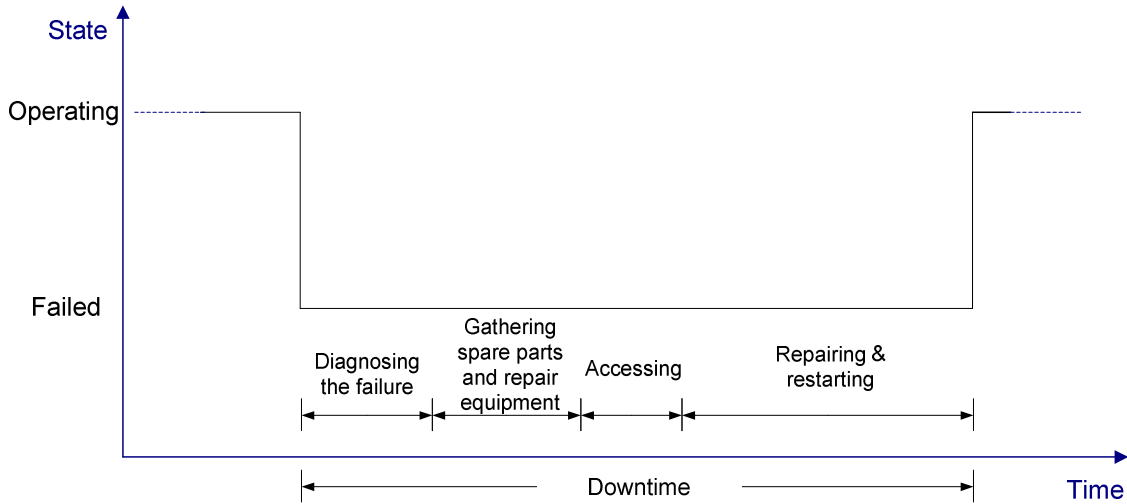


Figure 11. Breakdown of downtime

In LWK-SH downtimes are given every year aggregated for the total number of a certain subcomponent's failures (see Figure 9). In order to have one parameter that includes both frequency of failures and associated downtime, hours lost due to failures per wind turbine is estimated:

$$HL = \frac{\sum_{i=1}^I d_i}{\sum_{i=1}^I X_i \cdot T_i} \quad (\text{Equation 2})$$

HL Downtime due to failures per wind turbine per year [hours/WT/year]

d_i Downtime from subcomponent failures during the time interval T_i

X_i Number of wind turbines reported for the time interval T_i

T_i Time intervals (I in total of 1 year each one)

In order to assess the average downtime of one failure of a specific subcomponent, the mean downtime was calculated using the following equation:

$$MDT = \frac{\sum_{i=1}^I d_i}{\sum_{i=1}^I n_i} \quad (\text{Equation 3})$$

MDT Mean downtime of a certain subcomponent failure [hours/one failure]

d_i Downtime from subcomponent failures during the time interval T_i

n_i Number of subcomponent failures occurred during the time interval T_i

T_i **Time intervals (I in total of 1 year each one)**

An estimate of the average availability of each wind turbine model is possible because LWK-SH contains downtimes not only due to failures but also due to scheduled maintenance, grid problems, storm and icing:

$$A = \frac{8760 - \frac{\sum_{i=1}^I (D_i + l_i)}{\sum_{i=1}^I X_i \cdot T_i}}{8760} 100\% \quad (\text{Equation 4})$$

A **Average annual availability [%]**

D_i **Downtime due to failures during the time interval T_i**

l_i **Downtime due to other reasons during the time interval T_i**

X_i **Number of wind turbines reported for the time interval T_i**

T_i **Time intervals (I in total of 1 year each one)**

Annual failure rates of the selected wind turbines are presented in Figure 12 for LWK-SH, WMEP, and WMEP-Coastline. In LWK-SH total failure rates are in the order of 1,7 to 2,7 failures per year, while in WMEP values are much higher, ranging from 3,5 to 5 failures per year. A possible reason for this disagreement is the fact that WMEP includes wind turbines located in various German landscapes, while LWK-SH contains installations across the coastline only. There it is expected that failure rates are lower because fatigue loads, which can potentially result in failures, are lower than e.g. the mainland, where turbulence levels are higher due to the presence of physical and manmade obstacles.

By comparing LWK-SH and WMEP-Coastline, differences are smaller but still failure rates in the latter database are considerably higher. This could be attributed to the fact that WMEP database is a result of a well organised programme for which wind farm operators were obliged to hand in data, in contrast to LWK-SH. It is therefore reasonable to claim that participants in the “250 MW wind” scheme were more methodical in completing, storing, and delivering maintenance reports, which are the basis of reliability databases.

Failure rates of the “Danish concept” wind turbines Micon M1500 and Tacke TW600 lie between 1,7 and 3,8. Micon M1500 exhibits the lowest annual failure rate in LWK-SH with a value of 1,70 failures per wind turbine per year, although this is more than double (3,8) in WMEP. Failure rates of Tacke TW600 from

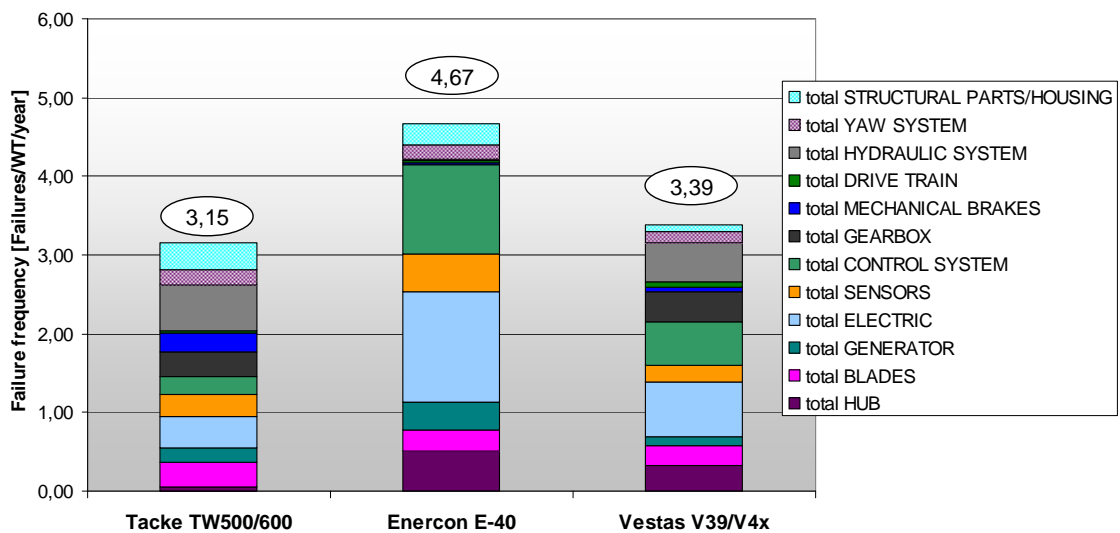
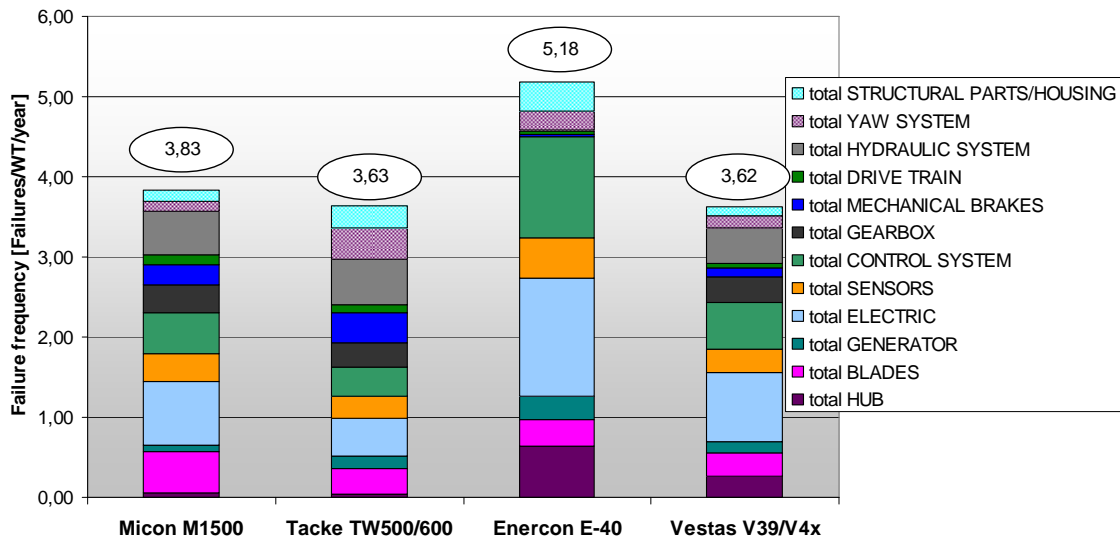
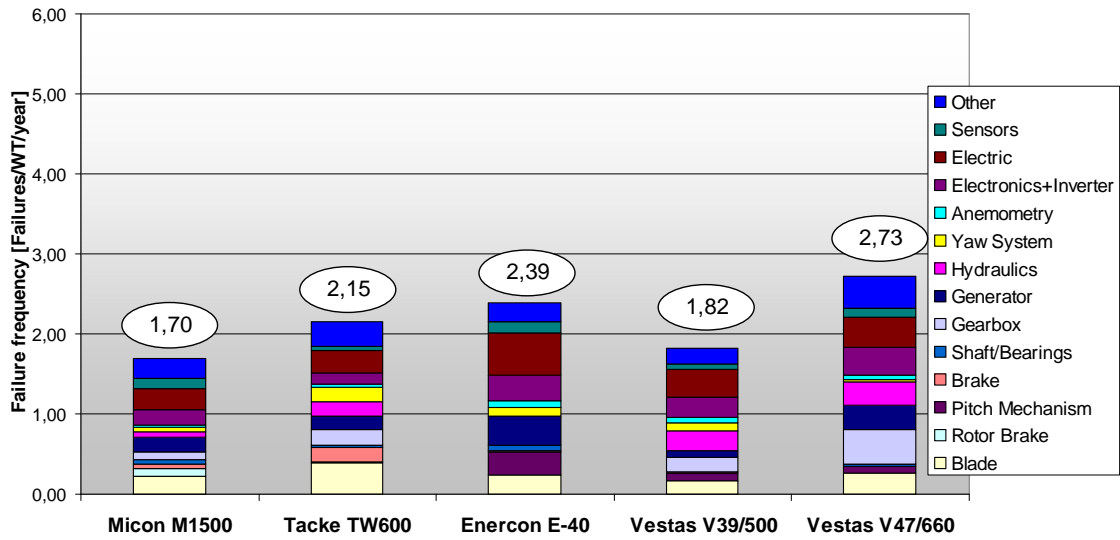


Figure 12. Average annual failure rates of selected WT's (LWK-SH / WMEP / WMEP-Coast)

3. Data Analysis

LWK-SH and WMEP-Coastline are 2,2 and 3,2 respectively, which is the closest agreement between the two databases for all models, still quite high. It should be mentioned that WMEP includes some Tacke TW500 machines, but the design is much similar to TW600e incorporating a 500kW instead of 600kW generator. The direct-driven topology represented here by Enercon E-40 shows the highest failure rate in WMEP with 5,2 failures per year and in WMEP-Coastline with approximately 4,7 failures per year. In LWK-SH Enercon E-40's failure rate is 2,4, ranked second highest below Vestas V47, which has 2,7 failures per year. Vestas V39 failure rate is relatively low in LWK-SH (1,8), while in WMEP and WMEP-Coastline significantly higher values are observed, namely 3,6 and 3,4, assuming that the Vestas V39/V4x category represents mostly Vestas V39 machines (approximately 92% of the Vestas group are V39s, see Table 10).

Since LWK-SH contains downtimes due to failures and other reasons, it is possible to estimate how much time per year each wind turbine model was able to operate. Using equation 4 and LWK-SH data, the annual average availability of the selected models is estimated; results, presented in Figure 13, show that availability of mid-class onshore wind turbines is very high, well above 98%. Note that although Tacke TW600's failure rate is slightly lower than Enercon E-40, Enercon E-40 demonstrates higher availability.

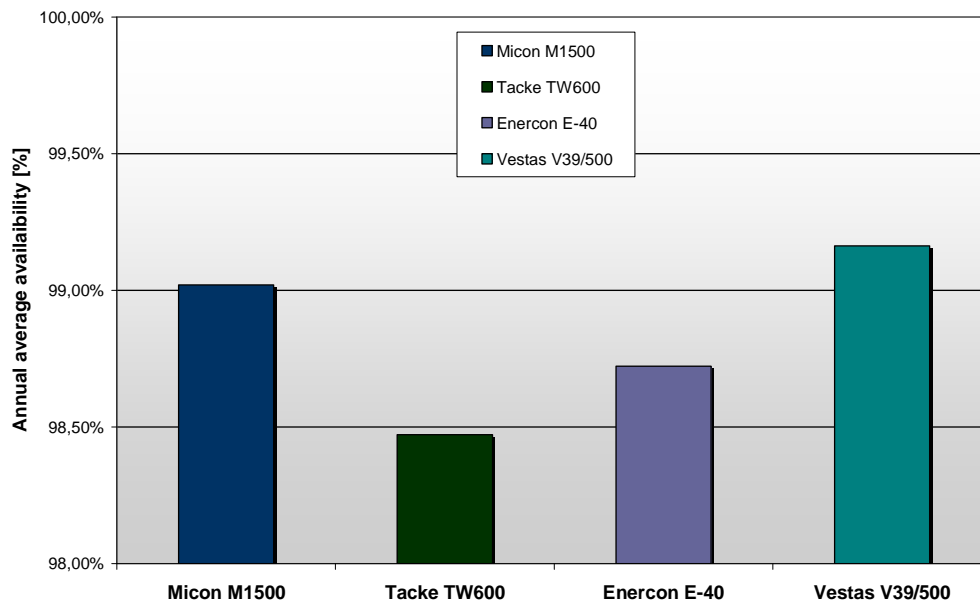


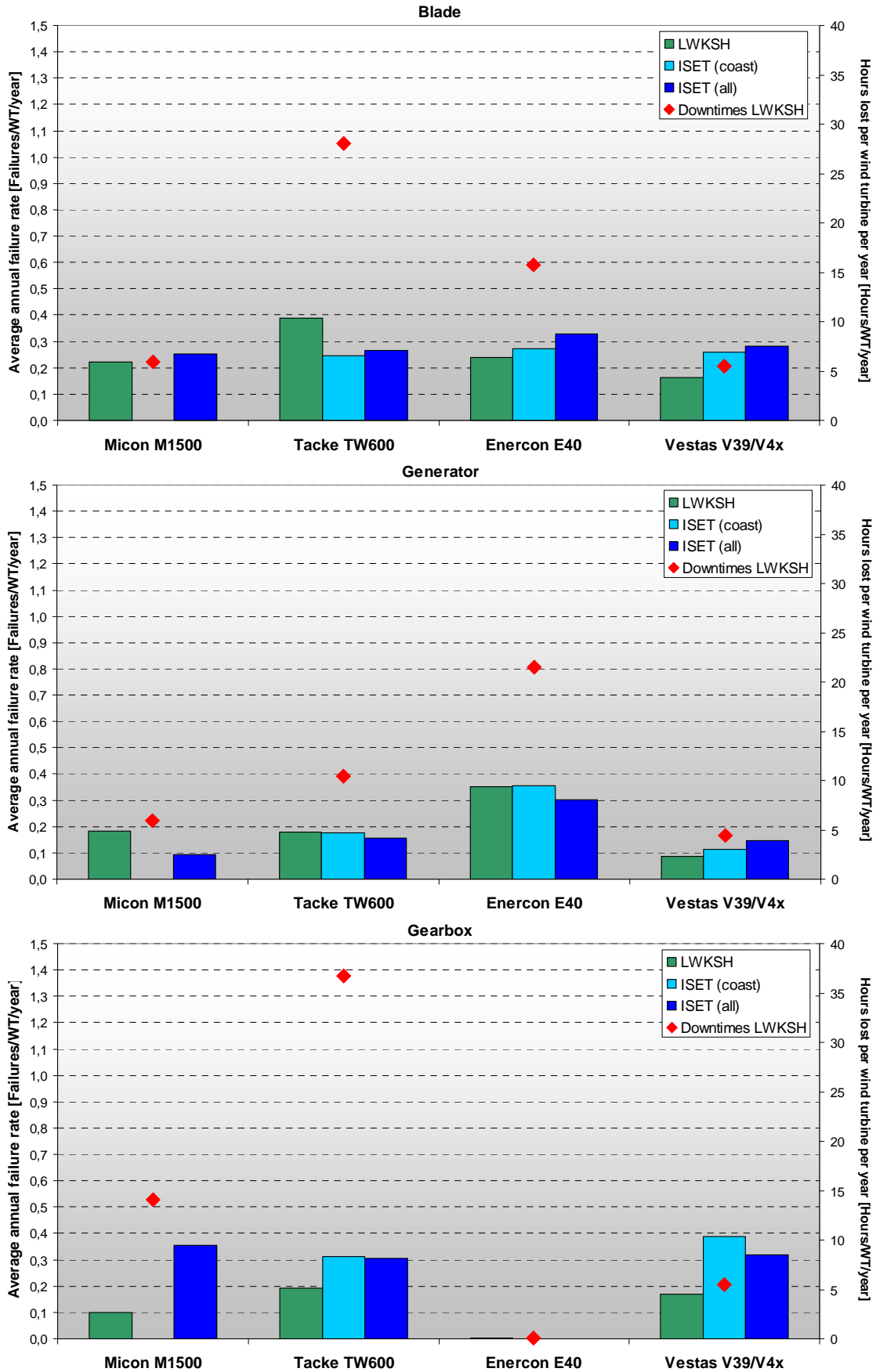
Figure 13. Average annual availability of selected WTs (LWK-SH)

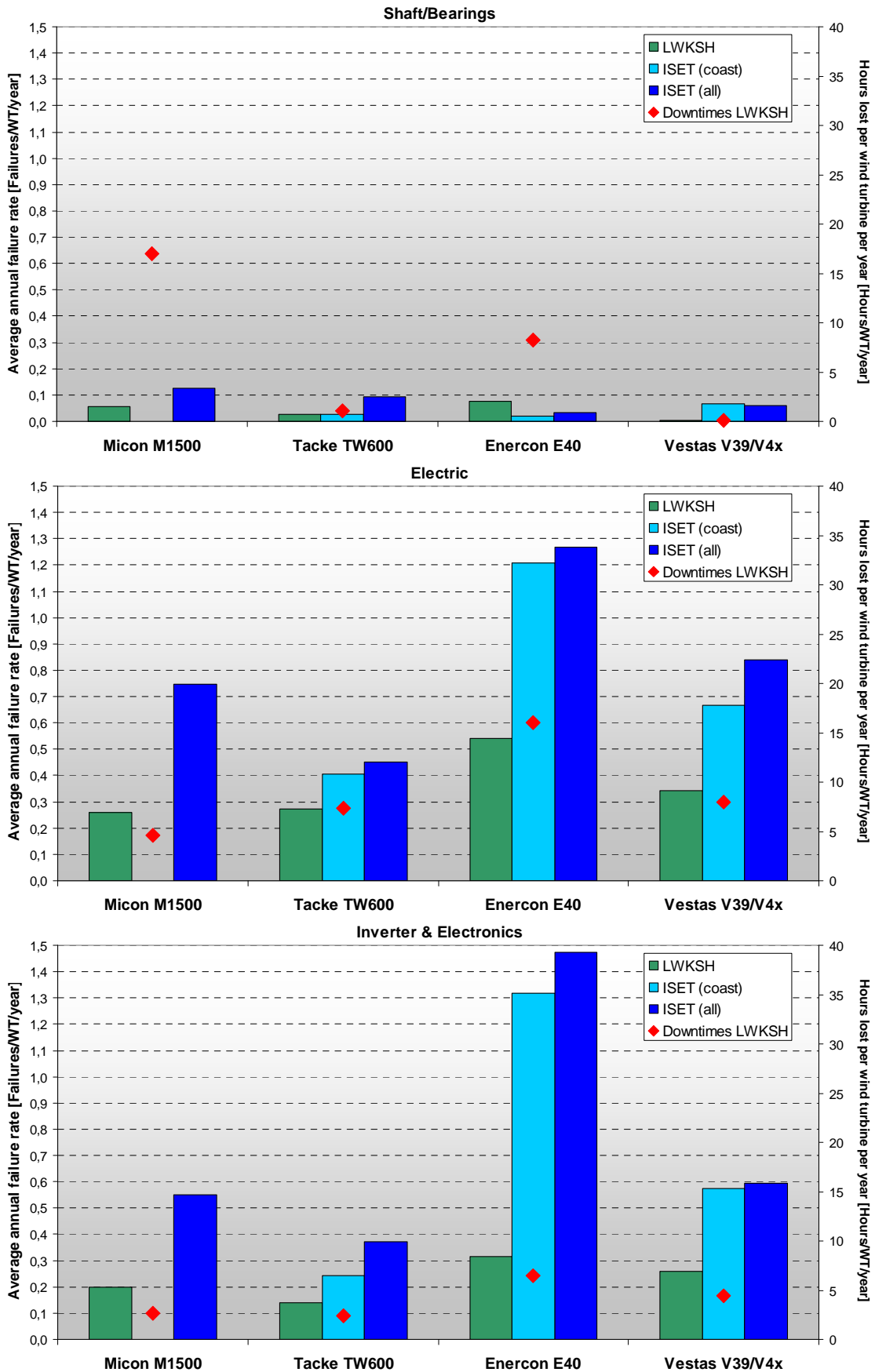
Apart from the overall failure behaviour of the wind turbine, reliability of the various wind turbine items is separately analysed so as to identify critical subassemblies of each topology. Total annual failure rates presented previously can be broken down into the different categories, as described in sections 3.1.1 and 3.1.2. Since categories are different in each database, data rearrangement was needed so that LWK-SH and WMEP data describe similar subcomponents (see Table 11). In the present thesis, category names of the LWK-SH database are used. Subcomponent failure rates are graphically presented in Figure 14. The annual average amount of stand-still time per wind turbine (calculated using Equation 2) is also included so as to identify critical subcomponents in terms of resulting downtime.

Table 11. LWK-SH and WMEP subcomponents categories

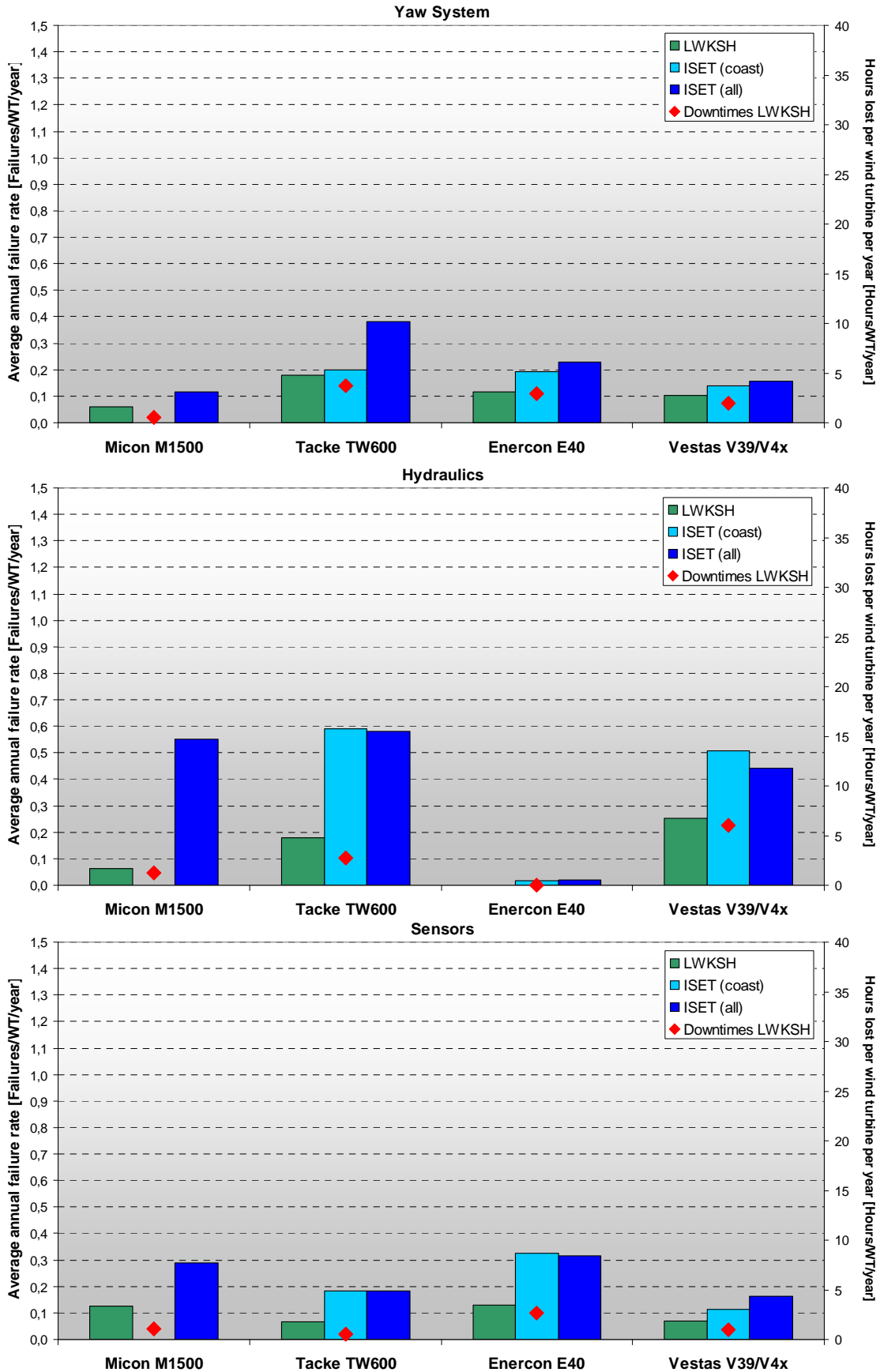
LWK-SH	WMEP
Blade	Blade Bolts + Blade shell + unspecified Blade
Generator	total Generator
Gearbox	total Gearbox
Electric	Fuses + Switches + Cables/Connections + unspecified Electric
Shaft/Bearings	total Drive Train
Inverter & Electronics	Inverter + total Control System
Yaw System	total Yaw System
Hydraulics	total Hydraulic System
Sensors	Vibration Switch + Temperature Antena + Oil Pressure Switch + Power Sensors + Revolutions Counter + unspecified Sensors
Aerodynamic Brake	Aerodynamic Brake
Mechanical Brake	total Mechanical Brakes
Pitch Mechanism	Pitch Mechanism + Pitch Bearings
Anemometry	Anemometry/wind vane
Other	total Structural Parts/Housing + Hub Body + unspecified Hub

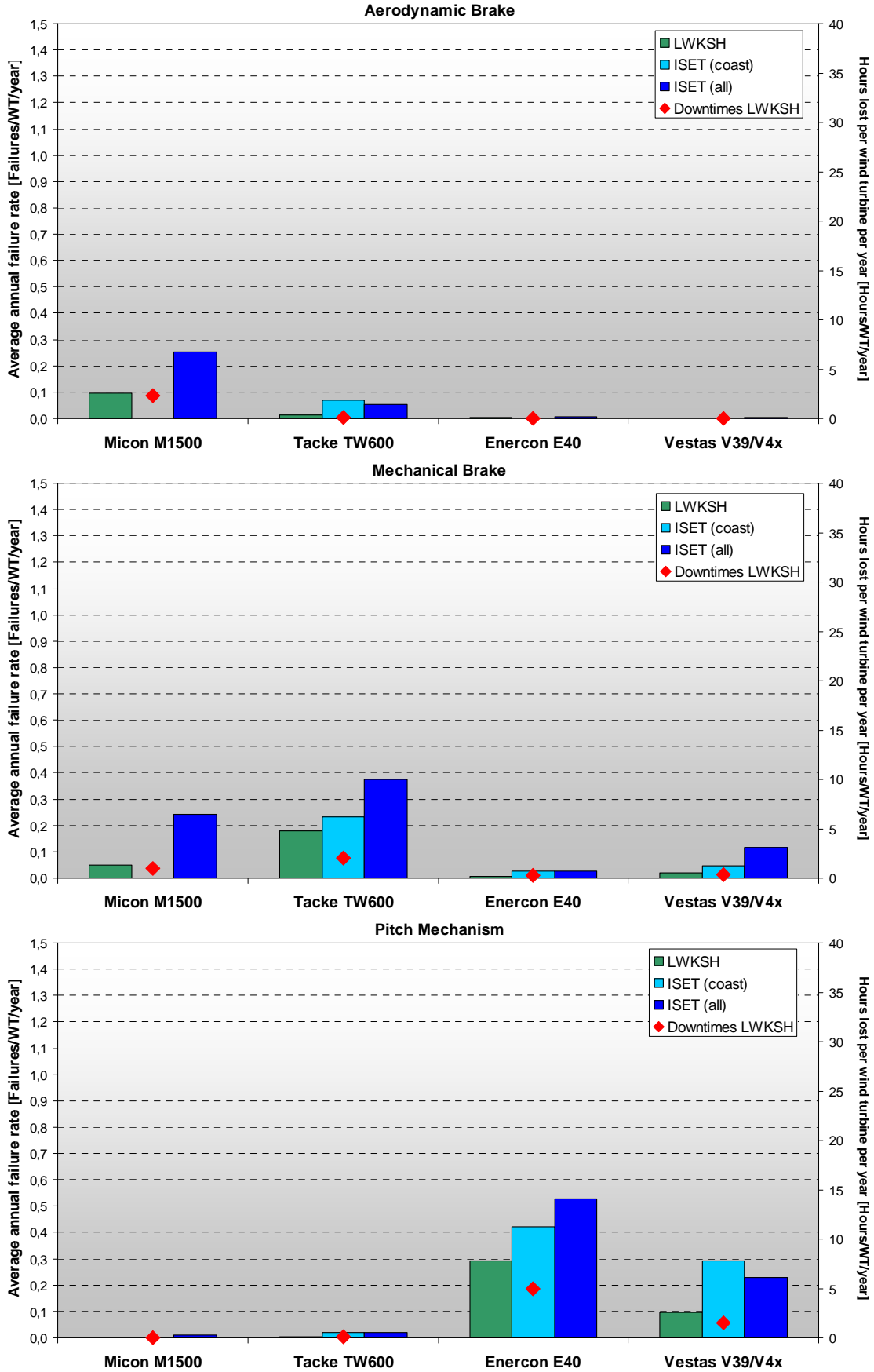
3. Data Analysis





3. Data Analysis





3. Data Analysis

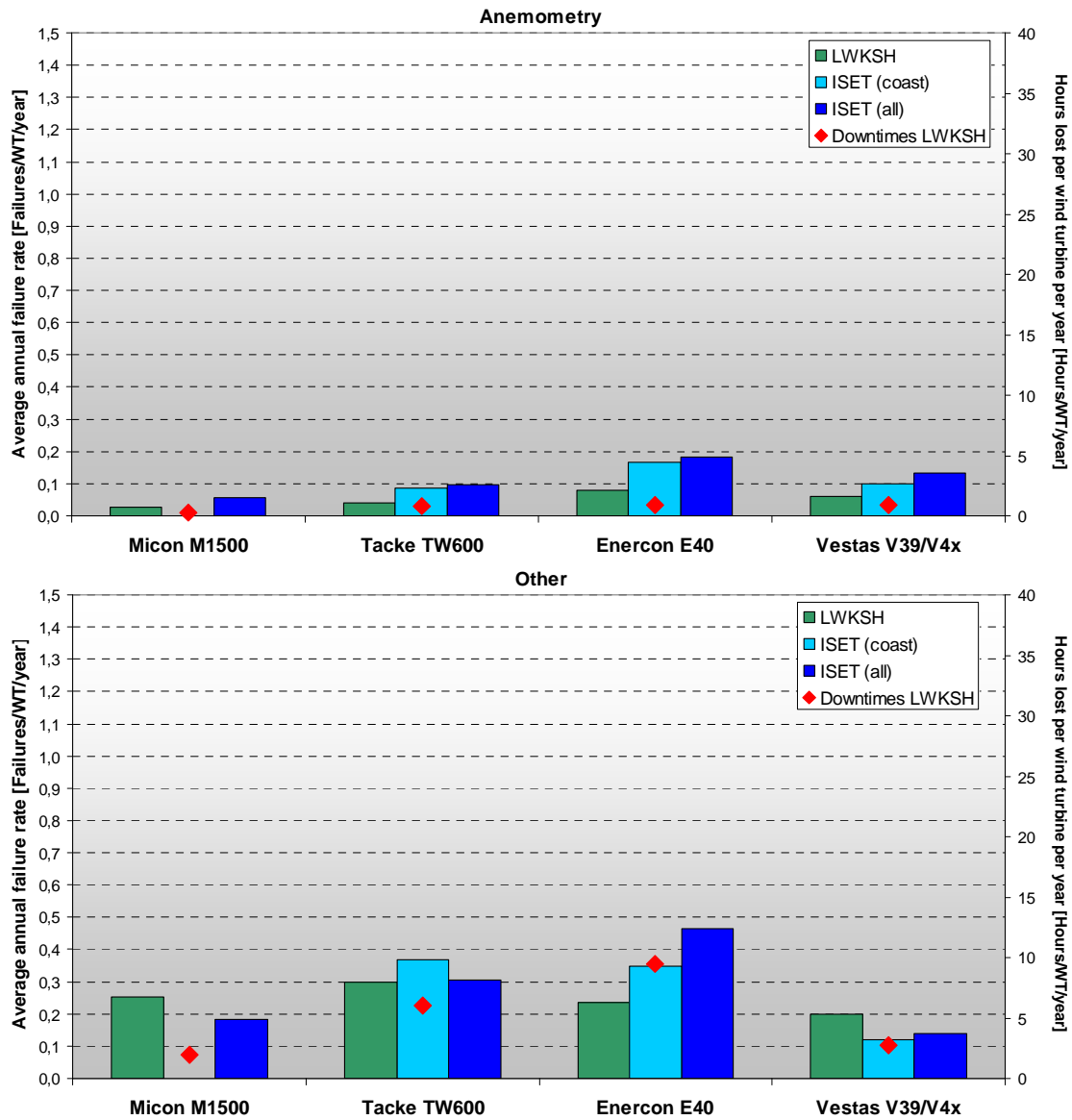


Figure 14. Annual failure rates and downtimes of subassemblies

The most frequent failing subcomponents for all wind turbines and in both databases are in descending order electric, electronics, blade, gearbox, generator, and hydraulics (for a complete list of annual average failure rates ranked from highest to lowest values, see Table 20 in Appendix C). By taking advantage of the LWK-SH downtimes information, critical subcomponents in terms of resulting downtime per wind turbine prove to be the gearbox, generator, shafts and bearings, blades, and electrical system. For each subassembly, the downtime due to one failure occurrence (Equation 3) is given in Appendix C (Figure 34). It should be mentioned that some wind turbines do not incorporate certain subcomponents. For example, Micon M1500 is a pure passive stall wind turbine with fixed blades that cannot pitch. Despite the absence of a pitch mechanism, some failures were reported for this subassembly in WMEP. These are included in the graphs just to illustrate that sometimes operators did not report the correct subassembly that failed when filling in the WMEP form (see Figure 29 in Appendix B). This might be due to different interpretation of categories by the various wind farm operators. Failure rates for Enercon and Vestas aerodynamic tip brakes,

as well as Enercon's gearbox and mechanical brakes are presented in the graphs for the same reason.

3.3.3 Comparison of topologies

Stall vs Pitch

Micon M1500 and Tacke TW600 are stall regulated machines while Enercon E-40 and all Vestas are pitch controlled. In order to compare reliability of pitch and stall wind turbines, we look up to failure rates of subassemblies, of which design depends on the type of power regulation. It should be underlined that reliability of other subassemblies than the ones described below can also be indirectly affected by the power control method, but the following systems are chosen as being the most indicative ones.

- Blades : Comparison of blade failure rates does not give any clear indication for which topology performs more reliably. For all topologies one blade failure occurred on average every 4,5 to 5,5 years, with the exception of Tacke TW600 in LWK-SH, where one blade failed as frequently as 2,5 years for unknown reasons. Downtimes due to blade failures are quite high, especially for Tacke TW600.
- Pitch mechanism : Judging from resulting downtimes, the pitch mechanism does not seem to be a critical item for wind turbine availability. In terms of failure frequency, Enercon E-40's pitch mechanism exhibits the highest value, failing once in less than 3,5 years (LWK-SH). Vestas pitch system is more reliable, failing once in more than 4 years. Tacke TW600a incorporates active stall technique for power control (see
-
- Table 8), so there is a pitch system present in some units of the Tacke TW600 category. This exhibits very low failure rates in all databases, although it should be noted that the number of TW600a's included in the TW600 category is unknown.
- Brakes : With the exception of Micon M1500 from WMEP data, failure rates of aerodynamic tip brakes are rather small. This type of braking is used only in stall machines. Since blades cannot pitch, additional mechanical brakes are necessary to ensure stoppage under any conditions. These exhibit rather low failure rates, but only when another type of braking system is present as well (Micon, Vestas). Both aerodynamic and mechanical brakes' failures result in similar stand-still times, which are low compared to other subassemblies.
- Hydraulics: This category includes hydraulic systems used for pitching the blades, actuating the disk brakes, lubricating the gearbox, etc. Although downtimes associated with failures of hydraulics are not very significant, frequency of such events is very high, as it can be seen especially from WMEP failure rates. It should be noted that hydraulics is one of the very few categories in WMEP for which failure rates at coastline are slightly higher than the ones in the mainland, probably as a result of the salty atmosphere.

Summed up failures rates and downtimes of the previous subassembly categories are graphically presented in Figure 15. The Enercon E-40 individual blade pitch philosophy and wide range variable speed leads to comparably lower failure rates, as observed in both databases. Stall turbine Tacke TW600 suffered from a number of blade failures that led to very high downtimes. Pure passive stall and fixed rotational speed concept, represented by Micon M1500 proves to be a rather reliable option at least close to the coastline, as failure rates from LWK-SH suggests. Note that in WMEP there are only 10 M1500's reporting

3. Data Analysis

compared to 40 units in LWK-SH (see Figure 10), and all of them are located further from the coastline. Vestas pitch controlled low range variable speed machines failed rather frequently in WMEP, but according to LWK-SH resulting downtimes are relatively low.

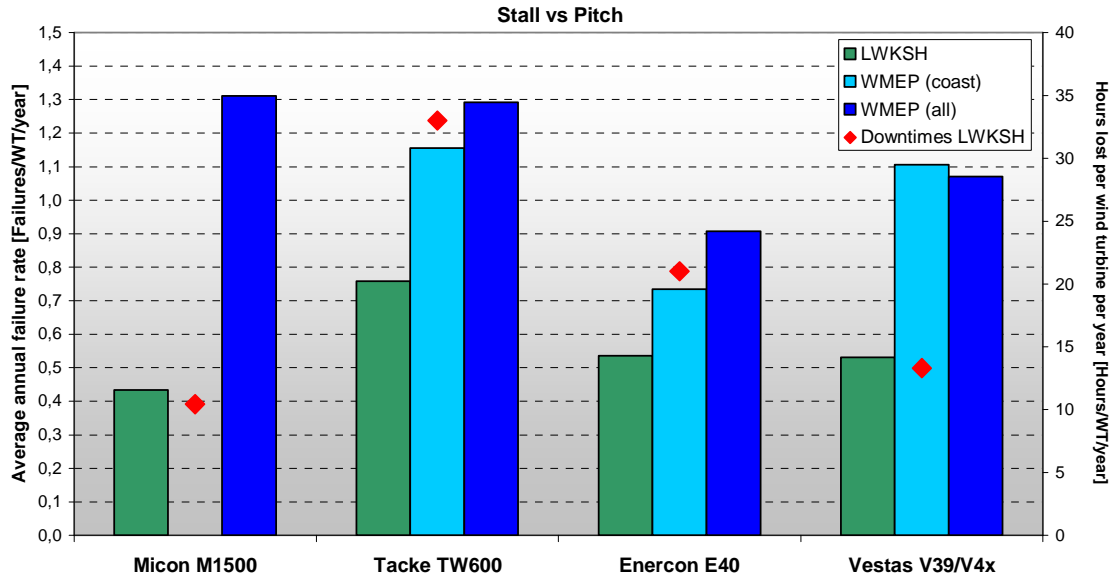


Figure 15. Stall vs. Pitch (Aggregated subassemblies failure rates)

Geared vs Direct drive topologies

In order to compare reliability of direct driven and geared wind turbines, the gearbox and overall drive train is not the only important subassembly to look at. The electrical system design depends on the presence of gearbox; direct driven wind turbines incorporate large multipole synchronous generators and full power electronic converters, while in geared concepts standard induction generators with no (or partially rated converters in case of doubly fed induction generators) are used.

- **Gearbox** : Based on the graphs, the gearbox does not fail as often as it is generally perceived, but it is still one of the most critical subassemblies, since very large associated downtimes are observed, especially for Tacke TW600. Enercon E-40, which does not contain a gearbox for stepping up the rotor speed, has a relative advantage in this case over the other topologies. In WMEP, gearboxes of Micon, Tacke, and Vestas machines failed once about every 3 years. In LWK-SH values are considerably lower, with one failure occurring approximately every 5 years or more.
- **Shaft/Bearings** : Main shafts and bearings exhibit rather low failure rates of one event per 10 to 30 years. No specific topology seems to clearly stand out in terms of failure frequency, and there is some divergence among databases, with the exception of Tacke in LWK-SH and WMEP coastline. On the other hand, downtimes resulting from shaft and bearings failures are very large, especially for Micon M1500 and Enercon E-40.
- **Generator** : Geared topologies utilize 4 or 6 pole induction generators that run on (possibly dual) fixed speed. These have been exercised in various applications other than wind turbines and are widely considered as robust machines. The latter is confirmed by the Micon and Tacke generators, which prove relatively reliable as they fail once in more than 5,5 years. Even lower failure rates are observed for the Vestas induction generator, which allows $\pm 10\%$ speed variations due to variable slip feature. The multipole synchronous generator of Enercon E-40 exhibits the highest failure rate, almost double

than the other types, and the highest associated downtime. However it is important to note that E-40 was the first commercial attempt of a medium power class wind turbine with direct-driven low speed synchronous generator, and most failures occurred especially during the first years of operation as it will be shown later in the reliability growth chapter.

- Inverter & Electronics : Type of electronics found in a wind turbine depend on electrical generator type, speed variation possibilities, and power control method. As all direct driven machines, Enercon E-40 incorporates fully rated power electronic converters so that output voltage and frequency levels match grid requirements. Failure rate in this case is very high, especially in the WMEP database, where one failure occurred every 9 months. Nevertheless, resulting downtime per wind turbine is only slightly higher than the other topologies. Micon M1500, Tacke TW600, and Vestas V39/V4x are directly connected to the grid, although thyristors that are often used exhibit lower failure rates. Downtimes in this case are similar as Enercon E-40. Especially for Vestas, the electronics/inverter category probably includes failures of the OptiSlip® components, e.g. of the electronically controlled resistance, which is in series with the rotor resistance in order to achieve variable slip for the generator, thus rotational speed variability.
- Electric : Electric components such as switchgear, transformer, batteries, and power cables, show a quite high record of failures, especially for the variable slip Vestas V39/V4x and the direct driven Enercon E-40. The latter has the highest downtime associated with electrical components' failures, but all machines experience considerable downtimes. Note that some operators may have marked failures in the electronics and inverter systems as electric failures and vice versa.

An overall comparison of geared and direct drive topologies is possible by aggregating annual failure rates of the related subassemblies and resulting downtimes (Figure 16). The fact that Enercon E-40 was the first direct driven wind turbine for commercial application must be taken into account, because there are always some design improvements after operational experience from the field is gained. Eliminating the gearbox seems to result in an increased number of failures for the electrical related subcomponents of E-40, possibly as a result of the complex generator and electrical system incorporated. Although Tacke TW600's failure rate is in the same order as the other wind turbines, significantly higher downtime are observed, mostly because of the time consuming activities needed to repair the gearbox.

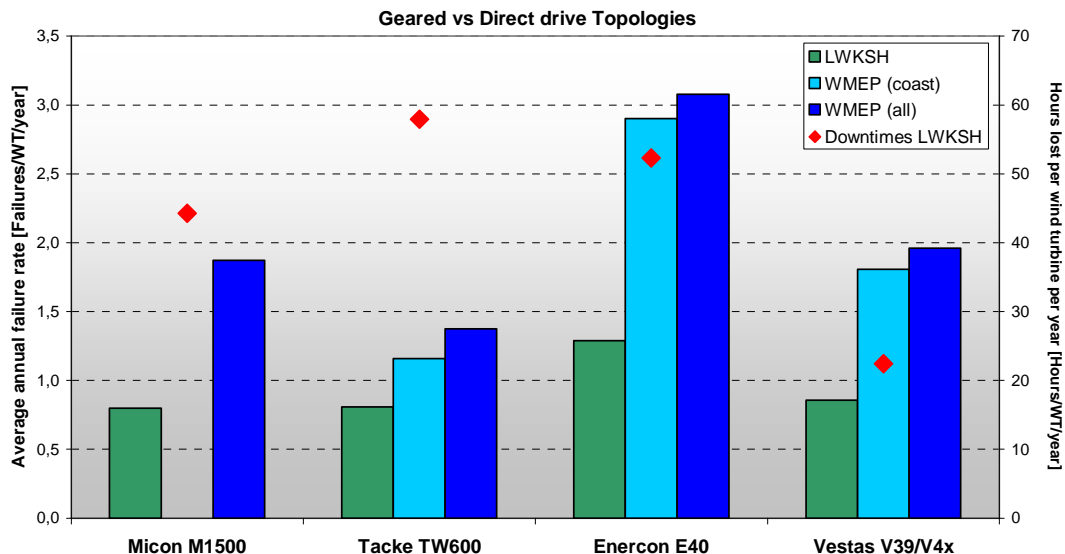


Figure 16. Geared vs Direct drive (Aggregated subassemblies failure rates)

3.4 Reliability growth tracking

The field of reliability growth management examines “the improvement in a reliability parameter over a period of time due to changes in product design or the manufacturing process” [5]. Reliability growth models have been developed so as to track changes in reliability during the different design phases of a product. Moreover, it is possible to use appropriate models on failure data collected in the operating field so as to investigate if the product’s reliability stays constants, changes randomly or shows any improvement or deterioration with time. Reliability growth has been thoroughly studied by the Army Material Systems Analysis Activity (AMSAA) department of the US army. The AMSAA Reliability Growth Management Military handbook MIL-HDBK-189 [4] written in 1981 still provides significant information and methods for reliability growth; an updated version entitled AMSAA Reliability Growth Guide TR-652 [5] was published in 2000, but still based on the 1981 version. An electronic handbook of engineering statistics [34] developed by the American National Institute of Standards and Technology (NIST) together with SEMATECH dedicates a detailed chapter on reliability issues, including reliability growth.

Reliability growth models described in the sources above are very commonly used in industry so as to assess product reliability and eventually improve it. Examples include vehicles, aircrafts, computer chips, machinery components, and medical hardware. The only –at least publicly available– publications that describe application of reliability growth models on wind turbine failure data come from Dr. Peter Tavner and Fabio Spinato, from Durham School of Engineering, UK ([35], [36], [37], [38]).

In this paper the AMSAA Continuous Reliability Growth Tracking Model for grouped field data will be applied on the LWK and WMEP datasets, which is intensively described in 2 documents published by the US Army ([5] and [4]). Explaining the detailed mathematics behind reliability growth models is out of the scope of this thesis, however some basic concepts will be described in the following sections.

3.4.1 The AMSAA Reliability Growth model for grouped data

Point Processes

A point process is generally a stochastic model which describes the occurrence of events in time; these occurrences are thought of as points on the time axis [6]. In reliability analysis, failures of repairable systems are the events which are tracked either in calendar time, for example hourly, annually, etc, or an operational parameter, like kilometres or flying hours. A random variable $N(t)$ that represents the number of events in the interval $(0, t]$ is called *counting random variable*. Subsequently the number of events in the interval $(a, b]$ will be $N(a, b) = N(b) - N(a)$, as illustrated in Figure 17.

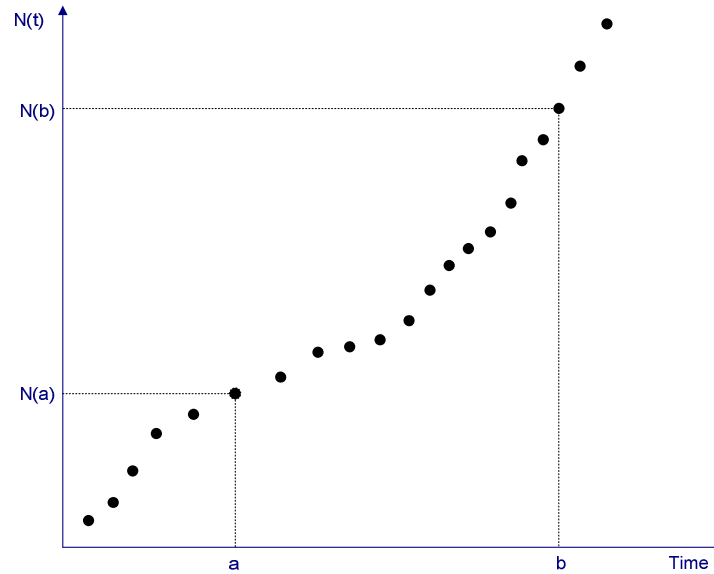


Figure 17. A counting random variable

The *Point Process Mean Function* $\Lambda(t)$ is the expected number of failures E , in the interval throughout time t :

$$\Lambda(t) = E[N(t)] \quad (\text{Equation 5})$$

The *Rate of Occurrences of Failure* $\mu(t)$ is the rate of change of expected number of failures:

$$\mu(t) = \frac{d\Lambda(t)}{dt} \quad (\text{Equation 6})$$

The *Intensity Function* $\lambda(t)$ is the limit of the probability, P , of having one or more failures in a small interval divided by the length of the interval.

$$\lambda(t) = \lim_{\Delta t \rightarrow 0} \frac{P(N(t, t + \Delta t) \geq 1)}{\Delta t} \quad (\text{Equation 7})$$

If the probability of simultaneous failures is zero, then:

$$\mu(t) = \lambda(t) \quad (\text{Equation 8})$$

Non Homogeneous Poisson Process (NHPP)

A counting process $N(t)$, e.g. cumulative number of failures after operational or calendar time t , is a Poisson process if the following three conditions are valid:

1. No failures have occurred before the initial time zero:

$$N(0) = 0$$

2. For any $a < b \leq c < d$ the random variables $N(a, b]$ and $N(c, d]$ are independent. This is known as the “Independent increments property”.

3. There is a function λ (*intensity function*) such that:

$$\lambda(t) = \lim_{\Delta t \rightarrow 0} \frac{P(N(t, t + \Delta t) = 1)}{\Delta t}$$

3. Data Analysis

Note that if λ is constant then the process is Homogeneous Poisson process (HPP), so in fact it is a special case of the NHPP.

4. Simultaneous failures are not possible:

Main property of NHPP : The number of failures $N(a, b]$ in the interval $(a, b]$ is a random variable having a Poisson distribution with mean value $\int_a^b \lambda(x)dx$.

Power Law Process

The chosen model that will be used for the intensity function is the power law process because of its flexibility, as it has the important advantage of modelling all three phases of the bathtub curve. Additionally, various literature sources covering the topic of reliability growth agree that the power law process can be used to describe systems of different fields, even if the number of available data is limited. A Non-Homogeneous Poisson process with intensity function $\lambda(t) = \rho\beta t^{\beta-1}$ is called a power law process. In that case, the cumulative number of failures through time t is given by:

$$N(t) = \rho t^\beta \quad (\text{Equation 8})$$

ρ **scale parameter (time unit)**

β **shape parameter (dimensionless)**

As for any stochastic process (see Figure 17), the expected number of failures for a specific time interval $(t_1, t_2]$ is given by:

$$N(t_1, t_2] = N(t_2) - N(t_1) = \rho(t_2^\beta - t_1^\beta) \quad (\text{Equation 9})$$

The failure rate (rate of occurrences of failures) is the time derivative of the cumulative number of failures:

$$\lambda(t) = \frac{dN(t)}{dt} = \rho\beta t^{\beta-1} \quad (\text{Equation 10})$$

From the last equation, it is obvious that failure rate is not necessarily constant but can vary with time. Whether it is constant, decreasing or increasing depends on the value of the shape parameter β . For β values smaller than unity, the rate of occurrences of failures is increasing with time, while for β values greater than unity it is decreasing. In both cases with β other than 1, the process is a Non-Homogeneous Poisson Process (NHPP). When β is unity, failure rate is constant over time, and therefore the process is a Homogeneous Poisson Process (HPP) as previously defined. The following table summarizes the trends of failure rate and number of failures for different values of the shape parameter β , while Figure 18 shows a graphical representation of both functions for each case. It should be noted that the functions are monotonic, meaning that they can either increase, decrease, or be constant.

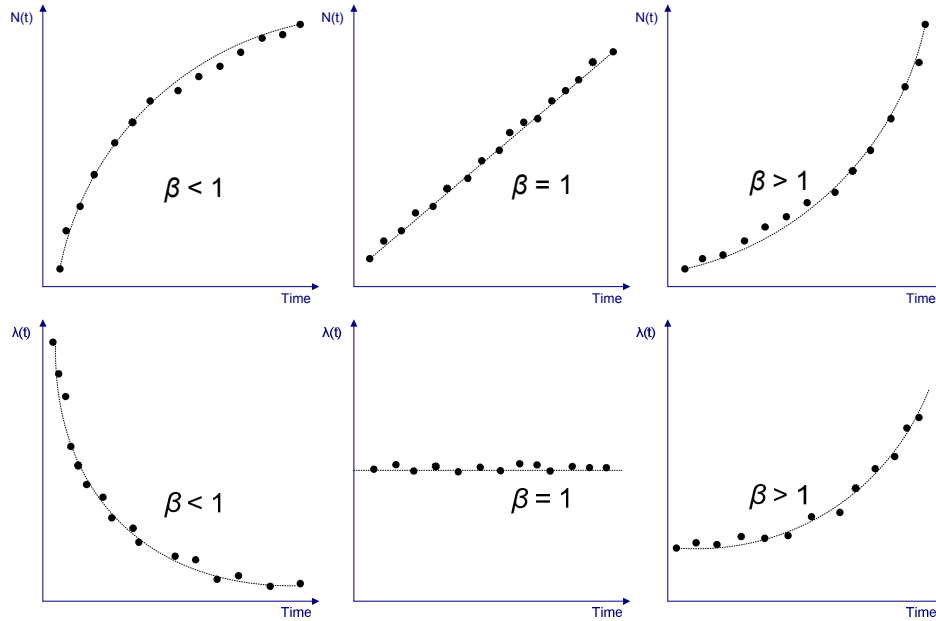


Figure 18. Cumulative number of failures and failure rate vs. time for varying shape parameter

Table 12. Variation of shape parameter around unity

	Number of failures	Failure rate	Type of Process
$\beta < 1$	Decreasing with time	Decreasing with time	NHPP
$\beta = 1$	Constant with time	Constant with time	HPP
$\beta > 1$	Increasing with time	Increasing with time	NHPP

Parameter estimation (MLE)

In order to get the β and ρ parameters of the power law process from grouped field data, arranged as shown in Table 13, the maximum likelihood estimator (MLE) is used as described below.

Table 13. Grouped field data arrangement

Interval	Time	Number of failures
1	$t_0 \cdots t_1$	n_1
2	$t_1 \cdots t_2$	n_2
3	$t_2 \cdots t_3$	n_3
...

$$\boxed{I \quad t_{i-1} \cdots t_i \quad n_i}$$

The MLE shape parameter $\hat{\beta}$ must satisfy the following nonlinear equation, where I represents the number of available time intervals, t_i the total time, and n_i the number of failures observed within time interval $[t_{i-1}, t_i)$, with t_0 defined equal to zero:

$$\left. \begin{aligned} \sum_{i=1}^I n_i \left(\frac{t_i^{\hat{\beta}} \ln t_i - t_{i-1}^{\hat{\beta}} \ln t_{i-1}}{t_i^{\hat{\beta}} - t_{i-1}^{\hat{\beta}}} - \ln t_i \right) &= 0 \\ t_0^{\hat{\beta}} &= \ln t_0 = 0 \end{aligned} \right\} \quad \text{(Equation 11)}$$

By solving the previous system for $\hat{\beta}$ with any analytical method for nonlinear equations, the shape parameter of the power law process is determined. The scale parameter $\hat{\rho}$ is then estimated by dividing the total number of failures over the entire time raised to the β^{th} power.

$$\hat{\rho} = \frac{\sum_{i=1}^I n_i}{t_i^{\hat{\beta}}} \quad \text{(Equation 12)}$$

χ^2 -test

The statistic value to check is given by the following equation:

$$\chi^2 = \sum_{i=1}^I \frac{(n_i - e_i)^2}{e_i} \quad \text{(Equation 12)}$$

$$\text{where } e_i = \hat{\rho}(t_i^{\hat{\beta}} - t_{i-1}^{\hat{\beta}}) \quad \text{(Equation 13)}$$

Hypothesis that data can be modelled using PLP is accepted if this statistic is distributed as a chi-square random variable with $I - 2$ degrees of freedom, where 2 comes from the number of the estimated parameters from the previously described method ($\hat{\beta}$ and $\hat{\rho}$):

Null hypothesis: The data n_i follow the power law process

$$\text{Accepted} \rightarrow \chi^2 \leq \chi_{(a, I-2)}^2$$

$$\text{Rejected} \rightarrow \chi^2 > \chi_{(a, I-2)}^2$$

where a is the level of significance (typically from 90% to 99%).

3.4.3 Application to datasets of wind turbine failures

The model described in the previous section tracks changes of reliability with time for only a single repairable unit, for example one wind turbine. In order to be able to apply the same model for grouped datasets of failures, as it is the case for LWK-SH and WMEP, the quantity time to test will be used in equations 5 to 13 instead of the actual calendar time. Time to test is simply the product of the number of monitored wind turbines in one interval, times the size of this interval, which is one year in both databases. In this way, failure rate describes failures per wind turbine per year instead of failures per year.

In order to apply the AMSAA reliability growth model to the LWK-SH and WMEP datasets of wind turbine failures, a simple MATLAB code was developed (see Appendix D). The

program first estimates the shape and scale parameters using Equations 11 and 12, and then checks whether the null hypothesis that the given dataset is described by the power law process, is accepted or not. This method is repeated for all subcomponent categories. Output is logged in an Excel spreadsheet and graphs showing the cumulative number of failures or failure rate versus time are plotted, given that the null hypothesis is accepted. The same procedure is used for all wind turbines using all available datasets (LWK-SH, WMEP and WMEP coastline). Maximum likelihood estimated values of the shape parameter, given that the null hypothesis is accepted, can be found in Table 21 Appendix E; examples of the resulting plots are shown in Figure 19. In these graphs failure data are depicted as green squares, while the red lines are plots of equation 8 using the estimated shape parameter value. Application of the PLP model to LWK-SH and WMEP datasets reveals some very interesting characteristics concerning the reliability of the selected wind turbines. Table 21 shows that the shape parameter is below unity for most subassemblies, which means that they experience an increased number of failures during the first years of operation and drop afterwards. For a period of 1 to 3 years after commissioning, on-field improvements and adjustments take place, resulting in lower failure rates for the following years. This is more prominent for components such as blades, electrics and electronics, hydraulics, sensors, and aerodynamic brakes. Reliability improvement with time is also observed for the Enercon E-40's generator, justified by the fact that it was the first commercial attempt of a multipole slow rotating electrical machine, and therefore on-field amendments had been implemented based on ongoing operational experience. On the other hand, failure frequencies of long lead mechanical subcomponents like the gearbox, the shafts, and the bearings, show an increasing trend with time. Such items fail more often after some years of operation due to inevitable wear out, and on-field improvements, other than minor adjustments like alignment or oil change, cannot be implemented.

It should be noted that when the null hypothesis is rejected, it is reasonable to assume constant failure rate (HPP), which implies that failures occur randomly with time and no particular trend can be tracked. Constant failure rate should be also assumed in cases where the estimated shape parameter is slightly higher or smaller than unity: changes of reliability with time in these cases are so small that can be neglected by assuming constant failure rate.

3. Data Analysis

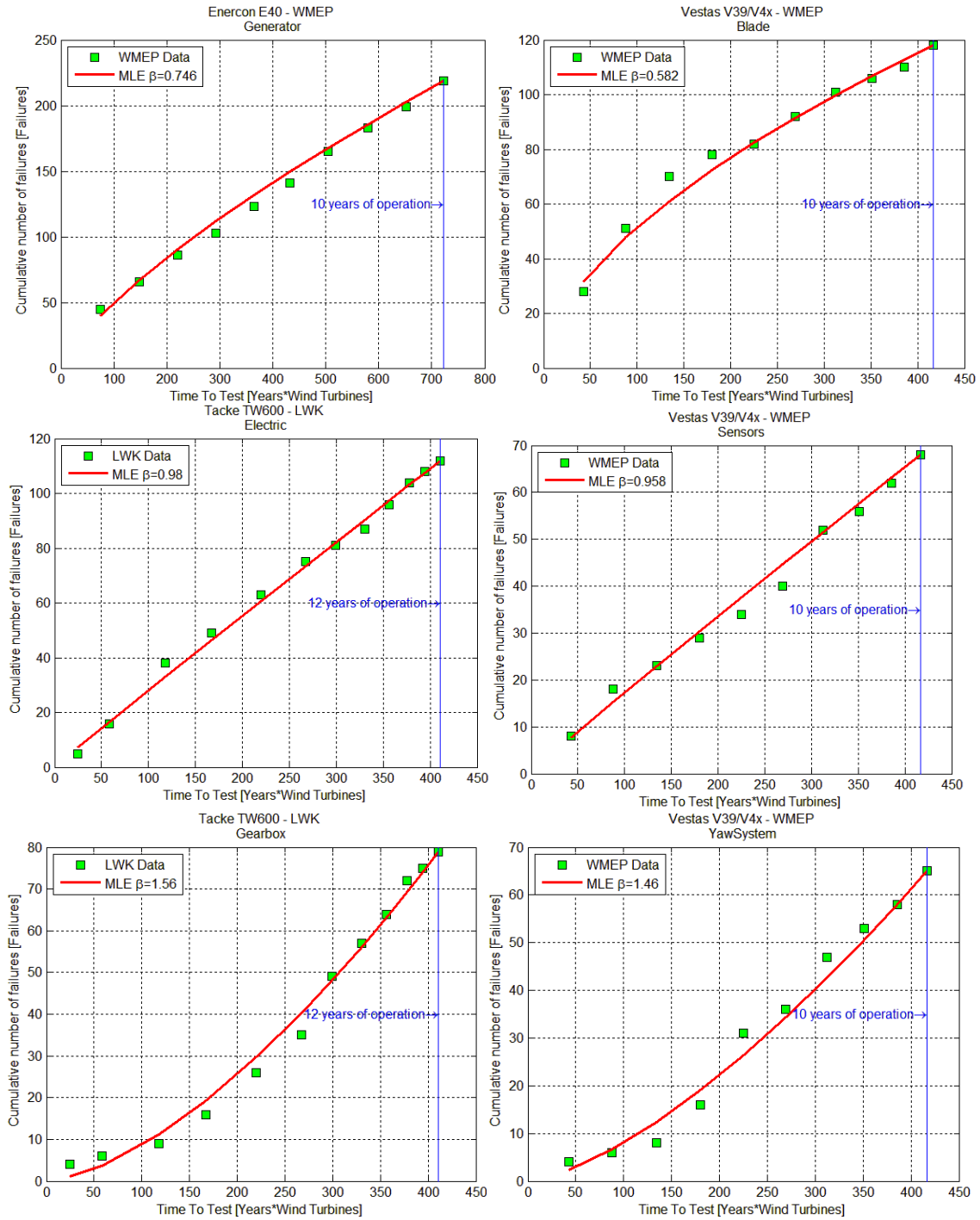


Figure 19. Examples of results ($\beta < 1$, $\beta = 1$, $\beta > 1$)

4. AVAILABILITY OF OFFSHORE WIND FARMS

4.1 Offshore wind farms' operation and maintenance activities

For every wind turbine of an offshore wind farm the most important operational parameters are continuously monitored and logged by a Supervisory Control And Data Acquisition (SCADA) system. During normal operation, monitoring and adjustments, like pitching the blades or yawing the rotor, can be performed remotely from an onshore location where all information from SCADA system is sent. If some parameters are not as expected, e.g. rotor speed is too high or generator's temperature has risen above specified limits, the wind farm operator will try to identify the source of the problem remotely, if possible, and act accordingly. Some problems can be solved from distance by, for example, resetting the wind turbine or adjusting some operational parameters.

In case of a failure that cannot be identified remotely, a specialized crew of technicians is needed to go to the offshore wind farm so as to diagnose on-site the exact source of the problem. When the required repair actions are determined, possibly needed spare parts are ordered, if they are not kept in stock near the closest to the wind farm port. Once all necessary spare parts, workers, tools, and transport means are available, the repair crew travels to the failed wind turbine(s), given that there is sufficient weather window to complete required repair activities. If weather conditions (wind speed, wave height, visibility) don't allow access, the wind turbine remains in its failed state until accessing is possible, which translates into additional revenue losses.

Actual repair time, meaning that travel and logistics time are not included, depends on the cause and severity of each failure. Some failures can be repaired within a few hours while for others it can take up to several days until the wind turbine can be restarted. Especially when a large subassembly has to be replaced, the wind turbine might remain in its non-operating state for a long period of up to weeks. The tedious task of exchanging a heavy component is not the only source of this high downtime. The jack-up barge, floating crane ship, or any other special lifting equipment required to complete the exchange can take days to arrive to the offshore wind farm, because it is very likely that they are busy on another mission, since the number of such heavy lifting equipment available in the wider offshore engineering market is very limited. Moreover, a relatively large and narrow weather window for access and operation is required by these special vessels, something which can increase waiting time especially during winter, when it is less probable to have sufficient period of favourable weather conditions.

In contrast to the previously described corrective maintenance (CM) activities, preventive maintenance (PM) tasks are generally easier to manage because they can be scheduled. Depending on the followed strategy, every wind turbine is inspected on-site either periodically or after a predefined threshold of an operational parameter, such as temperature of the gearbox lubricant, has been exceeded. It can also be the case that PM follows CM tasks in order to reduce annual visits per wind turbine, thus downtime and costs. During PM, which is usually carried out in one full day per turbine, all subcomponents in the interior of the nacelle and the tower are carefully checked by specialized personnel, consumables such as lubricants are replaced, and cleaning, e.g. of oil filters, takes place.

4.2 Experience from existing offshore wind farms

Operational experience from offshore wind farms is rather limited, mainly because offshore wind energy conversion is still in its infancy: wind turbines in the range of 450 to 600 kW were initially installed offshore in the early 1990s, but it is not until the early 2000s that large

offshore wind farms were realized. However there is some evidence that the offshore wind energy industry is already facing a number of problems associated with technical reliability. In a number of reported cases of offshore operational experience, significant failures occurred during the first period of operation, leading even to major components replacement. Most severe problems encountered are related either to the gearbox or electrical subcomponents (transformer, generator) as it can be seen from various published sources.

According to [39], the Danish Middelgrunden offshore wind farm commissioned in 2001 experienced a number of unexpected problems during the first years of operation, mainly in the transformer, drainage system, cooling system, switchgear, power cables, and structural parts of the 20 Bonus (now Siemens) 2.0MW, which are wind turbines of the Danish concept. At Horns Rev again in Denmark, all generators and transformers of the 80 Vestas V80-2.0MW were completely replaced during the first years of operation, after a series of failures occurred on a number of machines [40].

In British Blyth, generator failures occurred since the beginning of operation, and both Vestas V66-2.0 MW had to be retrofit [40]. Additionally, one of the three sea high voltage cables was cut down in late 2007, and the same problem happened in Scroby Sands in early 2008 [41]. For the later wind farm, serious gearbox bearings failures of the 30 Vestas V80-2.0MW led to availability of 84% in 2005 (monthly highest 97% in June, monthly lowest 64% in December) [42], and 81% in 2006 (monthly highest 92% in July, monthly lowest 64% in October) [43]. Some gearboxes were completely replaced, while for others the outboard intermediate speed bearing had to be exchanged. Generators were also problematic and at least 17 replacements took place, this time using conventional proven technology generators. O&M costs were approximately 1,3 c€/kWh both for 2005 and 2006, years which are within the 5-year warranty period.

The Kentish Flats offshore wind farm in the UK, consisting of 30 Vestas V90-3.0MW wind turbines, exhibited an availability of 87% (monthly highest 96% in August, monthly lowest 65% in December) during the first year of operation in 2006 [44]. Most downtime is attributed to 12 gearbox replacements and very frequent minor repairs. Generator bearings, generator rotor cable connections from slip-ring unit, and the pitch system caused a series of problems as well. O&M costs for this year were about 1,4 c€/kWh, noting that there is a 5-year warranty period active covering O&M expenses. In early January 2007, it was reported that 12 wind turbines experienced severe gearbox failures, which led to large downtime due to bad weather conditions and low accessibility [45].

The North Hoyle wind farm of 30 Vestas V80-2.0MW off the North Wales coast published 84% overall availability for the first year of operation 2004-05 (monthly highest 94% in May 2005, monthly lowest 63% in October 2004) [46], and 91% in 2005-06 (monthly highest 95% in October 2005, monthly lowest 84% in August 2005) [47]. Annual O&M costs were approximately 2 and 1,8 c€/kWh for 2004-05 and 2005-06 respectively. Most downtimes were attributed to generator and electrical system faults; especially during the 2nd year of operation, 6 severe gearbox problems occurred leading to 2 complete replacements. Recently, gearboxes of 9 out of the 36 Vestas V90-3.0MW had to be replaced at the first Dutch offshore wind farm located 10 to 18 km from the shore of Egmond aan Zee in the Netherlands [48].

All previously mentioned sources reported that the large downtime period is directly connected to the low accessibility of the offshore site when repair actions are needed. Waiting for sufficient operational weather window proved to be a critical parameter affecting downtime significantly. Availability of vessels was also an issue, since heavy lifting equipment needed for replacements, such as jack-up barge or floating crane ship, might have been busy in other missions. In almost all cases, targeted availability was estimated higher

4. Availability of Offshore Wind Farms

than the resulting one. This can lead in unexpected additional revenue losses, a fact that underlines the significance of estimating O&M parameters as accurately as possible.

Table 14. Availability of offshore wind farms in operation

Wind Farm	Year	Annual availability	O&M costs/kWh
Scroby Sands, UK	2005	84%	1,3 c€/kWh
Scroby Sands, UK	2006	81%	1,3 c€/kWh
Kentish Flats, UK	2006	87%	1,4 c€/kWh
North Hoyle, UK	2004-05	84%	2,0 c€/kWh
North Hoyle, UK	2005-06	91%	1,8 c€/kWh

4.3 Simulation tools for O&M parameters estimation (CONTOFAX)

Availability and O&M costs per energy produced are very important parameters in assessing the feasibility of an offshore wind farm and comparing operation and maintenance of different wind farms. The great advantage of these two parameters is that they include technical reliability and site accessibility, while they also reflect the result of the chosen maintenance strategy. Due to the stochastic character both of weather conditions and failures' occurrences, it is not possible to estimate O&M parameters straight-forward. More precisely, the following reasons hinder predictions concerning O&M of offshore wind farms:

1. Accessibility of vessels to wind farm is limited by weather conditions.
2. Availability of special lifting equipment (e.g. jack-up barge) is limited.
3. There is not enough information on failures of (multiMW) wind turbines.
4. Logistic and/or delivery times of spare parts may vary unpredictably.

Since no direct calculation method can be applied, special software tools have been developed, which usually calculate parameters such as O&M costs and downtimes associated with failures. The ones that were known to the author are listed below with a short description:

- "Operations & Maintenance Cost Estimator" developed by the energy research centre of the Netherlands (Energieonderzoek Centrum Nederland, abbreviated as ECN) [49].
- "MWCOST", which stands for "Modeling Windfarm Capex & Opex with Sloop Technology" developed by BMT Fluid Mechanics Limited [50]. It is an extension to the SLOOP software package, which is used to assess the O&M parameters of offshore oil and gas installations.
- A model developed by Frans de Jong and Mecal partners targeted for estimating O&M costs of onshore wind farms [51].

CONTOFAX (TU Delft)

CONTOFAX, developed at TU Delft by Christian Schöntag and Gerard van Bussel in 1996 [2], is a software tool, written in Excel with Visual Basic macros, for estimating various operations and maintenance parameters of an offshore wind farm using Monte-Carlo simulations. The program simulates operation and maintenance of a specified offshore wind farm for a defined period of time by following the state of each component of the wind farm (wind turbine, crew, transport vessel, spare parts, etc), one time step at a time. A simplified flowchart of the code structure is given in Figure 20. For each time step of 1 hour, it is first checked if the site is accessible, according to the distribution of stormy and non stormy intervals, which is simulated using a built-in storm model. It is assumed that it is possible to forecast the state of the weather at least for 12 hours in advance. The next step is an update of the status of every wind turbine. If a wind turbine is under corrective or preventive maintenance, it is continued or completed given that there is no storm. If a wind turbine is operating normally, it is stochastically determined whether a failure occurs in the current time step. After the status of all wind turbines has been logged, the status of maintenance resources, such as crews, spare parts, transport devices, is also updated. If there is a wind turbine in need of maintenance, weather conditions allow access, and all resources are available, a routine for deploying resources is called.

Inevitably it is not possible to model the operation and maintenance of offshore wind farms exactly as it is in reality. The CONTOFAX model contains some assumptions that are in general reasonable, but limit simulation possibilities in some cases:

- Failure rates of subcomponents are constant with time per one simulation. No increasing, decreasing, or bathtub curve trend can be implemented in one run, but since it is possible to manually define simulation time interval, this can be modelled by splitting the wind farm's lifetime into periods of different failure rates, which are constant for every period.
- Similarly, the time interval of scheduled preventive maintenance is fixed over the defined simulation period. This does not create any problems, since it is actually common practice to have a constant PM interval for the entire lifetime of an offshore farm.
- Distance and therefore travelling time from maintenance base to all wind turbines is the same. In reality there might be a considerable distance between units of a large offshore wind farm that covers a large area.
- 1 crew of X workers can be transported by 1 vessel and repair 1 wind turbine. The number of workers does not affect maintenance activities, but is only taken into account in cost calculations.
- Only 1 type of vessel for crew and spare parts transportation and 1 type of special lifting equipment for large components repairs can be used; these both have the same accessibility level. In reality large crane ships have limited operating capabilities compared to simple vessels.
- Only integer values are allowed for input times. This limits the minimum possible travelling time to 1 hour.

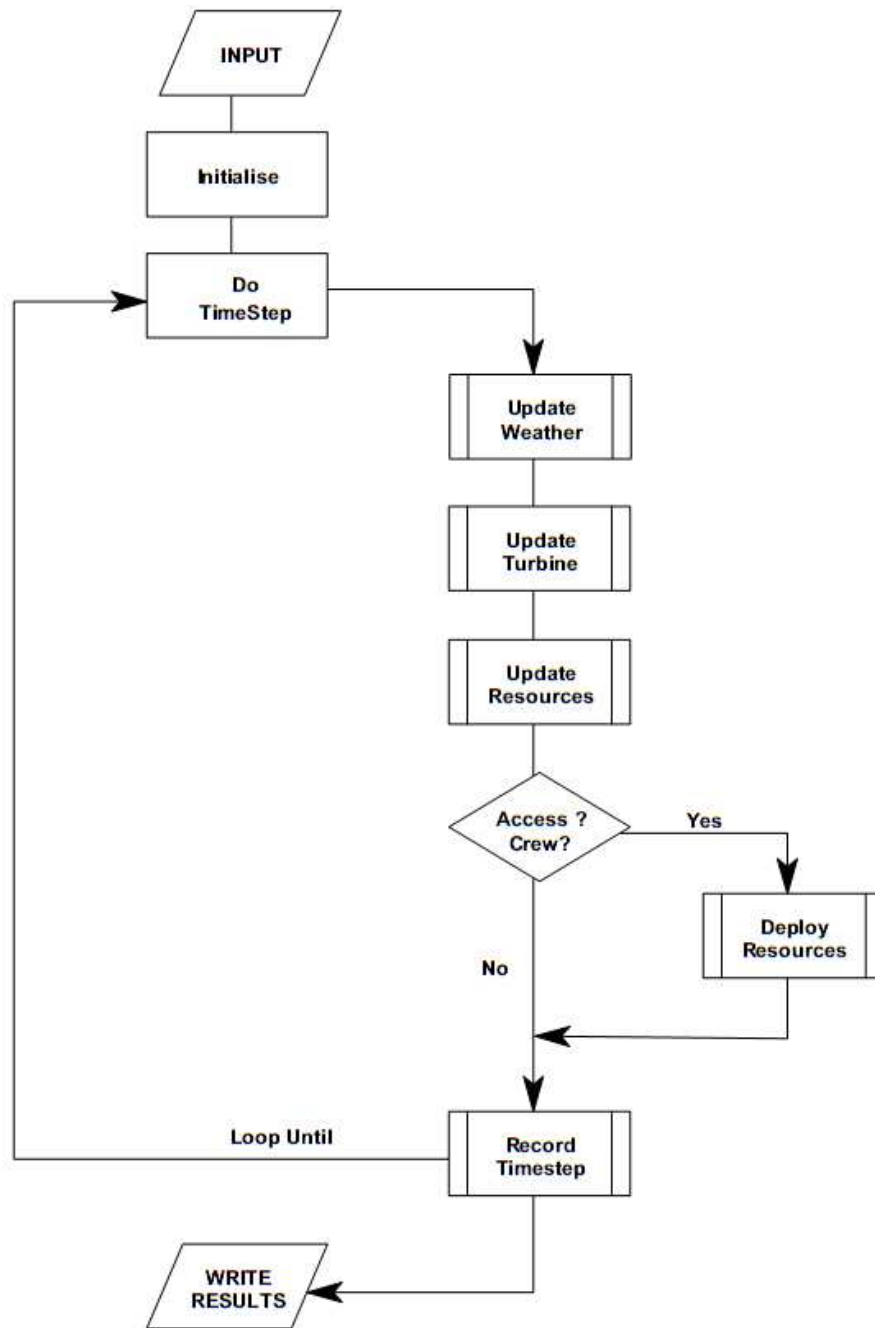


Figure 20. Simplified flowchart of CONTOFAX code structure

4.4 Simulations for Scira offshore wind farm

4.4.1 Baseline

Input parameters

The contracted offshore wind farm “Scira” in Sheringham Shoal, UK is used as a baseline case for the O&M analysis. It is located 17 to 23 km far from the coast of Sheringham covering a total area of 35 km². Total capacity is about 315 MW, but the exact wind turbine model is not yet decided; since failure data for Siemens 3.6MW were provided by ECN/Ecofys, in the following analysis Scira is assumed to consist of 88 Siemens 3.6MW. The annual energy yield based on the site’s wind speed distribution and turbine’s power curve (Appendix F) is estimated as 16.49 GWh per wind turbine assuming 100% availability. The most important parameters of Scira wind farm are summarized in Table 15.

Table 15. Characteristics of Scira wind farm

Parameter	Value
Number of Wind Turbines	88 Siemens 3.6
Nominal power	317 (88*3.6) MW
Distance to shore	17-23 km
Annual Energy Production (100% availability)	88*16.49 GWh

Table 16 provides all information regarding O&M activities simulated as the baseline scenario. All failure and vessel information was provided by ECN/Ecofys. Every wind turbine will be visited twice a year for a 24-hour preventive maintenance. In the baseline 2 crews of 2 workers each are available for 12 hours every day during all week. In order to be in accordance with the CONTOFAX model, it is assumed that 1 crew, is enough to perform any type of maintenance on 1 wind turbine, and that 1 vessel can carry 1 crew at a time.

Table 16. Maintenance parameters (Baseline)

	CONTOFAX Input Parameter	Value	
Preventive Maintenance	Number of scheduled visits	2	1/year/WT
	Duration	24	hours
	Costs	1000	€/PM task
Failure information	Failure rates (Siemens 3.6 from ECN))	Appendix	-
	Average repair time per failure mode	Appendix	-
	Costs for spare parts	Appendix	-
	Average waiting time for spare parts	Appendix	-

4. Availability of Offshore Wind Farms

Human Resources	Length of one Shift	12	hours
	Number of Shifts per Day	1	-
	Working Days per Week	7	-
	Number of Crews per Shift	2	-
	Number of Workers per Crew	2	-
	Maximum Overtime	0	hours
	Time Wage of Crew	70	€/hour
	Number of available devices	1	-
Transport devices (WindCat)	Travelling Time from port to site	1	hours
	Accessibility (throughout year)	77%	-
	Running costs	200	€/hour
	Number of available devices	1	-
Heavy lifting devices (Jack-up Barge)	Average Time for Mooring	10	hours
	Average Time for Lifting	24	hours
	Average Time for Demoorings	10	hours
	Accessibility (throughout year)	77%	-
	Mobilisation/Demobilisation Rate	330	k€/mob
	Daily rental rate	110	k€/day
	Minimum number of WTs for repair	1	-

The type of vessel used for simple repairs is a WindCat (Figure 39 in Appendix F), which is capable of operating for a sea state of up to 1,5 m significant wave height. According to the wave height distribution of Scira (Appendix F) this results in accessibility of about 77% in a year. All failures, including the ones that require special lifting vessel, are assumed to be diagnosed remotely, so there is no need to send a crew for on-site inspection and identification of the failure. For large and heavy components' failures, a jack-up barge (self elevating ship with built-in crane, see Figure 40 in Appendix F) is used for 24 hours per repair on average. It is not possible to define different accessibility for the special lifting equipment in CONTOFAX, so it is assumed that the jack-up barge can access the site for 77% of the time equally to the WindCat.

Baseline scenario results

Table 17 shows the resulting O&M parameters' values from 4 different runs of CONTOFAX simulating the baseline scenario; the last row contains the average values. More than 1 runs were performed so as to investigate possible variations of the results due to different distributions of the same storm percentage. This is possible in CONTOFAX by changing the

seed number of the built-in random number generator. Resulting average availability and O&M costs are 91,22% and 2 c€/kWh respectively.

Table 17. Scira Baseline results

Accessibility			Availability	O&M costs per kWh
Winter	Summer	Year	20 years	20 years average
70,55%	84,30%	77,78%	91,21%	0,0200 €
69,36%	84,92%	77,49%	91,40%	0,0198 €
69,64%	84,96%	77,67%	90,90%	0,0201 €
69,67%	84,79%	77,62%	91,38%	0,0201 €
69,80%	84,74%	77,64%	91,22%	0,0200 €

In order to identify which factors affect availability and O&M expenses, eventually aiming to optimise the O&M strategy, breakdown of downtimes and O&M costs of the baseline case (Figure 21) are depicted from CONTOFAX detailed output information.

4. Availability of Offshore Wind Farms

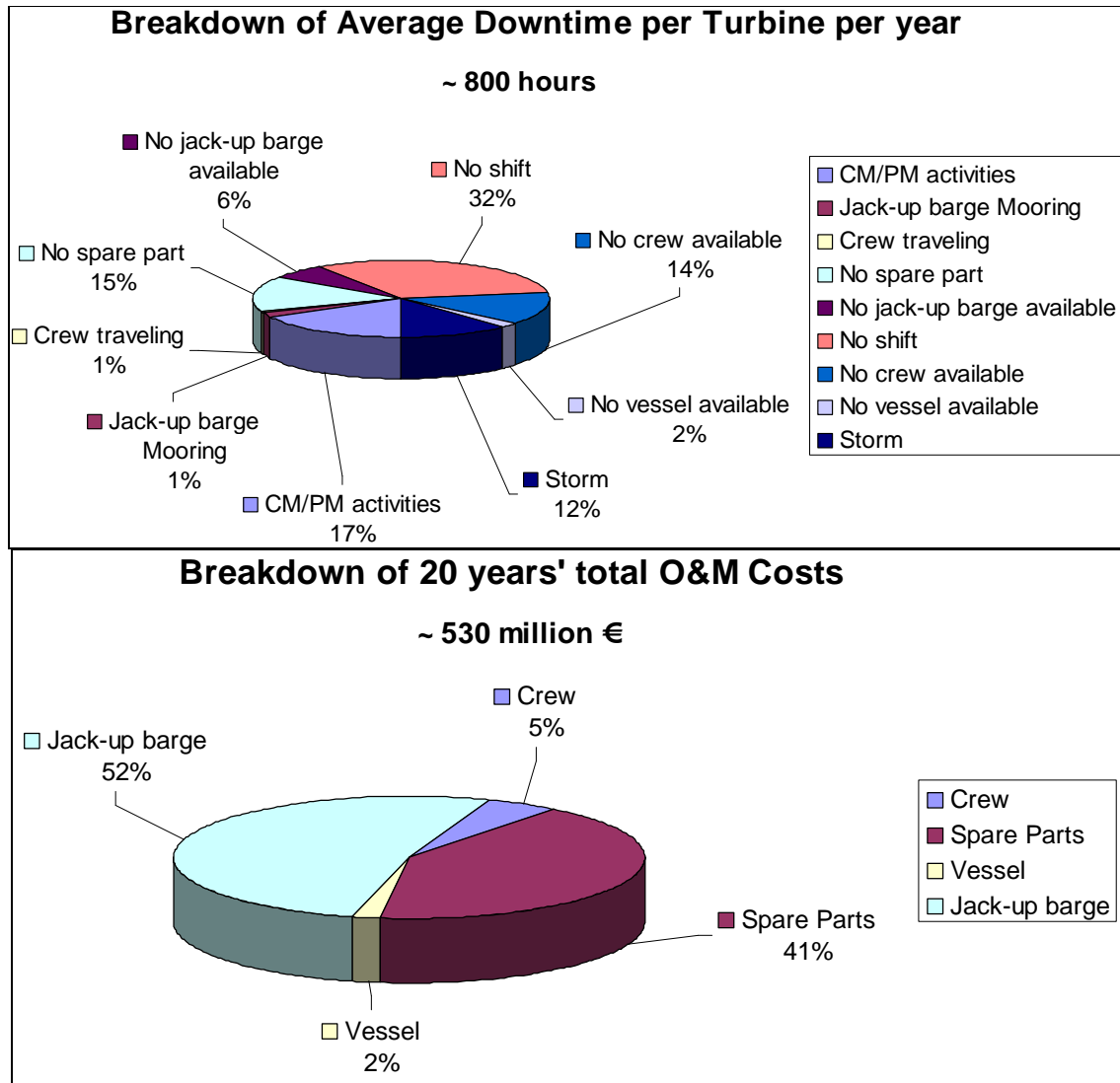


Figure 21. Breakdown of average downtime per WT per year and O&M costs (Baseline)

In the first graph, the total resulting downtime is split into the following categories:

- CM/PM activities: The actual time spent on wind turbine for servicing/repairing it. Downtime associated with working time of special lifting equipment e.g. jack-up barge, is included here.
- Jack-up barge mooring: This is the time needed for the jack-up to travel to the wind farm and position itself.
- Crew travelling: This is the amount of time spent for travelling to the failed wind turbine (only for CM, since for PM the wind turbine is assumed to be running until approached). Note that travelling from the repaired wind turbine back to the maintenance base is not counted in, since it is assumed that the wind turbine operates as soon as the required actions are accomplished in terms of repair time.
- No spare part: The ordering time for spare parts, if not available in stock, which is always the case for the baseline scenario.
- No jack-up barge available: When a certain repair requires jack-up barge but it is busy on another mission (4%) or another wind turbine of the wind farm (2%).

- No shift: The amount of time a wind turbine does not operate because there is no shift available when PM or CM actions are needed, or the available shifts ended before finishing the required tasks.
- No crew available: The amount of time a wind turbine is down because all available crews are busy in another wind turbine of the wind farm.
- No vessel available: The amount of time waiting for a vessel to be available for crew transportation; until then it is busy on another wind turbine which is under maintenance.
- Repair abandoned due to storm: Before finishing PM/CM actions, crew abandons maintained wind turbine and has to go back to the maintenance base because of an upcoming storm which would not allow travelling back.
- End of shift: Before finishing PM/CM actions, crew abandons maintained wind turbine because their shift (including possible overtime) ends.
- Storm: The amount of time a wind turbine is not operating because it cannot be accessed for CM or PM activities due to unfavourable weather conditions, based on the transport means' specifications.

CM/PM activities downtime depends not only on failure frequency, but also on the criticality of each failure and difficulty of repairing, since they outline the required repair effort. In other words, actual working time on a wind turbine under maintenance is solely influenced by the wind turbine's reliability. For a given wind turbine model with defined failure behaviour, no decrease in CM/PM activities downtime is possible by changing the maintenance strategy. From the rest of the categories, crew strategy (No shift, No crew available), spare parts ordering time, site accessibility (Storm), and jack-up barge availability contribute mostly to the total downtime in descending order. In terms of expenses, spare parts' price and rental charges for the jack-up barge dominate O&M activities. Combining the previous, variations of the baseline scenario will be carried out in order to see at what extent each category is affecting availability and O&M costs. This information can then be used for optimising the O&M strategy, in terms of achieving a good balance of these two parameters.

4.4.1 Variations of the baseline

Input parameters

In order to look investigate variations of the baseline scenario, the following iterative method is applied:

1. Define which parameters will be investigated.
2. For this parameters, chose a range of interest for input values.
3. Vary these parameters one step at a time and keep the rest input parameters same as the baseline scenario.
4. Run 4 simulations using the same seed numbers as in the baseline scenario, so that results can be comparable.
5. Repeat steps 3 and 4 for all the range defined in step 2.
6. Gather results and compare.

Following from the analysis of the baseline case, variations to be considered are given in Table 18, together with input values that are different from the baseline.

4. Availability of Offshore Wind Farms

Table 18. Maintenance parameters (Variations)

	CONTOFAX Input Parameter	Value	Step
Accessibility	Accessibility (throughout year)	50 - 100%	5%
Reliability	Total annual failure rate	1,5 - 6,5	1
Heavy lifting devices	Number of wind turbines to fail before jack-up barge is sent to the wind farm	2 - 14	1
Distance of wind farm from shore	Travelling Time from port to site (vessel)	2 - 5	1
	Average Time for Mooring (Jack-up Barge)	11 - 15	1
Spare Parts	Expenses for keeping stock of spare parts (% of their price)	8 - 18%	2%
Crew strategy	Length of one Shift	12 or 24	
	Number of Shifts per Day	1 or 2	1
	Number of Crews per Shift	2 - 4	1

- Accessibility effect on availability and O&M costs is studied by changing the desired annual average percentage, which represents either different weather conditions, or vessel type with different specifications. Simulations are performed for accessibility levels of 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, and 100%.

- Wind turbine's reliability influence on O&M parameters is investigated by increasing or decreasing the annual failure rate for every subcomponent with the same percentage, summing up to 1,5, 2,5 3,5, and 4,5 failures per wind turbine per year.

- Since the heavy lifting equipment (jack-up barge) rental expenses make up half of the total O&M costs (Figure 21), a different strategy is evaluated: instead of hiring a jack-up barge when one failure that requires such an equipment happens, clustering of 2 to 14 events will be simulated.

- In order to assess the effect of wind farm's distance to shore on O&M parameters, travelling time of 2, 3, and 4 hours for the simple vessel and respectively 12, 14, and 16 for the jack-up barge are simulated.

- Ordering time for spare parts can be eliminated by having available stock on an onshore location near the closest to the wind farm port. Rental costs and interest losses associated with keeping a stock of spare parts are input in the simulation program so as to see how the total O&M expenses are influenced. For easier comparisons, costs of having a stock of spare parts are calculated as percentage of their purchase price.

- Scenarios for different crew strategies will be simulated by varying the length of one shift, as well as the number of available crews and shifts.

Results

Resulting availability and O&M costs for different wind turbine reliability values are depicted in Figure 22; reliability is expressed in terms of overall wind turbine failure rate, ranging from 1,5 to 5,5 failures per WT per year. As it was expected, there is a substantial increase in availability and decrease in O&M costs for lower failure rates.

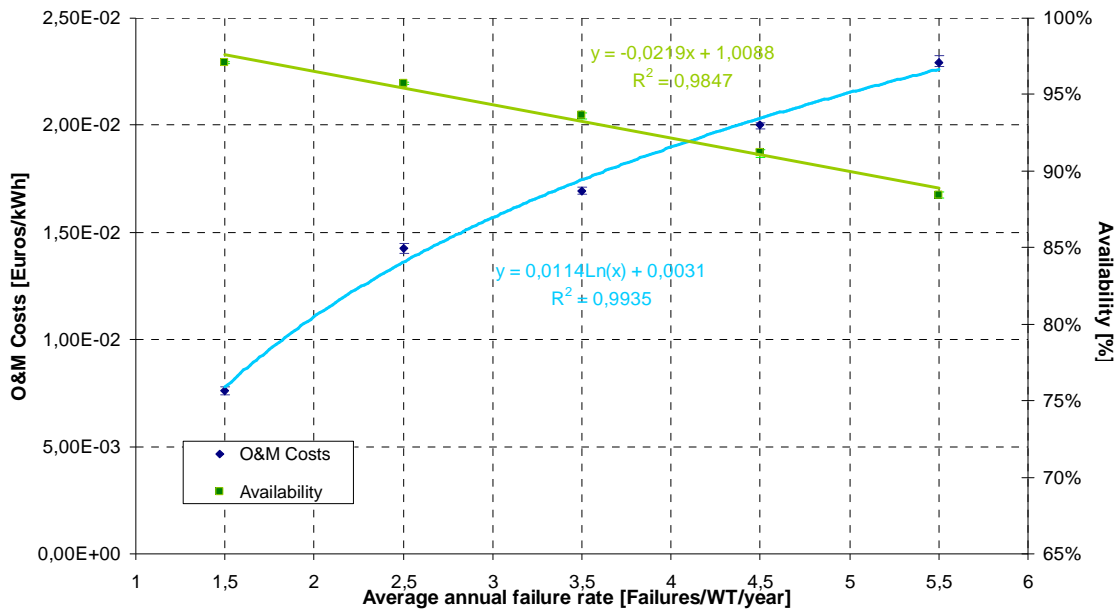


Figure 22. Availability and O&M costs vs. annual failure rate

Figure 23 shows what are the resulting availability and O&M costs per kWh produced for different accessibility values (50 to 100% with a step of 5%); the baseline scenario is illustrated in red. The lines connecting simulation points are just fitted trend lines to show divergence from linearity. As it was expected, high accessibility levels result in high availability and lower O&M costs. For the latter, blue bars indicating different simulations show that there is larger – still limited – uncertainty when site accessibility is less than 70%.

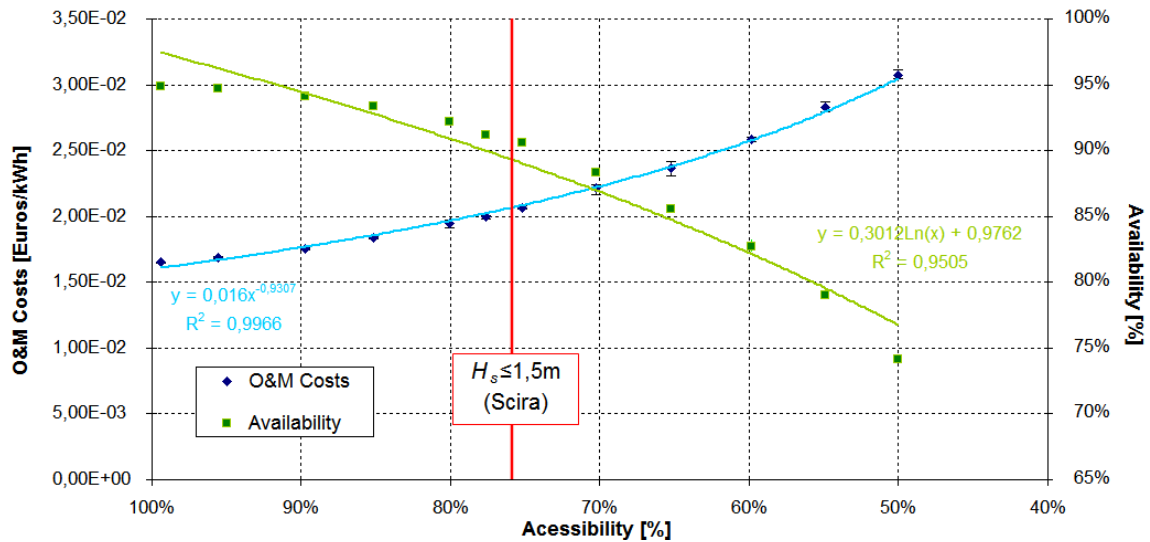


Figure 23. Availability and O&M costs vs. accessibility

The effect of wind farm’s distance from the closest port, where maintenance crews and vessels are typically located, is evaluated by changing input travelling time. For these simulations, the following assumptions were taken into account:

4. Availability of Offshore Wind Farms

- The same wind farm is moved to locations with exactly the same weather conditions as the baseline case, but different distance to shore.
- When travelling time using a simple transport means (e.g. WindCat) is x hours, travelling time for the jack-up barge is $2x$ hours.
- The human factor was not modelled, but it is expected that in reality repair times may be higher for long sea trips due to crew fatigue.

Figure 24 summarizes results from the described simulations. Note that on the x-axis travelling time of the simple transport means is shown; for the jack-up barge this is double. O&M costs per kWh seem to depend almost linearly with travelling time, but for higher values larger variations are observed. Additionally, for travelling times of 3 hours and above, availability drops quite significantly to 70% or less. As travelling time increases, it becomes less probable to have a sufficient weather window to approach the failed wind turbine and repair it. For example, when travelling time is only one hour a 6 hour weather window is sufficient for a failure that requires 4 hours repair; when travelling time is 3 hours, the required weather window increases to 10 hours. Moreover, for weather windows above the length of one shift, availability of crews becomes an important issue; however, this effect is possible to be reduced, if crew strategy is adjusted for far shore wind farms.

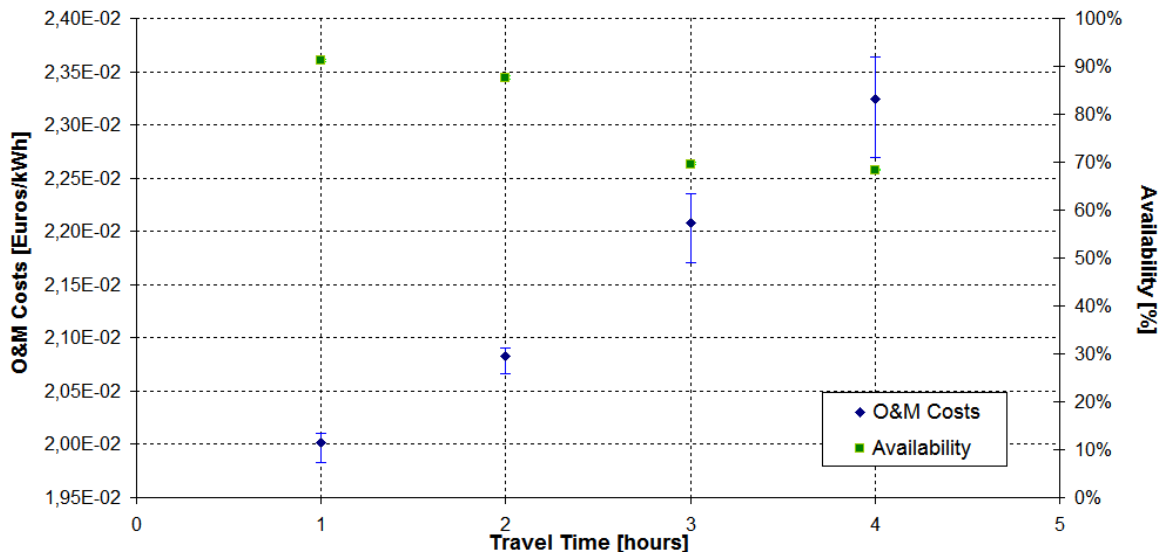


Figure 24. Availability and O&M costs for varying travel time

Large portion of O&M costs comes from heavy equipment rental and use (Figure 21). A way to reduce these expenses is by using the jack-up barge only after a certain number of wind turbines are in need for it. For the for the studied wind farm of 88 wind turbines, Figure 25 shows that for up to 9 wind turbines, clustering can reduce costs without sacrificing availability. The first point represents the baseline case where a jack-up barge is used immediately when needed. Note that when the number of clustered wind turbines is more than 10, availability varies significantly for different runs as illustrated by the error bars, showing that chances of having such a large number of failures, which require a jack-up barge, reduce.

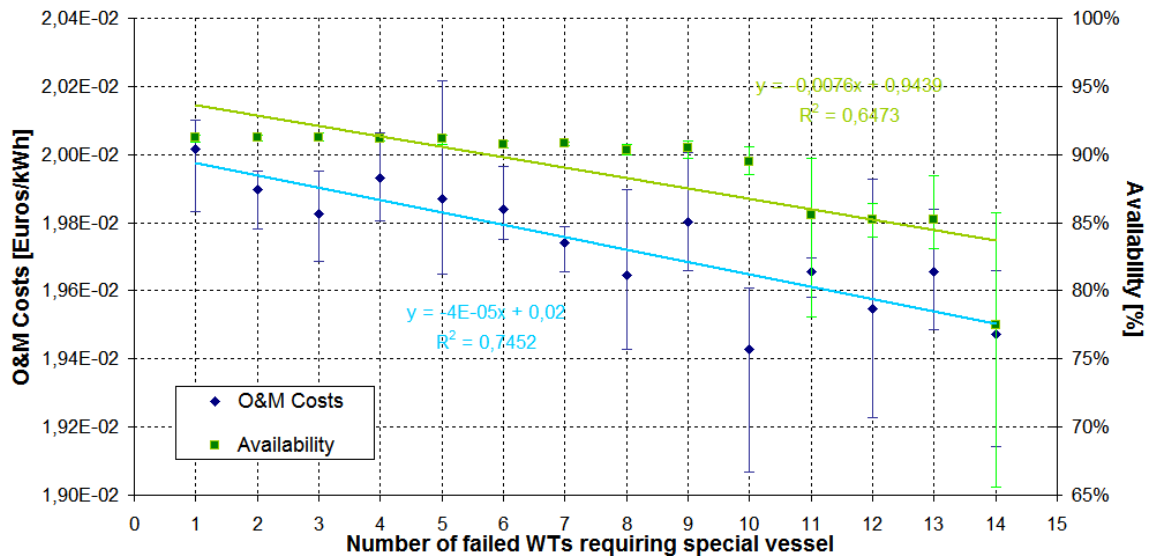


Figure 25. Availability and O&M costs when special vessel activities are clustered

Different crew scenarios were simulated and results are shown in Figure 26. The number of vessels is included because of the way CONTOFAX handles vessels, e.g. one vessel can carry only one crew. The most important conclusion from this analysis is that high availability with relatively low O&M cost per kWh can be achieved by using round-the-clock shifts, which means having crews available anytime during day and night. Note that the number of wind turbines influences if it is worth having round-the-clock shifts, since a wind farm of many units has increased chances to fail during night time.

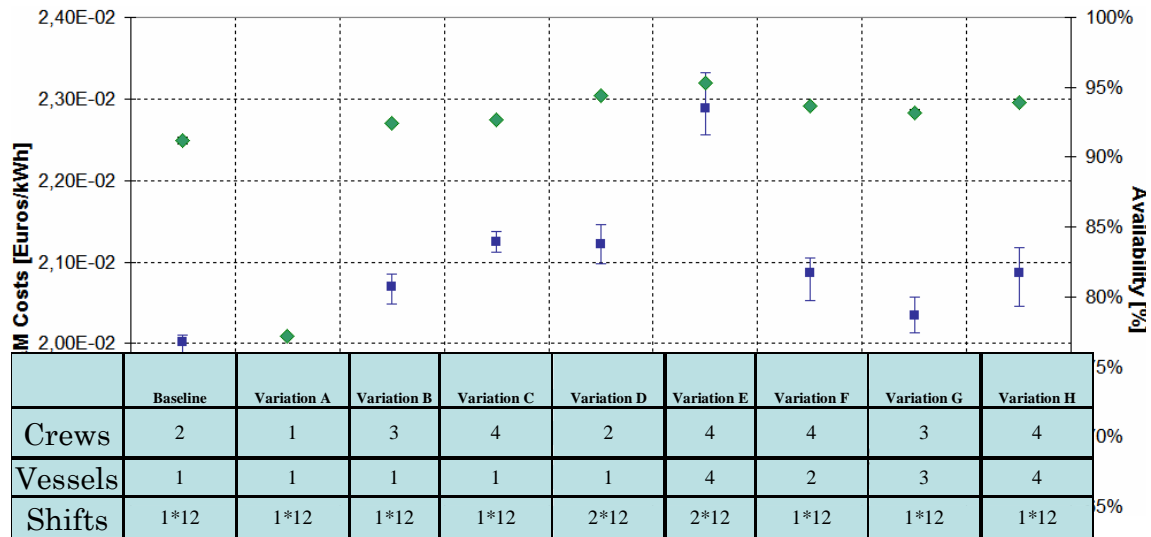


Figure 26. Availability and O&M costs for various crew strategies

In order to discover possible benefits from having a stock of spare parts instead of ordering them on the event of a failure, rental costs and associated interest rate are taken into account. Figure 27 shows what are the O&M costs per kWh for different price of keeping spare parts in stock, which is given as the percentage of their total purchase cost. Availability increases

4. Availability of Offshore Wind Farms

from 91,2% (baseline) to 91,8% when a stock of spare parts is made available. The variations of O&M costs for different CONTOFAX seed numbers, illustrated as blue bars, reveals that O&M costs are influenced by the amount of time the spare parts are kept in stock before a failure occurs and they are needed.

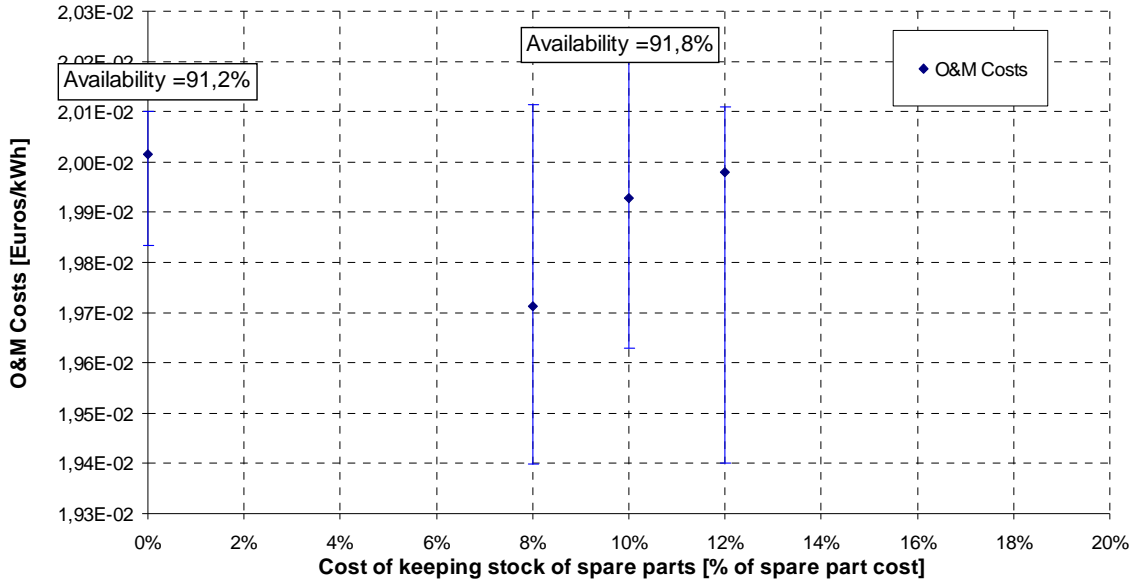


Figure 27. O&M costs for keeping stock of spare parts

A simulation was performed using a vessel that can go up to 1,5 m significant wave height and another simulation using an advanced access system that can operate up to 2,0 m (e.g. Ampelmann). In both simulations, the jack-up barge can access the site when significant wave height is below 1,0 m. The result (Table 19) shows that having such an access system would result in about 2% higher availability; O&M costs and total revenues depend on how much the advanced system would cost. It was calculated that it is worth using such a system if it costs up to 4 times the expenses of renting a standard vessel (e.g. WindCat, 200 euros/day). Selling price of produced electricity was assumed to be 8 c€/kWh.

Table 19. Standard vs. advanced access system

Parameter	Standard vessel	Advanced vessel
Availability	90,07%	92,16%
Rental price	200 €/day	4,1*200 €/day
O&M COSTS/kWh	0,0287 €	0,0299 €
Total Revenues excluding Capital Costs (Selling price: 8 c€/kWh)	1.340.134.990 €	1.340.111.758 €

5. DISCUSSION

5.1 Conclusions

Wind turbine technology has significantly evolved during the last 30 years, and nowadays various designs of horizontal axis machines are available in the market. In the first part of this thesis, the most important design choices were reviewed and compared, showing that every option has certain advantages and drawbacks, which should be taken into account during the various design phases of a wind turbine. Currently, the most widely used topologies include the Danish concept, which incorporates stall control with fixed rotational speed and induction generator, the geared variable speed architecture with pitch control for power regulation, and direct drive machines with slow rotating multipole synchronous generator and no gearbox. These types have been successfully operating in onshore environments, and are most likely to be used offshore, as if not already.

In order to assess reliability of the most important topologies, two databases of wind turbine failures, namely LWK-SH and WMEP, were analysed. Four wind turbine models each one representing a specific topology were selected based on the amount of available data in terms of number of monitored units and years of operation: Micon M1500, Enercon E-40, Tacke TW600, Vestas V39. From the analysis of more than 10 operational years of failure data for these onshore wind turbines located in Germany, it was found that mid power class machines experienced 2 to 5 failures per wind turbine per year. As it was expected, failure rates are lower for wind turbines close to the coastline where lower turbulence levels are observed. Comparison of the most common wind turbine topologies showed that, at least in the mid power class, no specific architecture clearly stands out in terms of reliability. There are certain characteristics however that seem to lead to more reliable designs: variable speed operation, power regulation by means of blade pitching, avoidance of functions that require hydraulic and complex electrical systems. Passive stall control may also be reconsidered for offshore applications, since results showed that downtimes are low for wind turbines located close to the coastline. Elimination of the gearbox can potentially result in reliable wind turbines, but it should be underlined that an increased number of failures should be expected during the first years of operation for the non conventional slow rotating generator and associated electrical system of direct drive machines.

As far as concerning reliability of wind turbine subassemblies, experienced operators consider gearboxes as a major problem, especially for large wind turbines. Complete gearbox replacements during the first operational years of an offshore wind farm are not uncommon. From the analysis, the gearbox did not prove to be the most frequent failing component of a wind turbine, but it is certainly a critical component in terms of reliability, since it leads to very large downtimes when there is a failure. Similarly, blades, electrical generators, shafts and bearings require relatively large repair times, although they do not fail very frequently. On the other hand, data showed that electric and electronic systems fail rather often, especially during the first years of operation. Since associated downtimes are relatively low, electric and electronic subassemblies are critical particularly for offshore applications, where access is limited by weather conditions and vessel availability.

For the majority of the subassemblies, constant failure rate is adequate to describe their failure behaviour. There are however some cases where failure rate is considerably varying as years of operation go by. In order to track changes of wind turbine reliability with time, the AMSAA reliability growth model was applied to the LWK-SH and WMEP datasets of wind turbine failures.

A great advantage of the applied technique is that it can model all three phases of the bath-tub life curve for repairable systems, namely early failures, intrinsic failures, and wear-out period.

It was concluded that failure rates of certain components such as the blades, electrical systems, and hydraulics decrease significantly with time as a result of on-field modifications, while other wind turbine parts such as the gearbox, the shafts, and the bearings tend to fail more often as time goes by, mainly due to normal wear out. The overall picture is that wind turbines experience a rather high number of early failures during the first 1-3 years of operation as a result of adaptations to the specific site.

Since the early 90s, wind energy industry has stepped offshore due to a number of interesting characteristics compared to onshore wind harvesting, such as high wind speed regime, low turbulence intensity levels, limited visibility issues, wider public acceptance, and availability of larger areas. At least when initially realized, offshore wind farms were not really different than onshore ones, since the same wind turbine technology with slight modifications was directly applied to the new environment. In these early cases, low water depths and small distance to shore may have justified this option. For future large scale offshore wind farms however, it is doubtful whether simply applying the existing onshore wind turbine technology will lead to the desired outcomes, e.g. high energy yield and revenues. This is mainly because offshore wind generated electricity is more expensive than onshore not only due to higher capital expenses involved, but also as a result of large variations of associated operation and maintenance costs. The latter make up about 30% of the total cost of energy offshore, and they depend primarily on technical reliability and site accessibility, which give rise to uncertainty in predictions.

Technical reliability is one of the most important factors influencing wind farm availability and therefore energy yield and revenues, but especially offshore it is not the only one. In order to investigate which parameters affect offshore wind farm availability and to what extent, several Monte-Carlo simulations were performed using CONTOFAX software tool, developed at TU Delft. For a large offshore wind farm of about 320 MW nominal power, 91,2% average annual availability and O&M costs of 2 c€/per kWh were estimated.

Breakdown of O&M costs revealed that expenses associated with heavy lifting equipment such as a jack-up barge, contribute more than half to the O&M costs per kWh. Costs for spare parts are also significant, in the order of 40%, while crew and transport devices expenses are about 7%.

By step changing important input parameters in CONTOFAX and keeping the rest unchanged, availability and O&M costs per kWh were obtained for different scenarios. With this method it was found that the most important parameters affecting offshore wind farm availability and O&M costs per kWh are mainly wind turbine reliability, site accessibility, distance of wind farm to shore, and availability of transports means and human resources. By optimising the chosen O&M strategy, higher availability and lower O&M costs can be achieved. This can be done for example by having round-the-clock crew shifts, by using heavy lifting equipment for more than one repairs, and/or by keeping a stock of spare parts on an onshore location close to the wind farm. Use of an advanced offshore access system that can operate under less strict weather conditions than conventional vessels is also advantageous, given that associated operational costs are within a certain range.

5.2 Recommendations for future work

The importance of wind turbine reliability especially for offshore projects shows that there is a strong need for further research in the direction of reducing failure events and associated downtimes. In this context, it is fundamental to build a carefully structured database of operational information using a properly organised collection system. Monitoring the performance of multi-megawatt wind turbines will help research to identify critical components from a reliability point of view, as well as classify all failure modes, with the aim to deal with the most important problems of modern machines. For the success of such a data

collection project, a large number of participants is necessary; in order to attract as many wind farm operators as possible and ensure confidentiality, an independent institution should be in charge of gathering and handling the data of competitive manufacturers. Additionally, standardisation of the method to collect wind turbine operational data on a European or even international level is essential so as to ensure a reliable database. Experience gained from relevant projects such as the WMEP programme would be valuable in this direction. An example of a very successful reliability data collection project is the OREDA initiative by the most important players in the offshore oil and gas market.

More accurate prediction of loads and re-evaluation of applied safety factors would be beneficial for the technical reliability of larger machines. As an example, new information about gearbox dynamics, such as that loading comes not only from the rotor but also from the generator side, show that there is not enough knowledge yet concerning the actual loads that a wind turbine gearbox experiences throughout its lifetime. Reliability of the power grid should also be thoroughly researched, since electrical and electronic parts of grid-connected wind turbines fail rather frequently, especially in their early life.

Especially for offshore applications, it would be valuable to design new wind turbines with focus on reliability and ease of maintenance. Applying the onshore technology to the sea with slight modifications seems to create a number of reliability problems. Dedicated offshore wind turbine designs with characteristics such as simplicity, reduction of parts, application of condition monitoring for failures prediction, and use of light subcomponents with modular parts that can be easily exchanged, are rather necessary for the future large offshore wind farms. Maybe it is the right time for manufacturers to re-consider abandoned concepts or invest on new innovative designs. In addition, systematic testing of all subcomponents and the wind turbine as a system would help in avoiding high numbers of early failures that are known to occur after commissioning.

For a more accurate prediction of O&M costs for offshore wind farms, focus on advanced simulation tools, which describe O&M activities very close to what is happening in reality, is highly recommended. Experience with software such as CONTOFAX has shown that the results' quality strongly depends on the quality of the input information. A properly structured database of offshore wind farms operational data as described in the beginning of this section could also be useful for such simulations.

APPENDICES

Appendix A. LWK-SH and WMEP maintenance report examples

Zusammenstellung der Stillstandszeiten für den WKA-Typ				
ENERCON E40				
für den Zeitraum:		1.96	- 12.96	
Anzahl WKA :		59		
Ø Anlagenalter Ende 96		27	Monate	
Stillstandsgrund		Anzahl Stunden	Anzahl betroffene WKA	Still- stand Anteil %
Wartung		598	46	0,12
Netzstörungen/-ausfall		482	18	0,09
Sturm		4	1	0,00
Vereisung		113	15	0,02
Abschaltungen	<i>gesamt</i>	1.084	59	
	<i>Ø je WKA</i>	18		0,23
Blitz		0	0	0,00
Rotorblatt		798	31	0,15
Rotorbremse		0	0	0,00
Pitchverstellung		268	14	0,05
Bremse mechanisch.		0	0	0,00
Wellen/Lager		622	3	0,12
Getriebe		0	0	0,00
Generator		2.639	26	0,51
Hydraulik		0	0	0,00
Windnachführung		33	3	0,01
Windmessung		40	5	0,01
Regelungstechnik		415	22	0,08
Elektrik		837	33	0,16
Wechselrichter		38	1	0,01
Sensoren		71	6	0,01
Sonstiges		250	15	0,05
Störungen	<i>gesamt</i>	6.010	59	
	<i>Ø je WKA</i>	102		1,16
Stillstand	<i>gesamt</i>	7.207	59	
	<i>Ø je WKA</i>	122		1,39
Verfügbarkeit 96	<i>Ø je WKA</i>		%	98,61

Figure 28. Excerpt page from the LWK-SH booklet [21]

<h2 style="margin: 0;">Maintenance and Repair Report</h2> <h3 style="margin: 0;">WMEP 250 MW-Wind</h3>		work carried out <table style="width: 100%; border: none;"> <tr> <td style="border: 1px solid black; width: 20px; height: 20px;"></td> <td style="border: 1px solid black; width: 20px; height: 20px;"></td> <td style="border: 1px solid black; width: 20px; height: 20px;"></td> </tr> <tr> <td style="font-size: 8px;">day</td> <td style="font-size: 8px;">month</td> <td style="font-size: 8px;">year</td> </tr> </table>				day	month	year	report-nr. <input style="width: 40px; height: 20px;" type="text"/>						
day	month	year													
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<input type="checkbox"/> overspeed <input type="checkbox"/> overload <input type="checkbox"/> noise <input type="checkbox"/> vibration	<input type="checkbox"/> reduced power <input type="checkbox"/> causing follow-up damage <input type="checkbox"/> plant stoppage <input type="checkbox"/> other consequences														
<h4 style="background-color: #cccccc; margin: 0;">reason for repair</h4> <p> <input type="checkbox"/> scheduled maintenance <input type="checkbox"/> scheduled maintenance with replacement of worn parts or repair of defects <input type="checkbox"/> unscheduled repair after malfunction </p>		<h4 style="background-color: #cccccc; margin: 0;">removal of malfunction</h4> <p> perfect functioning of plant after <input type="checkbox"/> control reset <input type="checkbox"/> changing of control parameters </p> <p>repaired or replaced components</p> <table style="width: 100%; border: none;"> <tr> <td style="width: 50%; vertical-align: top;"> <input type="checkbox"/> hub <input type="checkbox"/> hub body <input type="checkbox"/> pitch mechanism <input type="checkbox"/> pitch bearings <input type="checkbox"/> rotor blades <input type="checkbox"/> blade bolts <input type="checkbox"/> blade shell <input type="checkbox"/> aerodynamic brakes <input type="checkbox"/> generator <input type="checkbox"/> generator windings <input type="checkbox"/> generator brushes <input type="checkbox"/> bearings <input type="checkbox"/> electric <input type="checkbox"/> converter <input type="checkbox"/> fuses <input type="checkbox"/> switches <input type="checkbox"/> cables/connections <input type="checkbox"/> sensors <input type="checkbox"/> anemometer/wind vane <input type="checkbox"/> vibration switch <input type="checkbox"/> temperature <input type="checkbox"/> oil pressure switch <input type="checkbox"/> power sensor <input type="checkbox"/> revolution counter <input type="checkbox"/> control system <input type="checkbox"/> electronic control unit <input type="checkbox"/> relay <input type="checkbox"/> measurement cables and connections </td> <td style="width: 50%; 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Figure 29. Maintenance and repair report of WMEP [24]

Appendix B. Additional information of selected wind turbines

All following drawings were taken from the manufacturers' brochures, and pictures come from the internet.

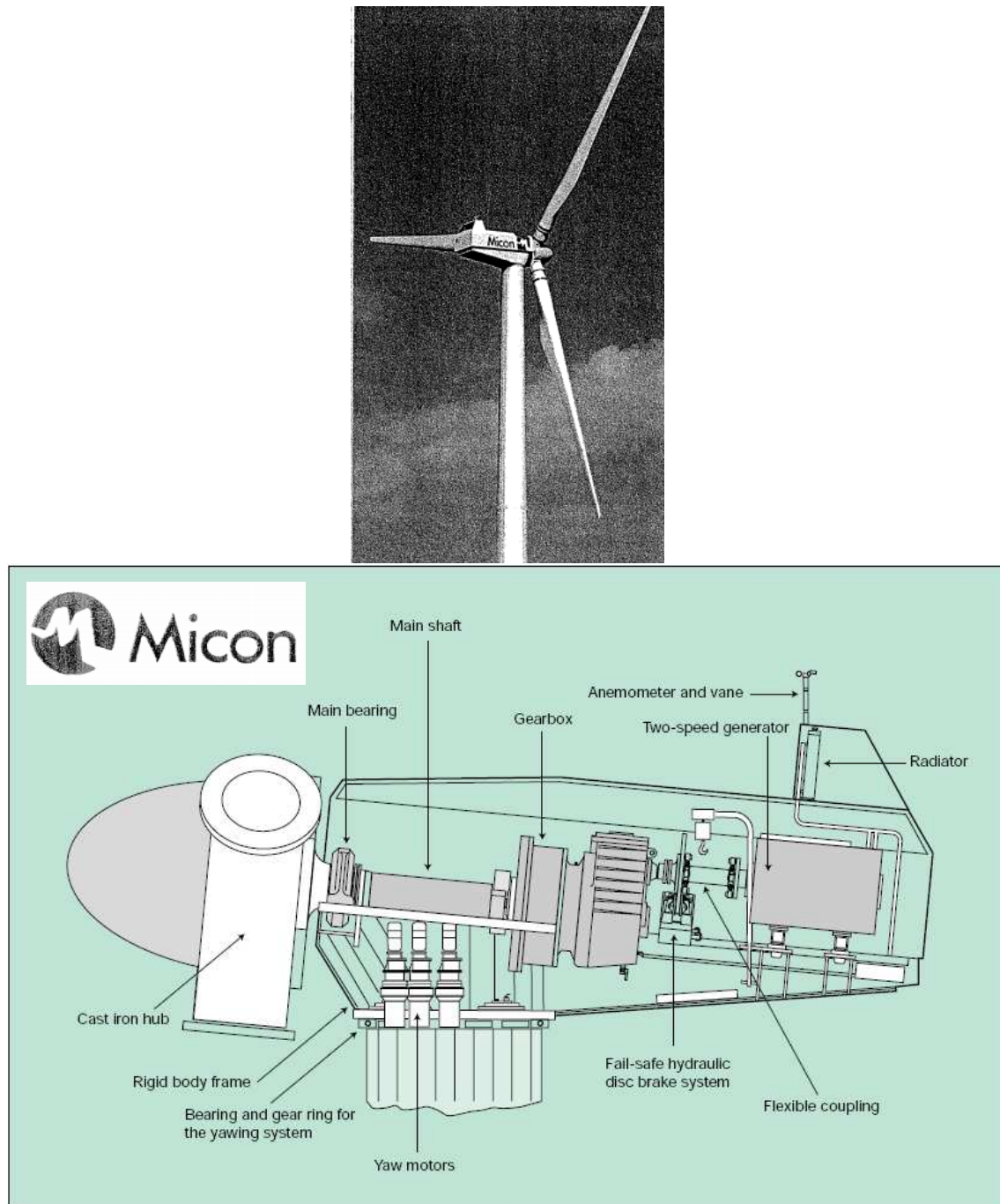
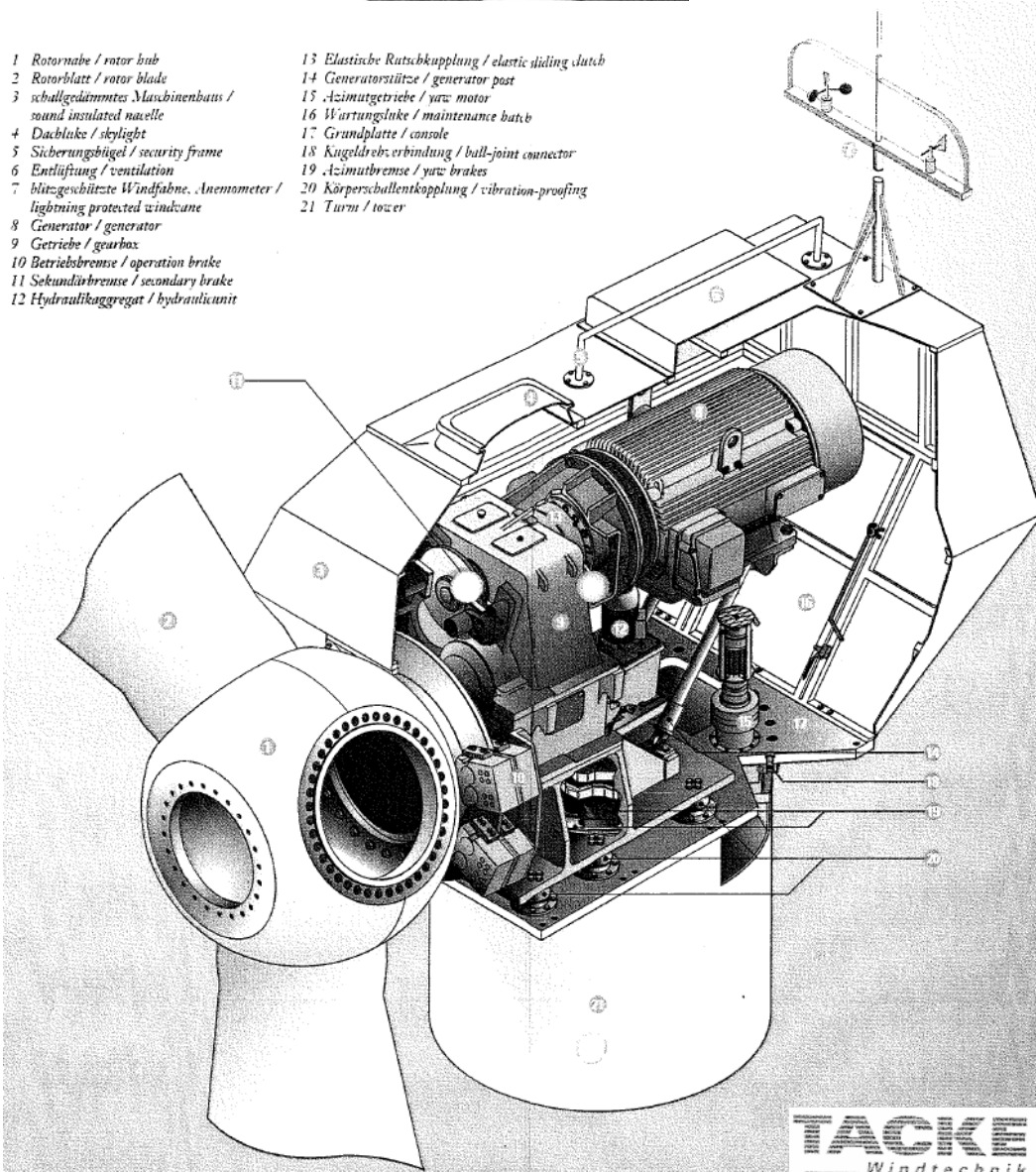
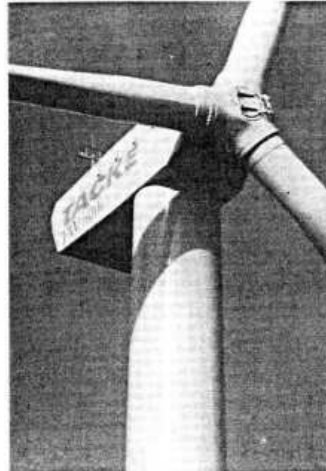


Figure 30. Micon M1500



- | | |
|--|---|
| 1 Rotornabe / rotor hub | 13 Elastische Ratschkopplung / elastic sliding clutch |
| 2 Rotorblatt / rotor blade | 14 Generatorstütze / generator post |
| 3 schalldämmtes Maschinenhaus / sound insulated nacelle | 15 Azimutgetriebe / yaw motor |
| 4 Dachluke / skylight | 16 Wartungsluke / maintenance hatch |
| 5 Sicherungsbügel / security frame | 17 Grundplatte / console |
| 6 Entlüftung / ventilation | 18 Kugeldrehverbindung / ball-joint connector |
| 7 blitzgeschützte Windfahne, Anemometer / lightning protected windvane, anemometer | 19 Azimutbremse / yaw brakes |
| 8 Generator / generator | 20 Körperschallentkopplung / vibration-proofing |
| 9 Getriebe / gearbox | 21 Turm / tower |
| 10 Betriebsbremse / operation brake | |
| 11 Sekundärbremse / secondary brake | |
| 12 Hydraulikaggregat / hydraulic unit | |

Figure 31. Tacke TW600e

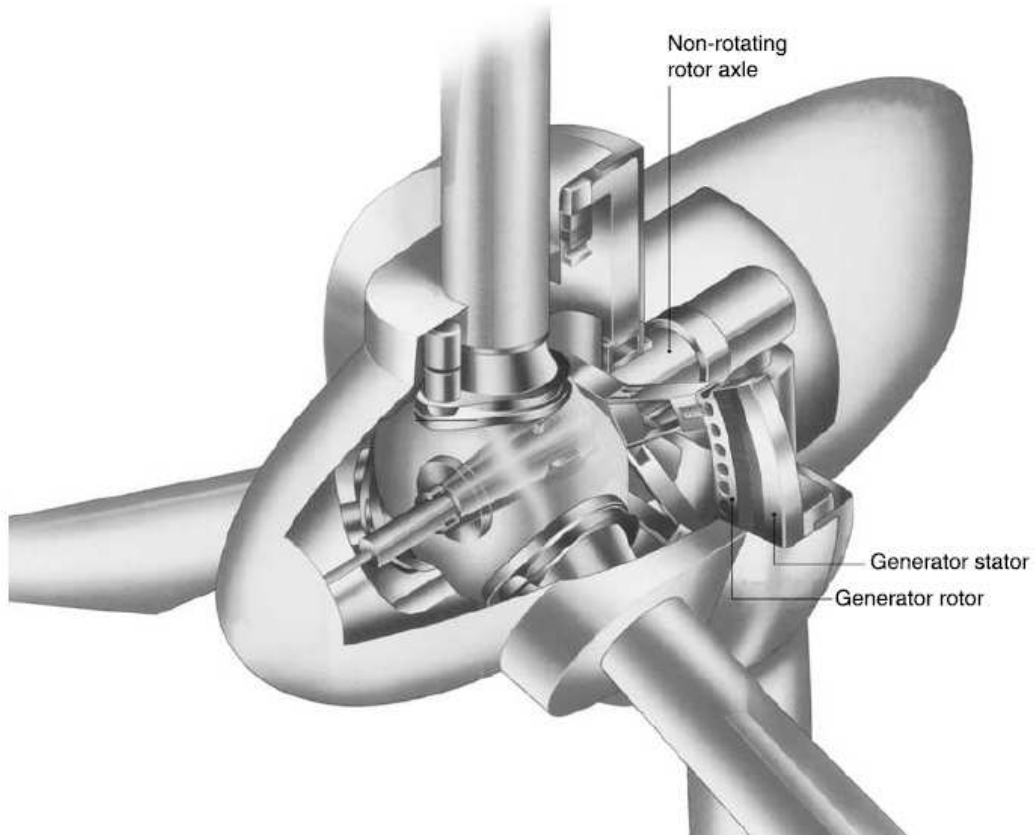
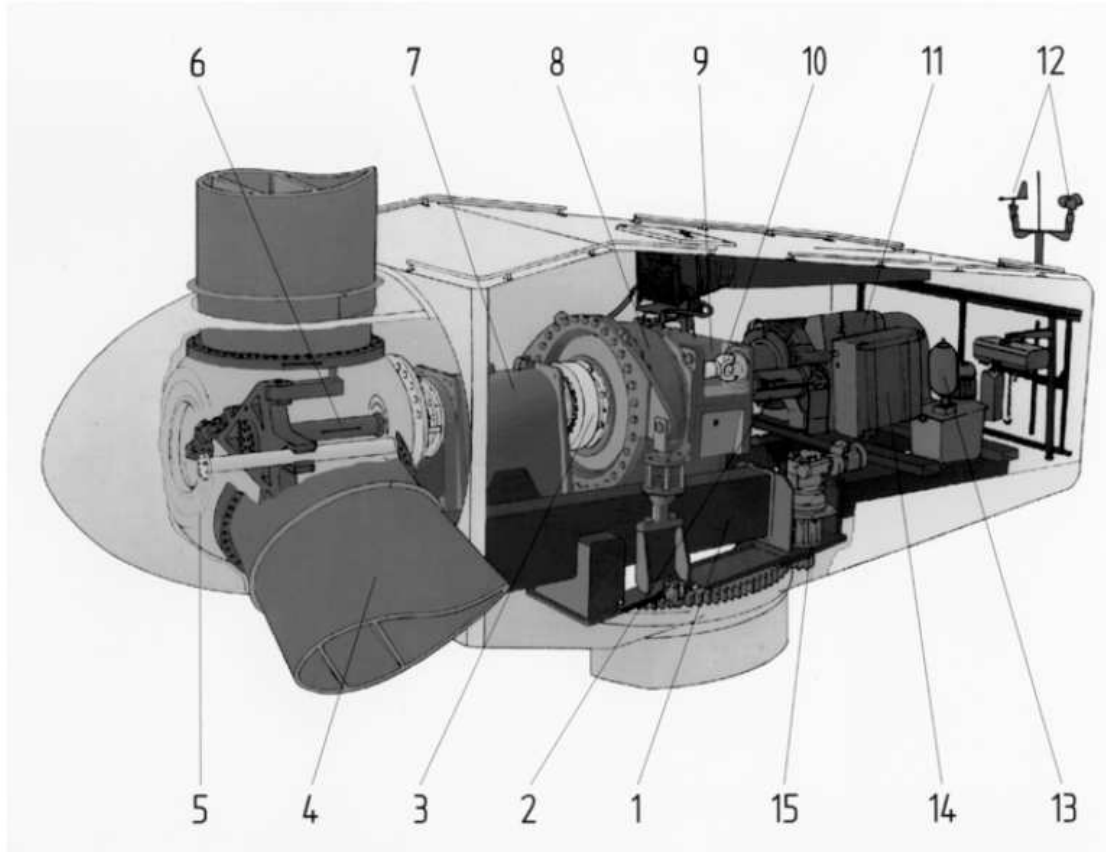


Figure 32. Enercon E-40 nacelle



- | | | |
|-------------------------|---------------------------|-------------------------------|
| 1. Nacelle bedplate | 6. Blade pitch mechanism | 11. Generator |
| 2. Blade pitch actuator | 7. Rotor main bearings | 12. Wind measuring system |
| 3. Rotor shaft | 8. Gearbox | 13. Hydraulic supply system |
| 4. Rotor blades | 9. Rotor brake | 14. Electrical control system |
| 5. Rotor hub | 10. Generator drive shaft | 15. Yaw drive |

Figure 33. Vestas V39 nacelle

Appendix C. Annual average failure rates and downtimes

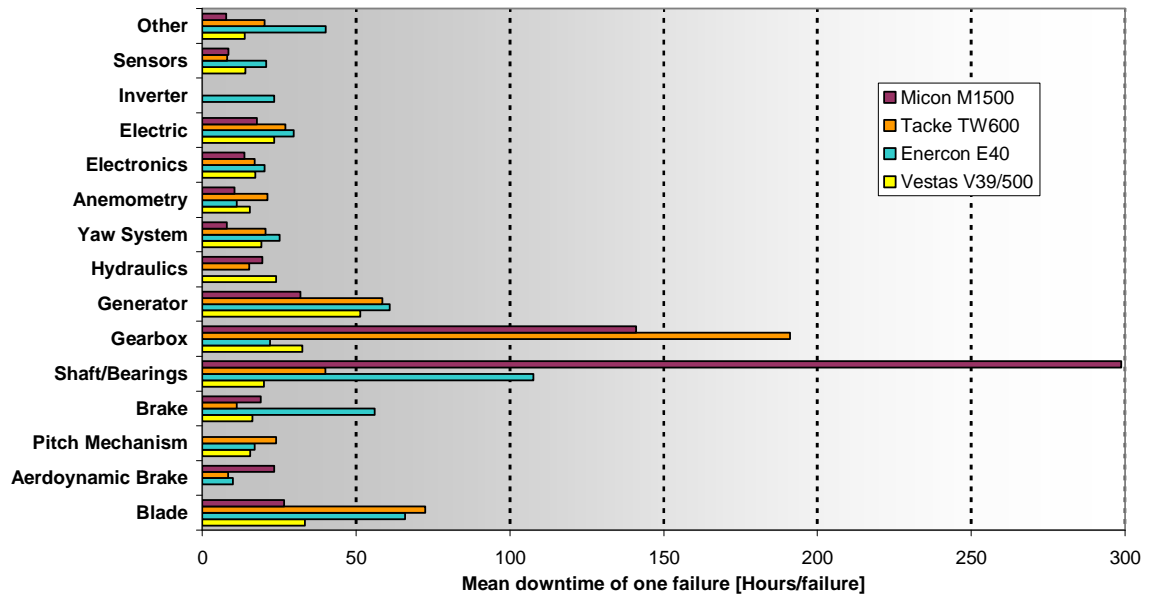


Figure 34. Mean Downtime due to a failure

Table 20. Ranking of average annual failure rates for all subcomponents

Micon M1500		Tacke TW600			Enercon E-40			Vestas V39/V4x		
LWK-SH	WMEP	LWK-SH	WMEP (Coast)	WMEP	LWK-SH	WMEP (Coast) Inverter & Electronics	WMEP Inverter & Electronics	LWK-SH	WMEP (Coast)	WMEP
Electric	Electric	Blade	Hydraulics	Hydraulics	Electric	Electric	Electric	Electric	Electric	Electric
Other	Inverter & Electronics	Other	Electric	Electric	Generator	Electric	Electric	Electronics & Inverter	Inverter & Electronics	Inverter & Electronics
Blade	Hydraulics	Electric	Other	Yaw System	Electronics & Inverter Pitch Mechanism	Pitch Mechanism	Pitch Mechanism	Hydraulics	Hydraulics	Hydraulics
Electronics & Inverter	Gearbox	Gearbox	Gearbox	Mechanical Brake	Mechanism	Generator	Other	Other	Gearbox	Gearbox
Generator	Sensors	Yaw System	Blade	Inverter & Electronics	Blade	Other	Blade	Gearbox	Pitch Mechanism	Blade
Sensors	Blade	Generator	Inverter & Electronics	Gearbox	Other	Sensors	Sensors	Blade	Blade	Pitch Mechanism
Gearbox	Aerodynamic Brake	Hydraulics	Mechanical Brake	Other	Sensors	Blade	Generator	Yaw System	Yaw System	Sensors
Aerodynamic Brake	Mechanical Brake	Brake	Yaw System	Blade	Yaw System	Yaw System	Yaw System	Pitch Mechanism	Other	Yaw System
Hydraulics	Other	Electronics & Inverter	Sensors	Sensors	Anemometry	Anemometry	Anemometry	Generator	Sensors	Generator
Yaw System	Shaft/Bearings	Sensors	Generator	Generator	Shaft/Bearings	Mechanical Brake	Shaft/Bearings	Sensors	Generator	Other
Shaft/Bearings	Yaw System	Anemometry	Anemometry	Anemometry	Brake	Shaft/Bearings	Mechanical Brake	Anemometry	Anemometry	Anemometry
Brake	Generator	Shaft/Bearings	Aerodynamic Brake	Shaft/Bearings	Gearbox	Hydraulics	Hydraulics	Brake	Shaft/Bearings	Mechanical Brake
Anemometry	Anemometry	Aerodynamic Brake	Shaft/Bearings	Aerodynamic Brake	Aerodynamic Brake	Gearbox	Aerodynamic Brake	Shaft/Bearings	Mechanical Brake	Shaft/Bearings
Pitch Mechanism	Pitch Mechanism	Pitch Mechanism	Pitch Mechanism	Pitch Mechanism	Hydraulics	Aerodynamic Brake	Gearbox	Aerodynamic Brake	Aerodynamic Brake	Aerodynamic Brake

Appendix D. Matlab code for AMSAA Reliability Growth model

Main Program

```

%Crow-AMSAA reliability growth model for LWK-SH Database (NHPP+HPP)
clear all;
load('Micon M1500-LWK.mat');
l=length(YEAROFOPERATION);
u={'Anemometry'
'Blade'
'Brake'
'Electric'
'Electronics'
'Gearbox'
'Generator'
'Hydraulics'
'Inverter'
'Lightning'
'Other'
'PitchMechanism'
'RotorBrake'
'Sensors'
'Shaft0x2FBearings'
'TOTAL'
'YawSystem'};

resultsAMSAA=zeros(1,5);

%User input for the type of plots required
plot_type=input('For plots of cumulative number of failures type 1 For
plots of failure rate type 2: ');
%User input for file type of the plots
plot_format=input('For .FIG format type 1 For .BMP type 2: ');
if plot_format==1
    clear plot_format
    plot_format='fig';
end
if plot_format==2
    clear plot_format
    plot_format='bmp';
end

%-----Main Program-----%

for w=1:17
disp('Processing LWK data of Micon M1500')
disp(u(w,1))

%Change to Total Test Time (TTT)
TTT_init=zeros(1,1);
TTT_init(1,1)=NumberOfWTs(1,1);
for f=2:1
    TTT_init(f,1)=TTT_init(f-1,1)+ NumberOfWTs(f,1);
end
clear f

if w==1;failures=NumberOfWTs.*Anemometry; end;
if w==2;failures=NumberOfWTs.*Blade; end;
if w==3;failures=NumberOfWTs.*Brake; end;
if w==4;failures=NumberOfWTs.*Electric; end;

```

```

if w==5;failures=NumberOfWTs.*Electronics; end;
if w==6;failures=NumberOfWTs.*Gearbox; end;
if w==7;failures=NumberOfWTs.*Generator; end;
if w==8;failures=NumberOfWTs.*Hydraulics; end;
if w==9;failures=NumberOfWTs.*Inverter; end;
if w==10;failures=NumberOfWTs.*Lightning; end;
if w==11;failures=NumberOfWTs.*Other; end;
if w==12;failures=NumberOfWTs.*PitchMechanism; end;
if w==13;failures=NumberOfWTs.*RotorBrake; end;
if w==14;failures=NumberOfWTs.*Sensors; end;
if w==15;failures=NumberOfWTs.*Shaft0x2FBearings; end;
if w==16;failures=NumberOfWTs.*TOTAL; end;
if w==17;failures=NumberOfWTs.*YawSystem; end;

%Calculate average annual failure rate
resultsAMSAA(w,5)=sum(failures)/sum(NumberOfWTs);

%Check if there are at least 15 failures in the current dataset
if sum(failures)<15;
    resultsAMSAA(w,4)=0;
    continue;
end;

%Rearrange bins so as to have at least 5 failures per bin
clear X
clear TTT
X(1,1)=failures(1,1);
TTT(1,1)=TTT_init(1,1);
if(X(1,1)>=5)
    bin_point=1;
else
    for bin_point=2:1
        X(1,1)=X(1,1)+failures(bin_point,1);
        if(X(1,1)>=5)
            TTT(1,1)=TTT_init(bin_point,1);
            break
        end
    end
end
end

for r=2:1
    if(bin_point==1); break; end;
    bin_point=bin_point+1;
    X(r,1)=failures(bin_point,1);
    TTT(r,1)=TTT_init(bin_point,1);
    if(bin_point==1); break; end;
    if(X(r,1)<5)
        for k=bin_point+1:1
            X(r,1)=X(r,1)+failures(k,1);
            if(X(r,1)>=5)
                TTT(r,1)=TTT_init(k,1);
                break
            end
        end
        bin_point=k;
    end
end
end

l_new=length(X);

```

Appendices

```
%Check if there are at least 3 bins each of at least 5 failures
if(l_new<3)
    resultsAMSAA(w,4)=0;
    continue
end

%If the last bin contains less than 5 failures, add it to its precedent
if(X(l_new,1)<5)
    X(l_new-1,1)=X(l_new-1,1)+X(l_new,1);
    TTT(l_new-1,1)=TTT(l_new);
    l_new=l_new-1;
    X=X(1:l_new);
    TTT=TTT(1:l_new);
end

%Calculate beta
beta=findzero(X,TTT,1);

%Calculate rho
N=sum(failures);
rho=N./(TTT(l_new,1).^beta);

%Goodness of fit
e=zeros(l_new,1);
tibeta=zeros(l_new,1);
tibeta=TTT.^beta;
e(1,1)=rho*tibeta(1,1);
for r=2:l_new
    e(r,1)=rho*(tibeta(r,1)-tibeta(r-1,1));
end
chisqr=sum( ((X-e).^2)./e );

%Keep values in workspace
resultsAMSAA(w,1)=beta;
resultsAMSAA(w,2)=rho;
resultsAMSAA(w,3)=chisqr;

if chisqr<chi2inv(0.95,l_new-2);
    resultsAMSAA(w,4)=1;
end
if chisqr>chi2inv(0.95,l_new-2);
    %Since NHPP rejected ,check if HPP can be accepted
    beta=1;
    rho=N./(TTT(l_new,1).^beta);
    e=zeros(l_new,1);
    e(1,1)=rho*TTT(1,1);
    for r=2:l_new
        e(r,1)=rho*(TTT(r,1)-TTT(r-1,1));
    end
    chisqr=sum( ((X-e).^2)./e );
    if chisqr<chi2inv(0.95,l_new-1);
        %Keep values in workspace
        resultsAMSAA(w,1)=beta;
        resultsAMSAA(w,2)=rho;
        resultsAMSAA(w,3)=chisqr;
        resultsAMSAA(w,4)=1;
    end
    if chisqr>chi2inv(0.95,l_new-1); resultsAMSAA(w,4)=-1; end
end
```

```

%Plots
if(resultsAMSAA(w,4)==1)
    if plot_type==1
        %Calculate cumulative number of failures
        for r=2:1;
            failures(r,1)=failures(r,1)+failures(r-1,1);
        end
        plot(TTT_init,
failures, 'rs', 'MarkerEdgeColor', 'k', 'MarkerFaceColor', 'g', 'MarkerSize', 8)
        grid on
        hold on
        plot(TTT_init, rho*TTT_init.^beta, 'r', 'LineWidth', 2)
        ylabel('Cumulative number of failures [Failures]');
        if max(failures)<1; ylim([0 1]);end;
        legend('LWK Data', ['MLE
\beta=', num2str(resultsAMSAA(w,1),3)], 'Location', 'NorthWest')
    end
    if plot_type==2
        %Calculate failure rates
        figure(w)
        grid on
        hold on
        ylabel('Failure Rate [Failures/WT/year]');
        X=failures./NumberOfWTs;
        clear interval
        interval=[0 TTT_init(1,1)];
        y=[X(1,1) X(1,1)];
        plot(interval,y, 'g', 'LineWidth', 2)
        interval=0:TTT_init(length(TTT_init),1);
        plot(interval, beta.*rho.*(interval.^(beta-1)), 'r', 'LineWidth', 2)
        legend('LWK Data', ['MLE
\beta=', num2str(resultsAMSAA(w,1),3)], 'Location', 'NorthWest')
        for s=2:length(TTT_init);
            interval=[TTT_init(s-1,1) TTT_init(s,1)];
            y=[X(s,1) X(s,1)];
            plot(interval,y, 'g', 'LineWidth', 2)
            hold on
        end
        if max(X)<1; ylim([0 1]);end;
    end
    hold on
    plot([TTT_init(1,1) TTT_init(1,1)], [0 max(ylim)], 'b', 'LineWidth', 1)
    text( TTT_init(1,1), max(ylim)/2, [num2str(max(YEAROFOPERATION)), ' years
of operation', '\rightarrow'], 'HorizontalAlignment', 'Right', 'Color', [0 0
1]);
    xlabel('Time To Test [Years*Wind Turbines]');
    title(['Micon M1500 - LWK ', u(w,1)]);
    hold off
    filename=char(u(w,1));
    if plot_type==1; filename =sprintf('Micon-cum%s',filename); end
    if plot_type==2; filename =sprintf('Micon-%s',filename); end
    saveas(gcf, filename, plot_format)
    close
end

end

%Results to EXCEL file
xlswrite('Micon-LWK-AMSAA', u, 1, 'A2');
xlswrite('Micon-LWK-AMSAA', {'Micon M1500-LWK'}, 1, 'A1');
xlswrite('Micon-LWK-AMSAA', {'beta'}, 1, 'B1');

```

```

xlswrite('Micon-LWK-AMSAA', {'rho'}, 1, 'C1');
xlswrite('Micon-LWK-AMSAA', {'xsqr'}, 1, 'D1');
xlswrite('Micon-LWK-AMSAA', {'Hypothesis'}, 1, 'E1');
xlswrite('Micon-LWK-AMSAA', {'Average annual failure rate'}, 1, 'F1');
xlswrite('Micon-LWK-AMSAA', {'1: Null hypothesis accepted'}, 1, 'I10');
xlswrite('Micon-LWK-AMSAA', {'-1: Null hypothesis rejected'}, 1, 'I11');
xlswrite('Micon-LWK-AMSAA', {'0: Not enough data'}, 1, 'I12');
xlswrite('Micon-LWK-AMSAA', resultsAMSAA, 1, 'B2');

```

Subroutine for estimating MLE parameters of PLP

```

function y = findzero(n, T, beta0)
options = optimset('Display', 'off'); % Turn off Display
y = fzero(@fun, beta0, options);
function y = fun(beta)
m=length(T);
y=n(1,1)*(log(T(1,1))-log(T(m,1)));
for k=2:m
    y=y+n(k,1)*(((T(k,1)^beta)*log((T(k,1)))-(T(k-1,1)^beta)*log((T(k-
1,1)))))/((T(k,1)^beta)-(T(k-1,1)^beta))-log(T(m,1)));
end
end
end

```

Appendix E. Results from AMSAA model applied to LWKSH/WMEP

Table 21. MLE shape parameter values

Wind Turbine Type	Subassembly Category	LWK-SH	WMEP	WMEP (Coastline)
Enercon E-40	Anemometry	0.964		
	Blade	0.608		
	Mechanical Brake		1.261	
	Electric	0.916		
	Electronics	0.961		
	Generator	0.930	0.746	0.847
	Pitch Mechanism	1.018		
	Sensors	1.109	0.862	
	Shaft/Bearings	1.293		
	Yaw System	0.711		0.914
Micon M1500	Aerodynamic Brake	0.565	0.278	
	Mechanical Brake	0.884	1.131	
	Electric	0.842	0.758	
	Gearbox	1.122	1.000	
	Shaft/Bearings	1.042		
	Yaw System	0.832		
	Hydraulics		0.274	
	Sensors		0.476	
	Inverter_Electronics		0.609	
Tacke TW600	Anemometry	0.976	0.813	0.888
	Blade	0.737		
	Mechanical Brake	1.151	0.925	
	Electric	0.980	0.767	
	Inverter_Electronics	0.873	0.641	
	Gearbox	1.563		
	Hydraulics	0.700		
	Other	1.000		
	Sensors	0.733		
	Aerodynamic Brake		0.640	0.568
	Shaft_Bearings		0.816	
Vestas V39/V4x	Anemometry	1.019	0.743	0.884
	Electric	0.880	1.104	1.016
	Hydraulics	0.793		0.814
	Pitch Mechanism	1.531	0.994	1.080
	Sensors	0.678	0.958	1.059
	Blade		0.582	
	Mechanical Brake		0.693	
	Yaw System		1.461	1.083
	Other		0.831	0.586
	TOTAL			0.817

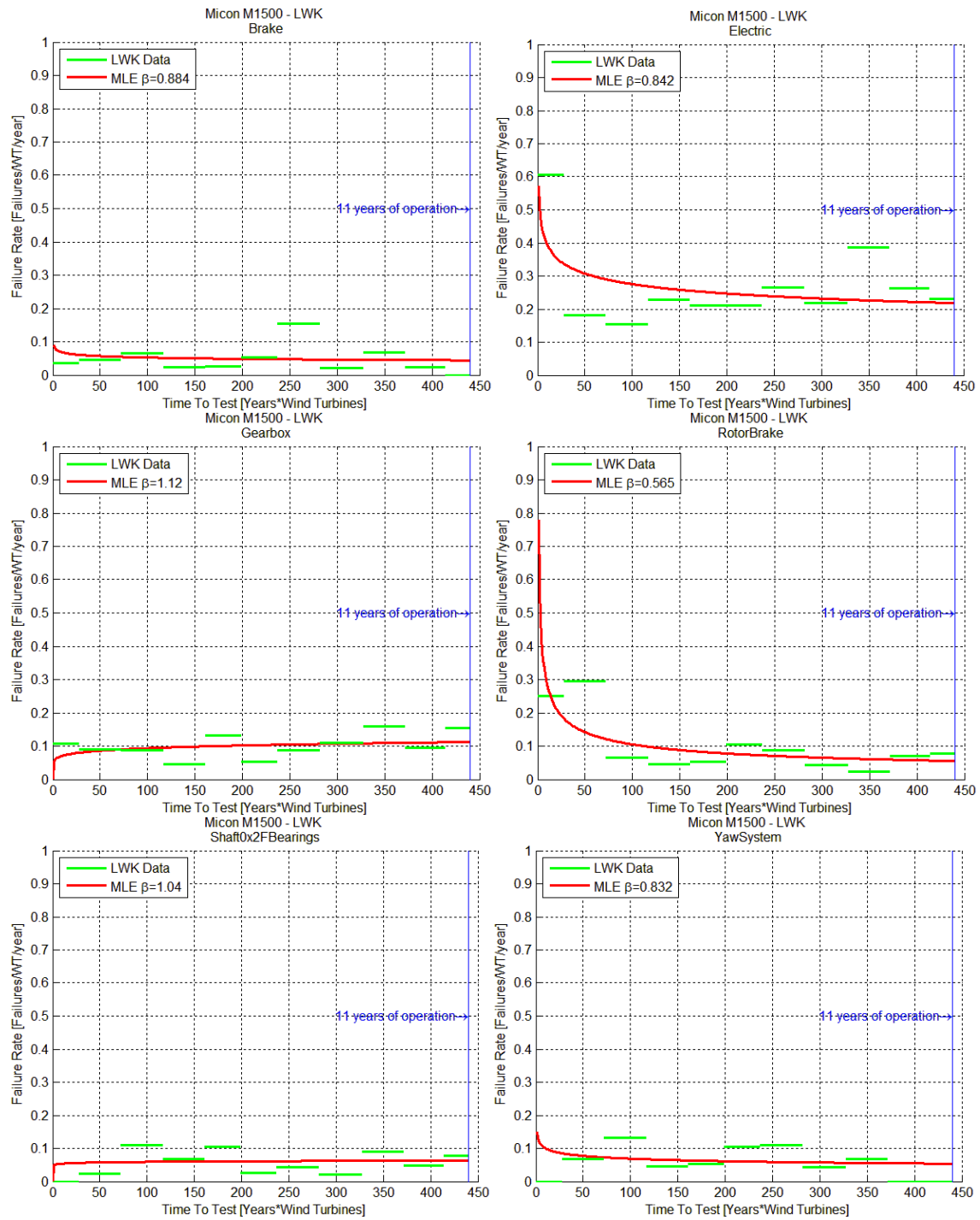


Figure 35. Examples of graphical results from Matlab code

Appendix F. Additional information for Scira offshore wind farm

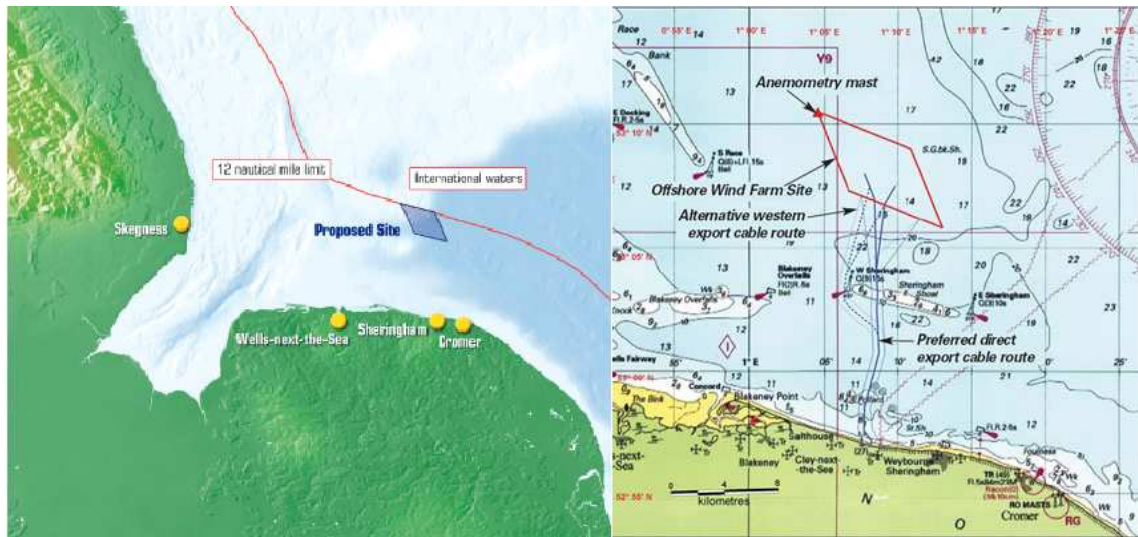


Figure 36. Scira offshore wind farm location

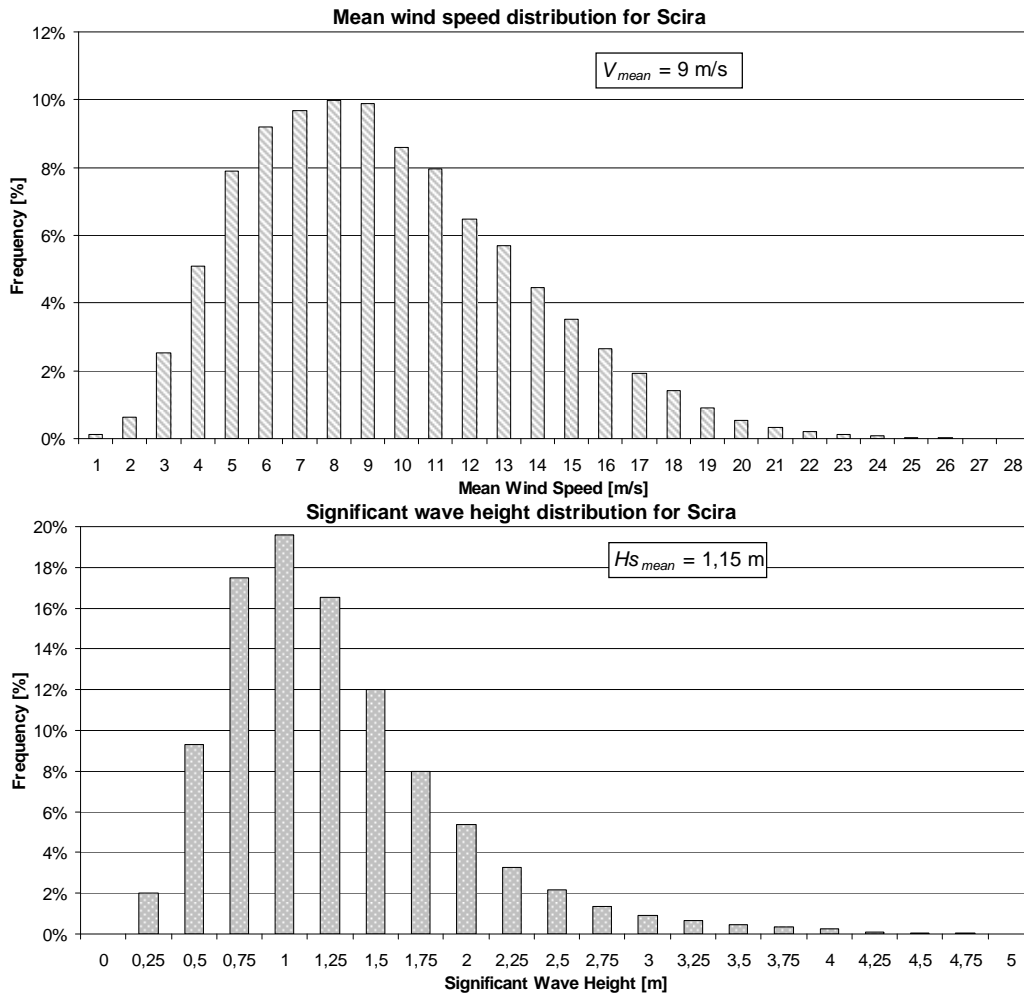


Figure 37. Wind speed and wave height distribution for Scira

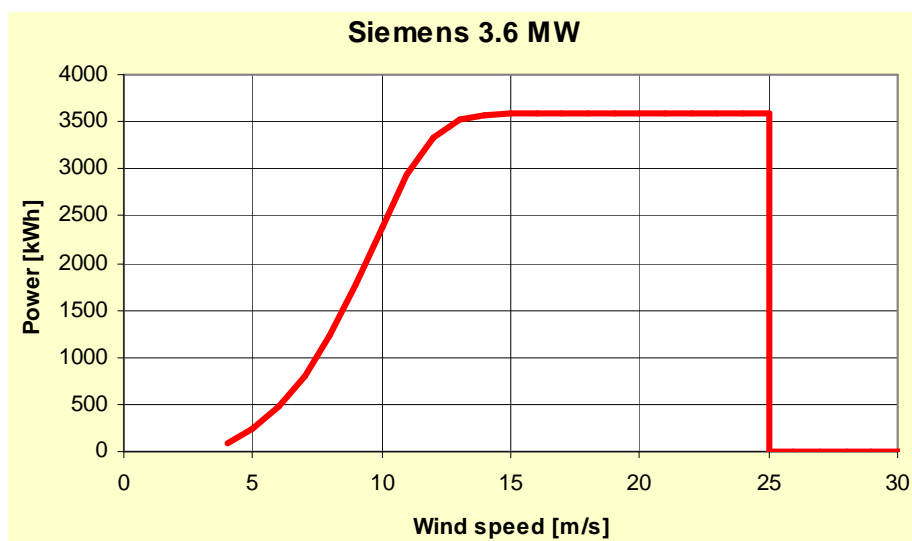


Figure 38. PV curve of Siemens 3.6

Table 22. Fault information for Siemens 3.6

Fault description	Failure Rate [failures/WT/year]	Repair Time	Material Costs [% of investment]	Logistic Time for spare parts [h]
small crew, Repair=4 hr, consumables	2,194	4	0,006%	0
small crew, Repair=4 hr, consumables	0,041	4	0,006%	0
small crew, Repair=4 hr, low costs	0,605	4	0,060%	24
small crew, Repair=8 hr, low costs	0,186	8	0,060%	24
small crew, Repair=8 hr, medium costs	0,666	8	0,600%	48
small crew, Repair=16 hr, medium costs	0,189	16	0,600%	48
small crew, Repair=8 hr, medium costs	0,154	8	0,600%	48
large crew, Repair=16 hr, high costs	0,099	16	6,000%	96
large crew, Repair=24 hr, high costs	0,122	24	6,000%	96
small crew, Repair=8 hr, medium costs	0,101	8	0,600%	48
large crew, Repair=24 hr, high costs	0,054	24	6,000%	96
large crew, Repair=24 hr, medium costs	0,050	24	0,600%	120
large crew, Repair=24 hr, high costs	0,041	24	6,000%	168
TOTAL	4,500			



Figure 39. Simple access system (WindCat)



Figure 40. Jack-up barge for heavy subcomponents' repairs

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