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“Integrated Wind Turbine Design”

Component reliability ranking with respect to WT concept and external environmental conditions

Deliverable WP7.3.3, WP7 Condition monitoring

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1. Introduction

Modern wind turbines achieve a quite high availability of about 95% to 99% [1]. Nevertheless, quite a number of faults cause unscheduled down times up to ten per year, resulting in high maintenance efforts, production losses and costs.
Overall objective of this report is to support the integration of new approaches for condition monitoring, fault prediction and operation & maintenance (O&M) strategies into the next generation of wind turbines for offshore wind farms. The knowledge of frequent failures or typical failures related to certain wind turbine topologies is an important basis for improvement of WT reliability and development of appropriate condition monitoring.

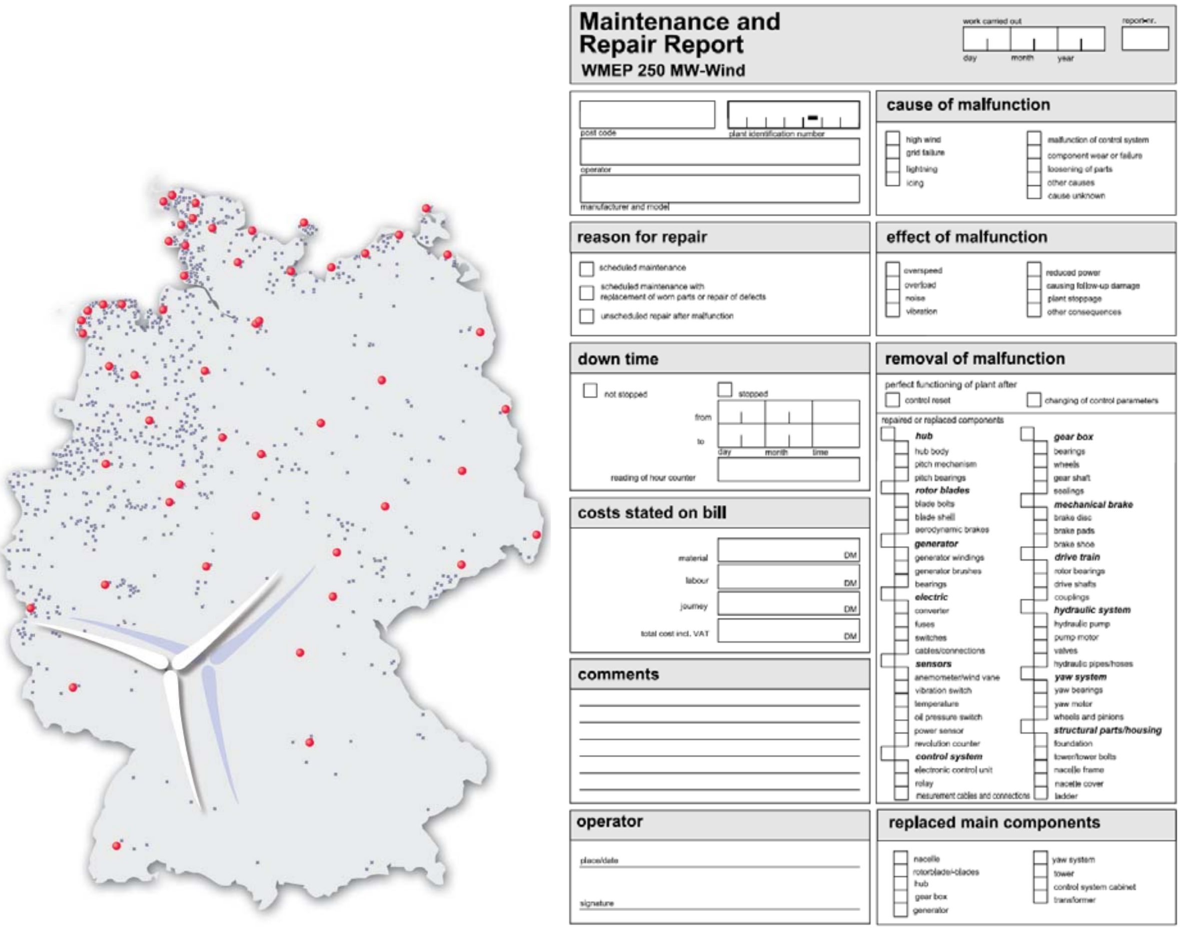
The report *Component reliability ranking with respect to WT concept and external environmental conditions* shall provide information about the reliability characteristics and by that about the strengths and the weak-points of different turbine concepts with respect to failure causes. The most frequent failures as well as the most severe failures, meaning those failures which have a great impact on annual downtime, will be shown. Hereby the turbines that are comparable with today's state of the art turbines are investigated in more detail. Furthermore, the failures have been separated according to their failure cause and a division in spontaneous failures as well as failures which may be detected in advance has been made.

2. Background

In the first instance the WMEP-Database, here the main source of information and the theoretical background for the later investigations will be described briefly.

2.1 Source of information

The Fraunhofer IWES (formerly the ISET) has been gathering operational experience from wind turbines since 1989 and is involved in different projects dealing with the topic of availability and reliability. IWES's database was established within a long-term German research programme. Owners or operators of wind turbines, receiving funding from government, were obliged to report on energy yields, on operational cost and on all maintenance measures. In the period of 17 years 64.000 maintenance & repair reports (shown in Figure 1) from over 1500 wind turbines were fed into a database at ISET. This database, which has been described in more detail in Deliverable 7.3.1 [2], is called WMEP database.



Maintenance and Repair Report
WMEP 250 MW-Wind

work carried out: day / month / year
report-nr.

post code
plant identification number
operator
manufacturer and model

reason for repair

☐ scheduled maintenance
☐ scheduled maintenance with replacement of worn parts or repair of defects
☐ unscheduled repair after malfunction

down time

☐ not stopped
☐ stopped
from: day / month / time
to: day / month / time
reading of hour counter

costs stated on bill

material: DM
labour: DM
journey: DM
total cost incl. VAT: DM

comments

operator

place/date
signature

cause of malfunction

☐ high wind
☐ grid failure
☐ lightning
☐ icing
☐ malfunction of control system
☐ component wear or failure
☐ loosening of parts
☐ other causes
☐ cause unknown

effect of malfunction

☐ overspeed
☐ overload
☐ noise
☐ vibration
☐ reduced power
☐ causing follow-up damage
☐ plant stoppage
☐ other consequences

removal of malfunction

perfect functioning of plant after
☐ control reset
☐ changing of control parameters

repaired or replaced components

- ☐ ***hub***
  - ☐ hub body
  - ☐ pitch mechanism
  - ☐ pitch bearings
- ☐ ***rotor blades***
  - ☐ blade bolts
  - ☐ blade shell
  - ☐ aerodynamic brakes
- ☐ ***generator***
  - ☐ generator windings
  - ☐ generator brushes
  - ☐ bearings
- ☐ ***electric***
  - ☐ converter
  - ☐ fuses
  - ☐ switches
  - ☐ cables/connections
- ☐ ***sensors***
  - ☐ anemometer/wind vane
  - ☐ vibration switch
  - ☐ temperature
  - ☐ oil pressure switch
  - ☐ power sensor
  - ☐ revolution counter
- ☐ ***control system***
  - ☐ electronic control unit
  - ☐ relay
  - ☐ mesurement cables and connections
- ☐ ***gear box***
  - ☐ bearings
  - ☐ wheels
  - ☐ gear shaft
  - ☐ sealings
- ☐ ***mechanical brake***
  - ☐ brake disc
  - ☐ brake pads
  - ☐ brake shoe
- ☐ ***drive train***
  - ☐ rotor bearings
  - ☐ drive shafts
  - ☐ couplings
- ☐ ***hydraulic system***
  - ☐ hydraulic pump
  - ☐ pump motor
  - ☐ valves
  - ☐ hydraulic pipes/hoses
- ☐ ***yaw system***
  - ☐ yaw bearings
  - ☐ yaw motor
  - ☐ wheels and pinions
- ☐ ***structural parts/housing***
  - ☐ foundation
  - ☐ tower/tower bolts
  - ☐ nacelle frame
  - ☐ nacelle cover
  - ☐ ladder

replaced main components

☐ nacelle
☐ rotorblade/-blades
☐ hub
☐ gear box
☐ generator
☐ yaw system
☐ tower
☐ control system cabinet
☐ transformer

Figure 1: Wind turbines and met masts in the WMEP (left) & maintenance-report (right)

The WMEP database contains a quantity of detailed information about reliability and availability of wind turbines (WT) and subassemblies and provides the most comprehensive study of the long-term behaviour of WTs worldwide and the most reliable characteristic values concerning reliability. At the moment it seems to be the only database, capable to evaluate operational experience in order to find failure rates, MTBF and downtimes with an appropriate number of WTs as a sample.

2.2 Maintenance strategies

The aim of maintenance work is to achieve high availability of wind turbines while at the same time keeping costs as low as possible. Unplanned outages should be avoided.

The maintenance organisation can basically be distinguished in reactive and preventive strategies. Some basic strategies are illustrated in Figure 2 to describe their different approaches. The curves show the dependency of the remaining component life time related to the operational time of the component in an idealised way. The operational time is related to the mean time between failures (MTBF).

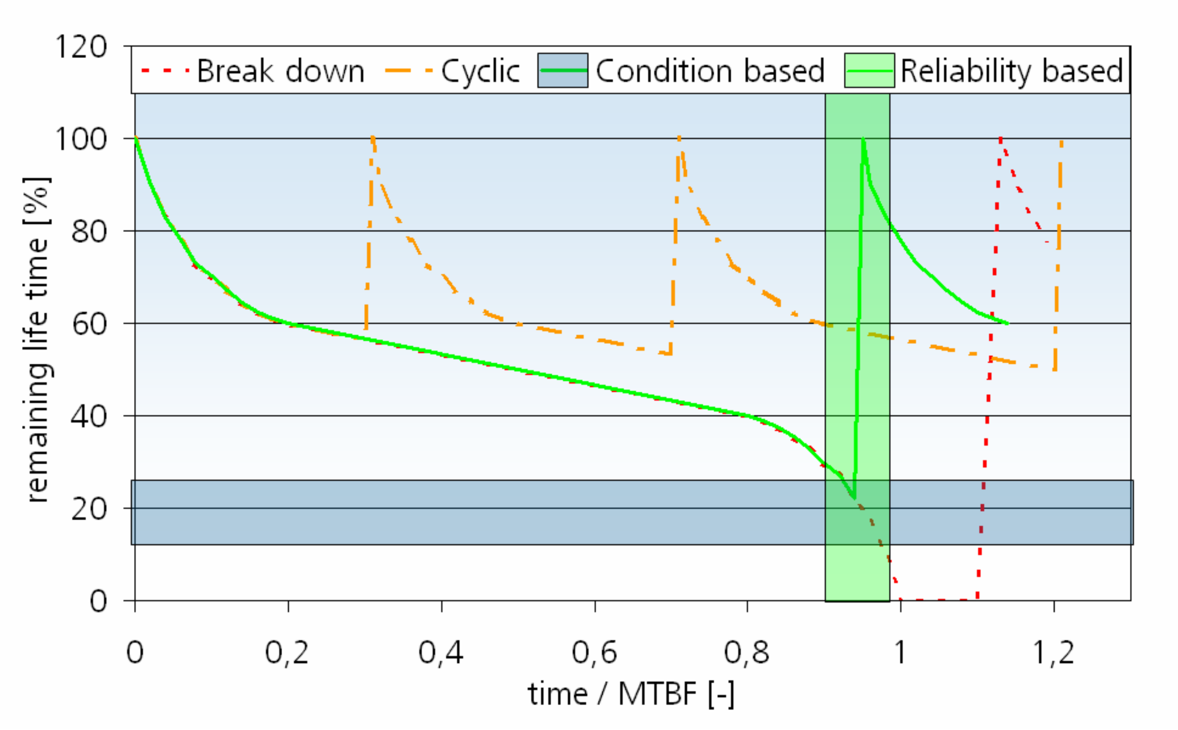


Figure 2: Maintenance strategies

The simplest strategy (reactive) is the break down maintenance strategy, which is shown by the red dashed line. This method differs strongly from the other (preventive) strategies, because the system will be operated until a major failure of a component will result in a shut down [3].

In contrary to the reactive maintenance also preventive strategies are applicable. With the cyclic maintenance strategy, which is shown by the orange dashed line, components will get maintained after fixed periods of time, e. g. on semi annual intervals, independent from their actual condition.

More sophisticated preventive strategies are the condition based and the reliability based maintenance. Both aim at finding the optimum point in time for carrying out the required maintenance actions.

The reliability based maintenance tries to find the right time for maintenance measures through analysing a broad database filled with experience from the past regarding reliability functions [4, 5]. It is shown in Figure 2 by the green shaded area that the reliability based maintenance strategy tries to identify the MTBF and by that the probability for failure occurrence.

The condition based maintenance tries to find that point by monitoring the real current status of the components. This is illustrated by the blue shaded area, which shows the attempt to find that point of wear out where the remaining life time of the component is dropping below a significant tolerance criterion. The main task of this strategy is to find out the propagation of degradation over the time of operation, i. e. the most important stressing parameters and their influence on the life time curve.

3. Methodology

Numerous parameters are important to describe the availability of WTs and should therefore be considered in an appropriate reliability analysis. Therefore, in the first step a selection of turbines has to be made. The influencing parameters and the selection made in these investigations are described in chapter 3.1.

In the second step the reliability characteristics are calculated for each single turbine (explained in chapter 3.2) and average values are determined (chapter 3.3).

Based on these results an overview of components with the highest mean annual downtimes can be presented (chapter 4.1). The most frequent failures are investigated in more detail in chapter 4.2. To determine failures, which are likely to be detected in advance through a condition monitoring system, a selection of gaugeable failure causes is made in the next step. The assumptions made are described in chapter 3.4.

An overview about the methodology for the investigations is shown in Figure 3.

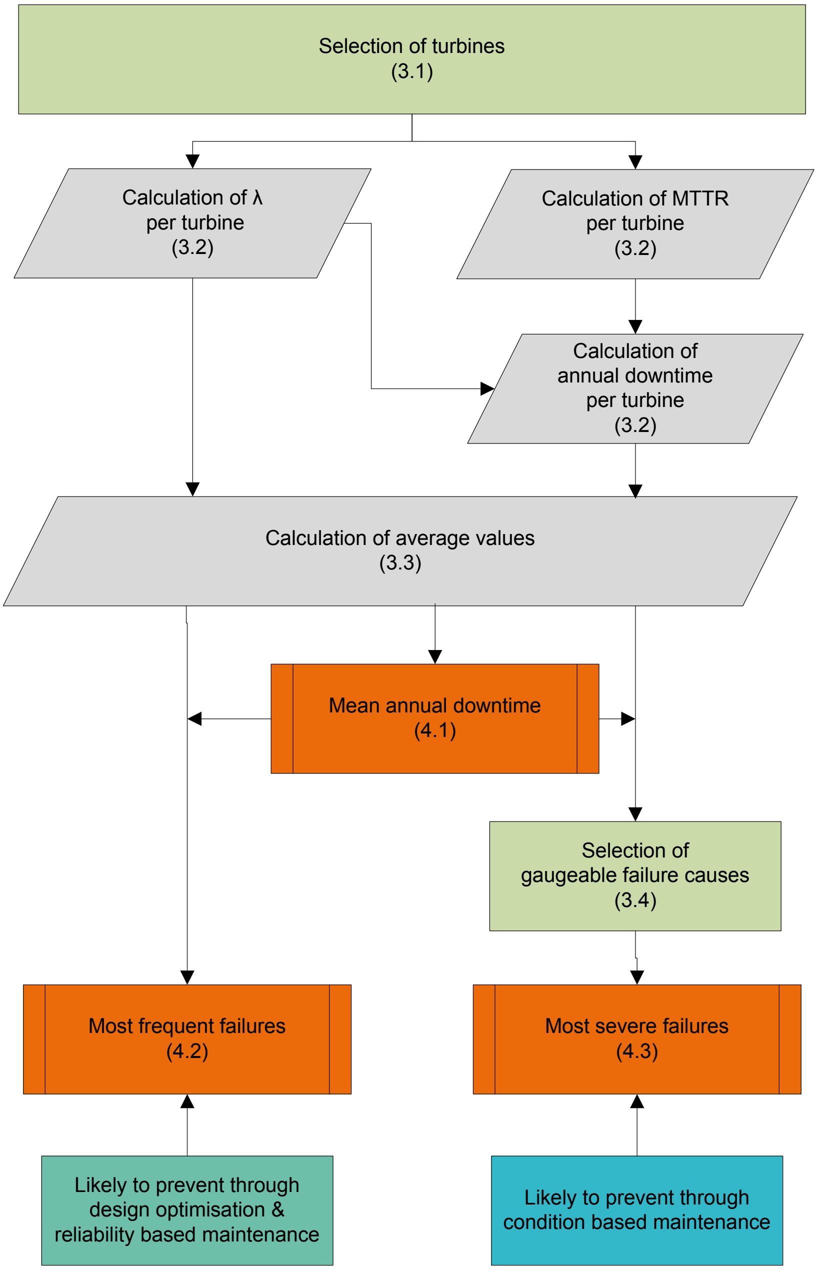


Figure 3: Methodology of investigations

3.1 Selection of turbines

The reliability of WTs is of course strongly dependent on the WT in use. An example can be found in the size of WTs. Besides the size, the technical concept of the WT is a very important influencing parameter regarding reliability. The investigations to this report classify different WTs from the WMEP database in groups of WT concepts as described in the following.

Wind energy technology has progressed enormously from the beginning of modern wind energy application in the middle of the 1980s until today. The trend towards larger and more powerful turbines characterizes the previous development. This continuous expansion of wind energy use has enabled manufacturers to make enormous technical progress. But while the performance and efficiency of WTs and hence the energy yields have been continuously improved, there is still a significant need for optimising the reliability of WTs. In the following the evolution of technology will be illustrated by three different technical concepts. To allow a comparative analysis, the different WTs are classified in three groups of concepts. An overview of the characteristic features of the concepts is given in the table below.

Table 1: Features of the technical concepts

	I	II	III
	Simple Danish concept	Advanced Danish concept	Variable-speed concept
Exemplary turbine groups	AN Bonus 100/150 Vestas V 17/20	Vestas V 25/27/29 Ventis 20-100	Vestas V 63/66 Enercon E 66
Control	Stall	Pitch	
Speed characteristic	constant		variable

Figure 4 shows the distribution of the WMEP WTs compared to the distribution of the whole German wind turbine population in respect of technical concept, and basically emphasises the representativeness of the WMEP WTs.

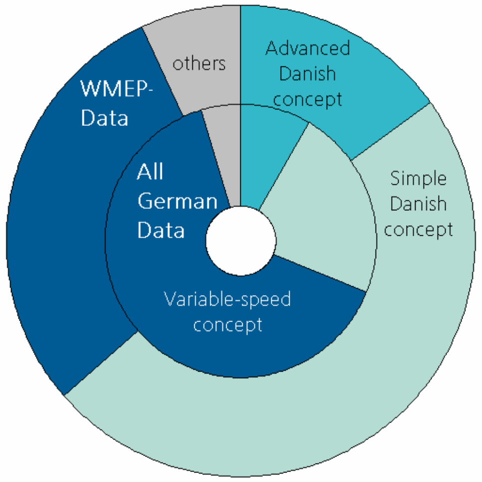


Figure 4: Proportions of different concepts

The chosen groups of wind turbine concepts are somehow reflecting the evolution of wind turbine technology through time. Even if most of the turbines in use can be described by these concept groups, still some turbines don't fit in one of the classifications, e.g. Enercon E 16/17/18 with stall control and variable speed. Although these turbines have been included in the analysis shown in previous publications, they should not be investigated here.

Besides technical concepts there are more parameters, which should be considered in an appropriate reliability analysis as carried out in [6].
An important variable can be described by the time dependency. The principal development of failure rates with time of operation is well known in other technical areas. Another time dependent influence comes from the maturity of the turbine model. It is of importance whether a turbine model has been build since several years or a new concept has been developed.
The influence of operational conditions is also indeed important to indicate the reliability characteristics of WTs. The wind speed is an example for those parameters, which were already analysed in general by [7] and a physical check on the similarities between failure rate and wind energy index was performed in [8]. The influences of the parameters mentioned will be described in chapter 4.

3.2 Calculation of Reliability characteristics per turbine

Some general definitions of the variables taken into account for reliability assessment are described in the following.

Annual Failure rate (λ)
The failure rate λ is the reciprocal of the MTBF (Mean time between failures). It is calculated for each turbine, for every subassembly and every failure cause using equation (1).

$$\lambda = \frac{\sum n}{T} \qquad (1)$$

For explaining what exactly has been calculated, a closer look at both variables, number of failures n and time of operation T, will be taken.

Number of failures
The number of failures varies with subassemblies and failure causes.

$$n = n(failure\,cause;\ Subassembly)$$

Sometimes damages affect several components at the same time, allowing several repairs within one measure. This leads to the fact that the overall number of failures per turbine $n_{Turbine}$ is always smaller than the sum of failures counted per all single subassemblies $n_{Subassemblies}$.

$$\sum n_{Turbine} \leq \sum n_{Subassemblies} \qquad (2)$$

To determine the effect of different subassemblies on the reliability, failures, which have led to a turbine shut down, should get distinguished from failures, which occur only as concomitants. Unfortunately, in case of multiple repairs within one maintenance measure, the WMEP database does not contain the information, which failure had triggered the shut down. Therefore, a worst case scenario has been chosen, and it has been assumed that every failure, which occurred, could have been a reason for the resulting downtime.

Time of operation
The time of operation T also needs some more definitions. There are at least two possible definitions for the time as a basis for further calculations. The simplest method would be to use the 'Nominal time', which is the total consecutive reporting period. Another possibility would be to take the part of time, in which the turbine really was in operation. The difference between these time spans is the 'non-available time'. The 'non-available time' is made up of

a scheduled part (maintenance jobs) and an unscheduled part (breakdowns and damage). Depending on which subassembly is investigated, the time, in which the turbine stands still and is waiting for wind could also be taken into account. The time of operation Ton for these components can be calculated using equation (3).

$$T_{on} = T - \left(T_{Downtime} - T_{Service} - T_{Waiting\ for\ Wind}\right) \qquad (3)$$

By determining the time of operation downtimes, service times and the time of waiting for wind are actually required. Unfortunately, the time the WT is waiting for wind is unknown. Besides, some failures also occur because of deteriorations due to a variety of stresses, which are not necessarily dependent on real operation of the turbine (e.g. component thermal ageing). Due to these difficulties the actual calendar time ('Nominal time') has been chosen for the calculations in here.

Mean time to repair (MTTR)

The Mean time to repair is the average time that a subassembly will take to recover from any failure.

$$MTTR = \frac{T_{Downtime}}{\sum n} \qquad (4)$$

The reciprocal of MTTR is the repair rate, μ.

The variables used for the calculation have already been described in the section before.

Annual downtime (ADT)

The annual downtime refers to periods when the wind turbine is unavailable. It can be calculated as the product of the reliability characteristics described above as shown in equation (5).

$$ADT = \lambda \cdot MTTR \qquad (5)$$

3.3 Calculation of average values

In preliminary evaluations the reliability characteristics have mostly been calculated as average values, and all turbines have been weighted equally. This methodology is expedient when looking at the whole population of WTs. However, the results are dominated by the most common turbines in the database [9]. Thus, for achieving a comparative analysis this methodology may be misleading. The results may differ strongly by either taking the average value of the whole population or firstly determine the mean failure rates for the individual types of turbines and calculate the average of the population out of these individual values per type afterwards.

$$\lambda_{Average\ Database} \neq \lambda_{Average\ Turbine\ Types} \qquad (6)$$

Thus, all wind turbine types were characterized and grouped by a set of parameters. To calculate the reliability characteristics, the appropriate values were determined for each wind turbine type individually and afterwards aggregated to the typical value of the group of turbines considered. This is illustrated in Figure 5.

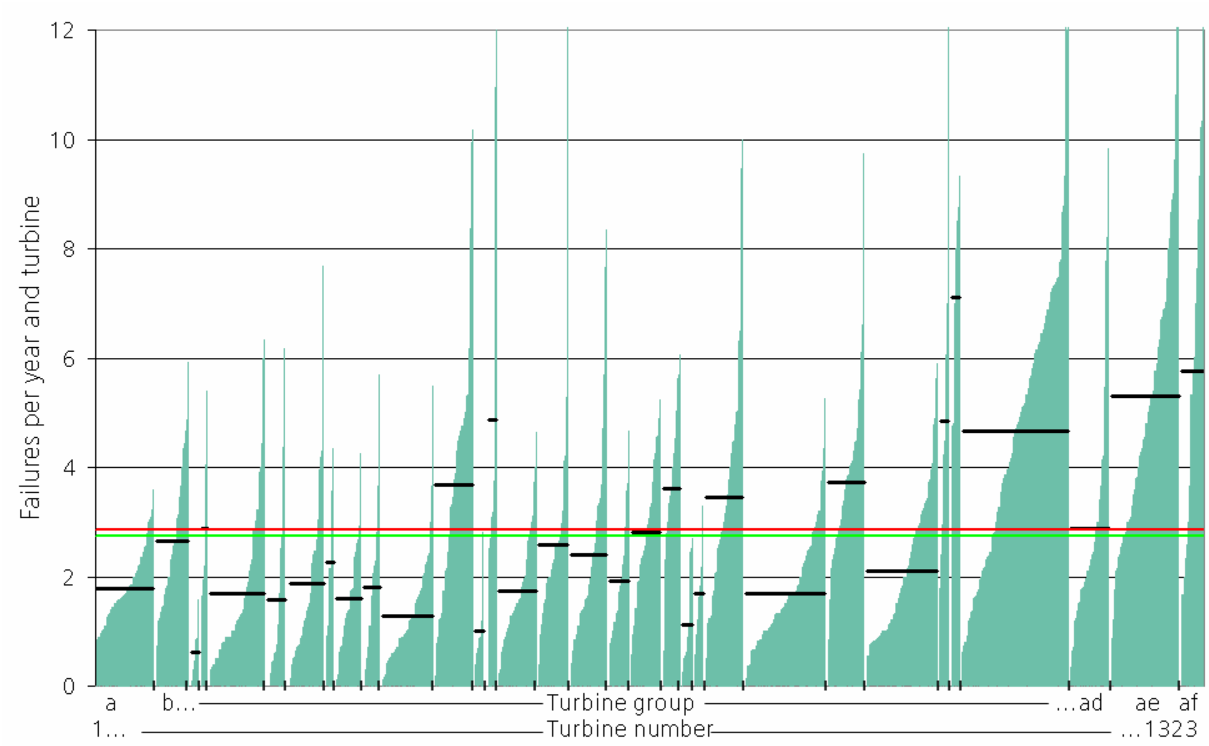


Figure 5: Comparison of mean annual failure rates

The figure shows the annual failure rate for each single turbine in the WMEP-database as a single vertical bar (because of the large number they do appear as continuous areas for each turbine group rather than as single bars). All individual turbines of the same type are aggregated to turbine groups (e.g. Vestas V 25/27/29 is one group, Vestas V 63/66 another). Additionally, they are sorted according to their turbine reliability, the turbine with the lowest failure rate on the left of the group, the one with the highest failure rate on the right. The average values for the different turbine groups are illustrated as black horizontal lines.
The difference stated in equation (6) is presented as two red and green horizontal lines. The average value for the whole population of turbines in the WMEP (average for all vertical bars) is shown by the red line and slightly higher than the average value for the turbine groups (average of the black horizontal lines), illustrated by the green line.
In the following the consolidating method (average of groups) has been chosen. For assuring a statistical relevancy, only turbine types, which the database contains at least ten specimen of, are included in the investigation.

3.4 Selection of failure causes

Besides knowing which subassembly is affected, the WMEP also gives the possibility for a Root Cause Analysis since the failure causes are stated in the incident reports. Figure 6 gives an overview of all failure causes for each individual turbine.

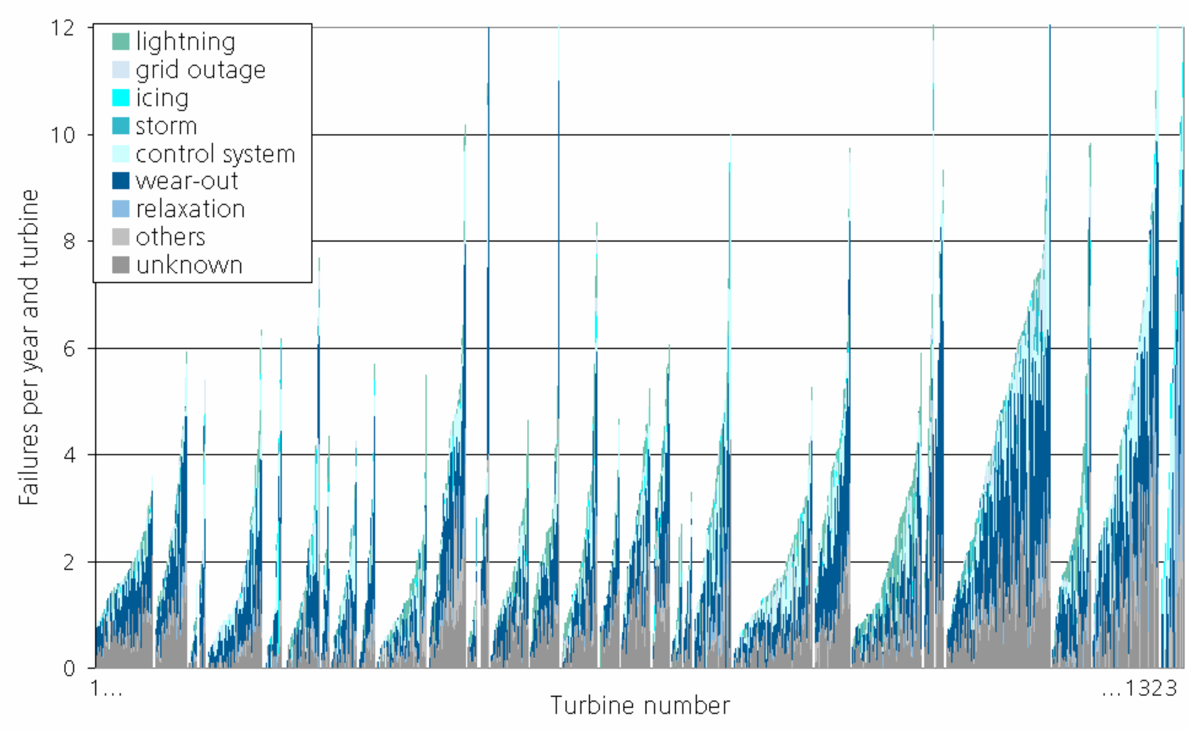


Figure 6: Failure causes for single turbines

The failure causes are more or less miscellaneous, but in most cases of turbine shut down wear out has been the failure cause. In less than a quarter of all cases the faults were caused by external influences. Further more, storms, lightning, ice accretion or grid outages mostly affect electrical subassemblies rather than mechanical ones and cause predominantly spontaneously occurring failures.

Figure 7 depicts the results for electrical subassemblies (left side) compared to some “large” components, such as drive train or gear shaft (right side).

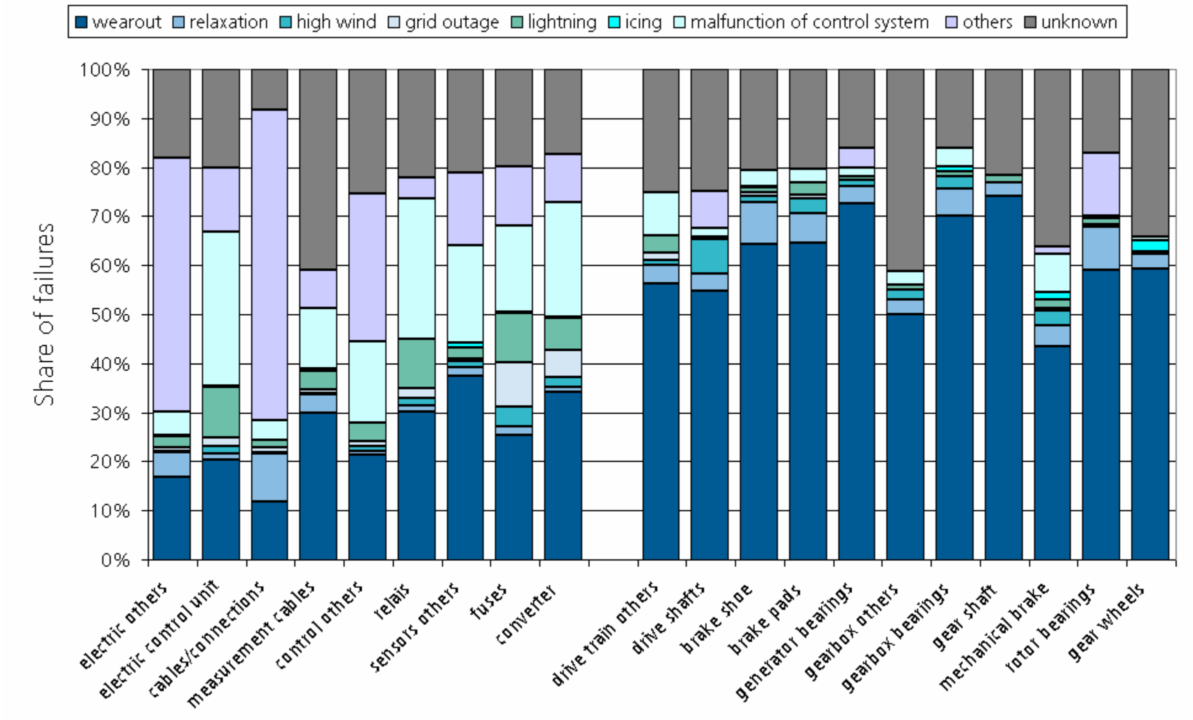


Figure 7: Failure causes for different components

It can be seen that the failures of large mechanical components are more likely due to wear out while the failures of the electrical subassemblies show numerous failure modes. Even though, deterioration for the electrical subassemblies may be important too.
Nevertheless, in most instances the external causes and the following failures are difficult to predict and are more likely to prevent by design optimisation or safety measures. However, for doing so deep knowledge about different failure modes is needed.

For further analyses, failure causes are divided in three groups, according to frequency and severity of initiated failures. There appear lots of minor failures, which can get repaired within few ours and there occur more seldom, but severe failures, which cause downtimes of several days. However, the frequent failures can often not be detected in advance and are more likely to prevent through design optimisation. The majority of sever failures are dominated by unexpected wear out and are therefore more or less predictable by sophisticated condition monitoring systems. Failure causes are often stated as unknown or others due to insufficient documentation, which makes an appropriated prevention more difficult.

Table 2: Failure causes and the possibilities for preventing

Failure cause	Likely to prevent through
Lightning	Design optimisation
Grid outage	
Malfunction of control system	
Icing	
Storm	
Wearout	Condition based maintenance
Relaxation	
Others	Unknown
Unknown	

4. Component reliability ranking

Examples for reliability characteristics are variables like MTBF (Mean time between failures) or MTTR (Mean time to repair), which are useful for answering the questions "How often does a system fail?" and "Which downtimes are associated with a failure?". Furthermore the mean annual downtime is of great interest because of its importance for the choice of a maintenance strategy.

Since there is a substantial variation in downtimes after failures, looking only at one of these variables is not enough to describe reliability appropriately. On the one hand there are failures, which occur frequently, but can be repaired quickly and on the other hand there are some failures, which occur rarely, but cause long downtimes.

A division of failures according to the resulting downtime per failure is shown in Figure 8. The red line shows for logarithmic scaled groups of downtimes the corresponding share of failures while the blue line shows the share of the total annual downtime for each group of downtimes.

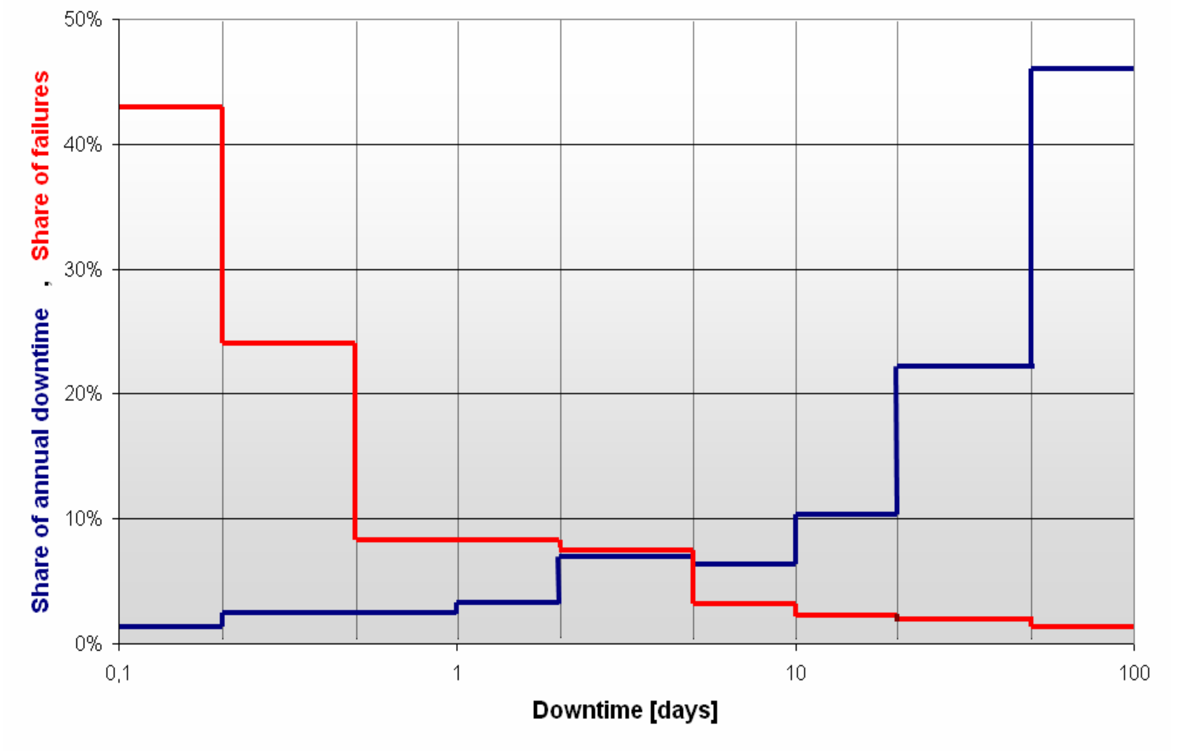


Figure 8: Share of failures and annual downtime according to the downtime per failure

As one can see, the influence of the large number of short shut downs on the annual downtime is rather small. When dividing failures according to their duration in shorter or longer than one day the less severe failures, representing about 75% of all failures, are responsible for only 5% of the total downtime, whereas the remaining 25% of failures are responsible for 95% of the downtime [10].

Nevertheless, these 25% of failures are spread over all subassemblies. For a sophisticated condition based maintenance strategy the components with the greatest share of annual downtime are the ones which the development of condition monitoring systems (CMS) needs to concentrate on.

However, the less severe failures cause relatively little downtime, but they require considerable attention in the maintenance strategy by causing a significant effort for repair. When WTs are installed offshore it is likely that these failures may assume more significance because they cannot be resolved quickly as access to turbines is more difficult. The small failures and their consequences are more likely to be avoided by improving the reliability of the affected subassemblies through design improvements and reliability based maintenance.

For further investigations concerning these two possibilities, two weak point analyses are presented in this paper. The first one is about the most frequent failures meaning those failures, which are likely to prevent through design optimisation and reliability based maintenance. The second one shows the most sever failures on which the development of condition monitoring systems (CMS) needs to concentrate on.
However, before doing so a selection of turbines like explained in chapter 3.1 is made.

4.1 Reliability in respect to wind turbine concept

It is clear that all parameters described in chapter 3.1 (age, size and location of turbine) are important for the reliability of turbines. However, because of the parameter diversity the statistical basis is getting insufficient at a certain level of detail by breaking down the total of turbines in different groups of identical parameters. Therefore, in the investigations to this report only the technical concept has been taken into account. No differentiation concerning age, size and location of turbine has been made. Nevertheless, some former results, which have to be kept in mind when looking at the reliability characteristics, should be shortly repeated here:

- The failure rate rises with an increasing turbine size but the downtimes per failure decline for larger turbines. The annual downtime is therefore about the same.
- Turbines from the first year of serial production show the highest failure rates in the first operating year. With increasing experience both, in production and in operation, the failure rate decreases and reliability increases respectively.
- Especially WTs located near the coast and in the highlands suffer high failure rates.
- The failure rate increases with higher wind speeds. Failure rates of subassemblies of the electrical system show the strongest dependency from wind speed. The dependency of the failure rate on wind speed is generally also present, but significantly weaker for other main subassemblies.

An analysis of the advantages and disadvantages of the different technical concepts has been done in [11]. It has been shown that most of the wind turbine types show similar development and similar figures of failure rates, but some types show significant differences. In the first step it was pointed out that the failure rate of nearly all subassemblies except of the mechanical brake is increasing with the development to pitch regulated turbines. In a second step it has been shown that with the introduction of variable speed turbines more failures appear especially in the electric systems as a whole, e.g. cabling, sensors, control, converter and generator.
In most cases a trend in the direction of higher failure rates can be observed. These increasing trends occur for the electric system, the electronic control, the sensors, the yaw system, the rotor blades, the generator and the drive train. The only downward trends can be seen for the mechanical brake and for support & housing. For the other subassemblies (hydraulic system, rotor hub and gearbox) no obvious trend can be recognized.
However, in the development of the technical concepts a clear shift in the proportion of the different subassemblies affected by failures can be observed. While the frequent failures with short downtimes are getting even more frequent, the seldom failures resulting in long downtimes are getting even more seldom. On the one hand the share of the more frequent failures of the electric subassemblies, which are qualified with comparatively short downtimes, increases with the development of the technical concepts. The share of the rotor system, consisting of rotor blades, rotor hub and yaw system as well as the hydraulic system (mostly used for pitching) remains constant for all concepts. The same is true for support & housing. On the other hand the share of failures in the drive train system, consisting of the mechanical brake, the gearbox and the other drive train components, decreases. This is not necessarily related to an increased reliability but could rather be explained by the overall larger number of failures.

From Figure 4 it is clear that regarding the turbines from the WMEP the technical concept standard variable-speed is of special interest for further analyses. These turbines are somehow representing the concept of the state of the art turbines and should therefore be investigated in more detail.

Figure 9 concise the results for the standard variable-speed concept. It shows the share on the annual downtime dependant on the affected subassembly. Hereby the different components have been sorted according to the characteristic of the failure. The frequent failures with short downtimes can be seen on the left side of the graph and the seldom failures with large downtimes are on the right. In the area between there are many components, which neither are subject of frequent failures nor are these failures combined with large downtimes or high costs.

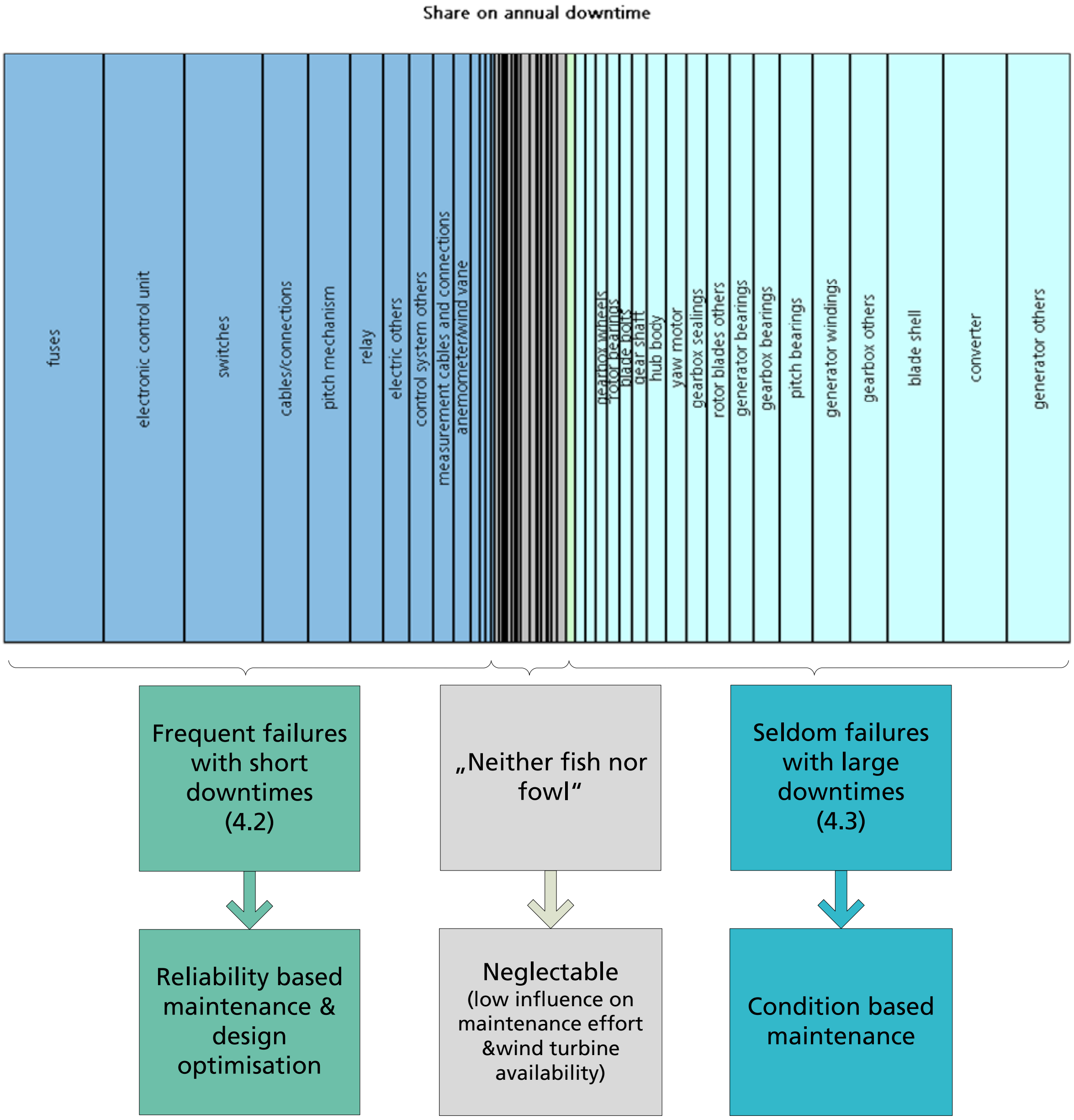


Figure 9: Share on annual downtime

Although this classification is just arbitrary and approximate the difference between the two kinds of failures is getting clear. The failures on the left side of the graph represent the frequent failures, which are investigated in chapter 4.2, the failures on the right side can be seen as more severe failures since they are combined with long downtimes and high costs. However, for examining the failures, which may be detected in advance through appropriate condition monitoring systems, more limitations regarding the failure cause should be made. These investigations are described in chapter 4.3.

4.2 Frequent failures

The previous chapter has classified the components according to the characteristic of their failures. Here, the frequent failures, which can be prevented by a reliability based approach, will be examined. The following Figure shows a pareto chart of the most frequent failures.

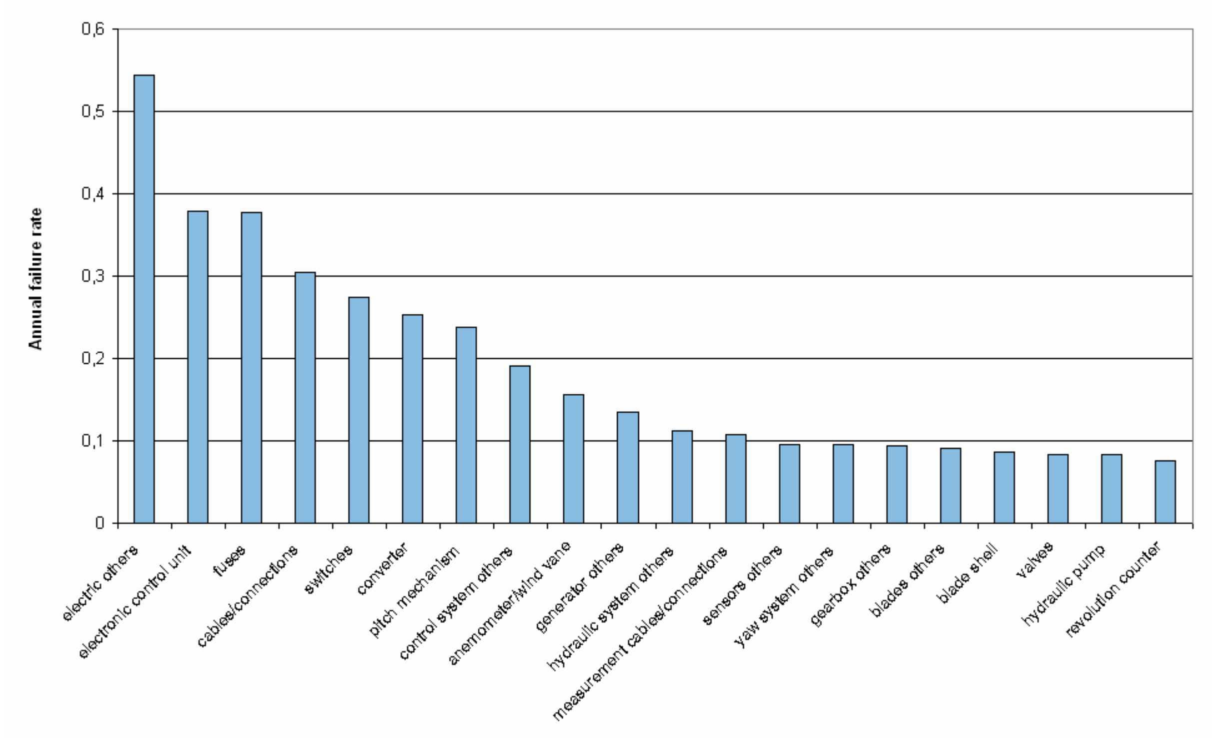


Figure 10: Most frequent failures

It can be seen that a large number of the frequent failures are affecting the electric and electronic components. However, faults of electrical subassemblies may occur at a variety of different parts, are located in different components and may suffer from different root causes, making a prediction of these faults difficult or even impossible. It also would require an extraordinary effort to equip all electrical components with a condition monitoring system. In addition, the propagation of faults will differ depending on the operational conditions of the single WT. Causes and developments of faults in the electrical system are not yet sufficiently known. So, a prediction of remaining life time of components with faults in early stages as well as a prediction of how the fault will progress in future under real operational conditions is still missing. These results lead to the fact, that the implementation of condition based maintenance is, at least for the electrical subassemblies, an ambitious challenge.

Evaluating empirical data could provide some valuable help. By statistical means, weak points could be identified, typical cases could get distinguished, and typical fault propagations could be found. All these results would help to diagnose faults more accurate and to predict remaining life time. Thus, reliability based maintenance should be taken into account for these components. Operational experience, documented in a way it can be evaluated by statistical and scientific means, can give valuable findings about weaknesses of the technology in use.

4.3 Severe failures

Unfortunately, the WMEP database does not contain sufficient information to assess fault severity by repair cost, but analysis of downtime durations may indicate fault severity. In order to distinguish more severe failures from those which are less severe, the WMEP failure data has been divided into the two types of failures (frequent with short downtimes & infrequent with long downtimes). Assuming that these failures with long downtimes cause not only long downtimes but also relatively high repair costs, condition monitoring development should concentrate especially on these failures.

However, for the use of condition monitoring also the failure causes need to be taken into account. As already mentioned, the failure causes are more or less miscellaneous, but in most cases of turbine shut down wear out has been the most frequent failure cause, which may be detected in advance. In other cases the faults are caused by external influences. The turbine control is another important failure cause, but in most cases the failure reason is unknown or stated as ‘others’. This indicates the difficulties of detecting the proper failure modes of wind turbine failures.

A comparatively large share of especially the electrical failures occurs due to failures in the control system. To specify the root cause malfunction of control system, the distribution of root causes was identified by examining the additional comments given in the WMEP incident reports. Almost a three-quarter of failures occurring due to malfunctions of the control system are caused by hardware problems of the control unit itself. Regarding these failures, mainly the board or the processor was affected. In the case of electronic components the deterioration might play an important role but is not apparent at first glance. Nevertheless, there are also other root causes for the malfunction of the control system. Failures due to software or communication problems as well as because of not adequately control parameters play a major role for this failure cause and therefore also for the electrical subassemblies.

Besides the control system also the external causes are important when looking at different failure causes. While grid outages are not dependent on season or location, the other external conditions show both; a clear seasonal and geographic dependency. However, external conditions as well as most of the malfunctions in the control system cause predominantly spontaneously occurring failures. Thus, in most instances the external causes and the following failures are difficult to predict and so more likely to prevent by design optimisation or safety measures.

In the following investigations a selection of failure causes has been made according to the described methodology. The failure causes are chosen with respect to Table 2 and only failures, which may be detected in advance, have been taken into account.

Therefore, the following analysis only deals with failures of variable-speed turbines, which are due to wearout, relaxation, storm events as well as other and unknown causes and which caused long downtimes of more than one day per failure.

The annual downtime of the affected subassemblies is shown in Figure 11. The components can roughly be categorised in three groups: drive train components, structural components and electrical components.

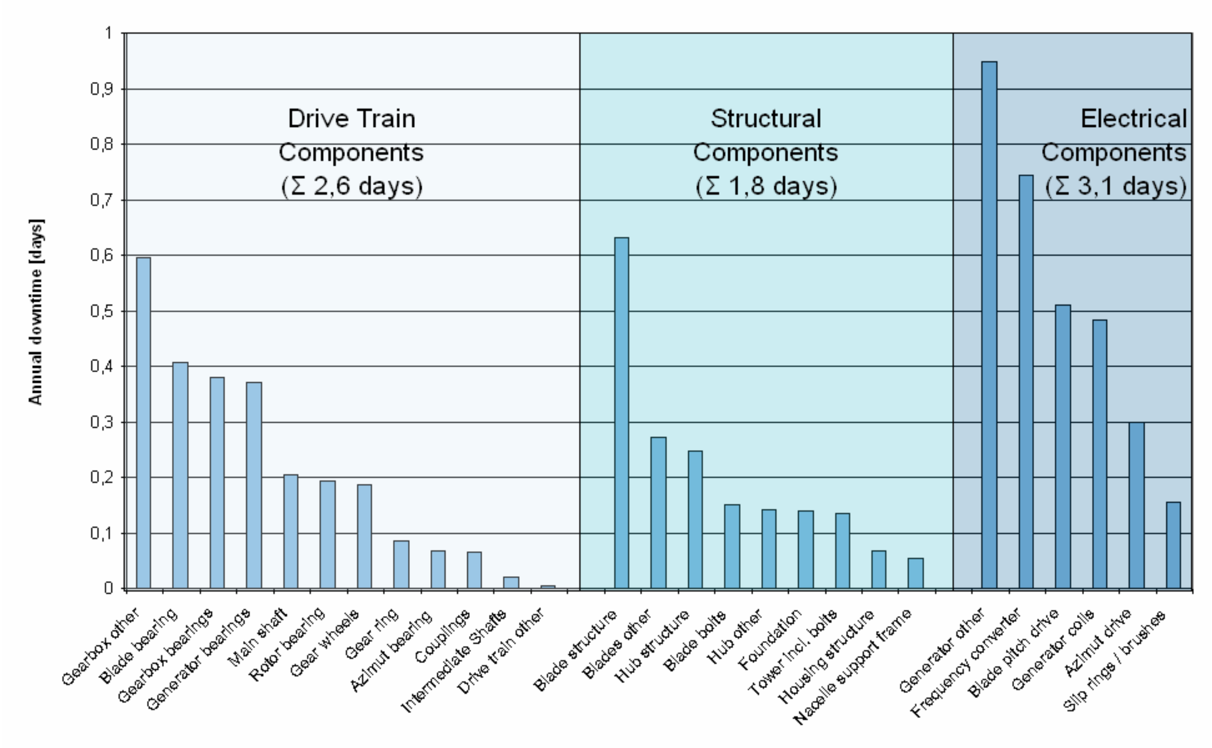


Figure 11: Most severe failures

The drive train components group consists of all rotating elements of the drive train, incl. bearings with rolling elements, shafts gear wheels, etc.; rotational frequencies of these components are multiples of the rotor rotational frequency, which induces typical vibration patterns for each component. Faults in components are leading to variations in these vibration patterns. For variable speed wind turbines, the fault frequencies are not fixed but will vary in the rpm range of the turbine's rotor.

The deviations from the normal patterns can be detected by use of fault prediction algorithms. Some of these algorithms are based on statistical signal analysis methods, which give a more generalised picture of the component's condition. The use of advanced spectral analysis methods, all based on modifications of the standard Fast Fourier Transform (FFT) algorithm, can indicate in more detail to the faulty subcomponent, e. g. a fault in an inner ring surface of a roller bearing on the generator shaft.

A developing fault in a rotating component will cause increased amplitudes of spectral components, variations in the ratio of side band amplitudes, etc. To filter this information from the vibration analysis results, a trend analysis has to be performed. Since the absolute level of the above mentioned fault indicators can differ quite significantly even when looking at different turbines of the same type, a trend analysis has to be performed for each individual wind turbine.

Structural components are mainly characterised by their natural frequencies. Contrary to the rotating components, fault frequencies are not directly induced by the rotation of the rotor. Typical faults in these components are distortion, buckling, cracks, delamination (in case of FRP structures), loosening of bolts, etc. In most of the cases, a shift in the individual natural frequency of a component points to a developing fault. For example, if a blade delaminates, the stiffness decreases and, therefore, the natural frequency decrease, too.

Monitoring of the natural frequencies can be done with FFT based algorithms and a trend analysis of the frequency shift and the variation of the amplitudes, quite similar to the algorithms described in the pervious section. Again, the absolute values of the fault indicators can be differ quite a lot from turbine to turbine.

Detection of faults in electrical components strongly depends on the type of the component. Insulation faults in the coils of electric machines cause high frequency harmonics in the related currents. These harmonics can be detected be spectral analysis algorithms. Faults in frequency converters cause asymmetries in the phase currents. Electrical components are not yet in the focus of condition monitoring in wind turbines. The causes and consequences of faults and their development have to be investigated in more detail as subject of future research work. It is likely that the fault development will be quite individual for individual wind turbines, even of the same type. So, detection of these faults will require turbine specific trend analysis, as mentioned already in the two previous sections.

Details for the above mentioned faults and their monitoring and prediction can be found in various publications, e. g. in [12, 13, 14].
In general, all faults and their development in the above mentioned groups of components behave individually for the wind turbine in scope. But, with a growing number of data sets in a fault statistics data base, it is likely to identify common patterns in the trend development of fault indicating characteristic values as mentioned above. If these patterns cannot be found in relation to the absolute levels of the characteristic values, maybe the growth rate of the values can show common patterns. In any case, an appropriate number of data sets from as much as possible different wind turbine types in conjunction with condition monitoring system measurements have to be analysed to build a basis for a condition based maintenance strategy.

5. Conclusions

The investigations to this report could demonstrate reliability characteristics for different turbine concepts with respect to failure causes. A component reliability ranking by comparing the share of failures and annual downtimes has been carried out. By looking at the standard variable-speed concept, which is somehow reflecting today's state of the art turbines, the share on the annual downtime dependant on the affected subassembly has been analysed. It can be distinguished between frequent failures with short downtimes, seldom failures with large downtimes and many components, which neither are subject of frequent failures nor are these failures combined with large downtimes or high costs. For preventing frequent failures, which often caused by external conditions, a reliability based approach in terms of design optimisation is suggested where by severe failures due to wear out might be detected in advance with sophisticated condition monitoring systems. To translate these findings and advices into practice, detailed documentations of all maintenance measures of a large population of plants and a purposeful structured database are necessary to extract sound conclusions out of the operational experience. After a certain period and with adequate statistical basis some reliability characteristics such as failure rates, repair times, etc., with respect to technical concepts (e.g. generator or gearbox-type), operating conditions (e.g. wind conditions or ambient temperatures) or plant ages can be determined with such a documentation. This provides a number of possibilities for optimising availability of WTs both in design & construction and in operation & maintenance.

An example for optimisation by design is the possibility for lowering the influence of the reliability of a subassembly on the availability of the whole system by making use of redundancy. Numerous elements in the electric and the control system are already redundant in modern WTs. A good example for an efficient use of redundancy can be seen in the wind vane. The annual failure rate of the wind vane has been relatively high in the past. Modern WTs are now having two wind vanes instead of overreliance on just one.

Operation & maintenance can get improved by adapting control strategies. The reliability of certain subassemblies may be improved by the change of some control parameters, e.g. using another power curve. This option may be also interesting regarding the electrical subassemblies.

However, main object of the reliability oriented strategy is to predict the probability of failures for certain components or subassemblies. This prediction allows to prior notice failures likely to occur and prioritise work as well as preferring measures or merge with other work. Thus, reliability based maintenance strategy can transform unscheduled outages into planned maintenance activities and reduce or even avoid downtimes as well as maintenance costs.

The statistical analyses need a broad database to deliver sound results. Such a broad database can only get built up, if several operators and service companies collaborate. To do so, all participants have to use a uniform designation of components, operating conditions and failures and need to use the same structure for data storage. Also there is a need to gain much more data and information than today, which leads to the necessity of electronically supported reporting by service teams.

As a result, the monitoring process can be simplified, the financial and technical reporting improved and cooperation with similarly oriented businesses enabled. Participating in a collaborative data collection and analysis also provides the opportunity for statistically reliable statements on the failure behaviour already mentioned and for benchmarking with other companies. Through this, weak-points can be easily recognized and components can be qualified in cooperation with the suppliers and ultimately reliability and availability can be increased despite a reduced maintenance effort.

6. Outlook

In other well-established areas like aviation or carrying-trade maintenance optimisation and sophisticated maintenance strategies are implemented as a standard since many decades. These techniques should also gain in importance in the wind energy sector.

For the accomplishment of these strategies appropriate failure statistics are required. Since there are many factors influencing WT reliability, it is necessary to classify turbines into groups of similar technology and similar operational conditions etc. Because of the diversity of these factors the division of WTs will lead to several groups with an inadequate statistical basis for analyses, even from a broad database. To overcome this limitation a collaborative reliability database with standardized data structures is proposed, using as much experience as possible. Therefore, it is proposed in Germany that the WMEP programme should be continued by an offshore monitoring programme, in which reliability data are collected in a standardised way and used to improve the maintenance of offshore WTs. This new project is named 'Offshore~WMEP' (O~WMEP) [15] following the former German onshore monitoring programme.

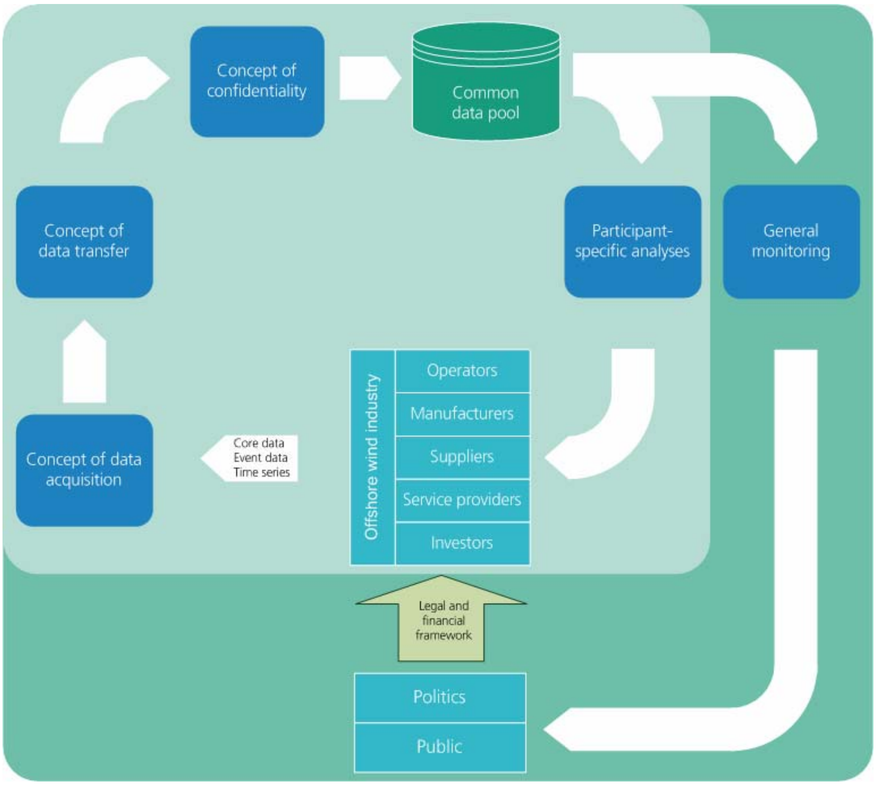


Figure 12: Concept of the Offshore~WMEP

The project is currently running in a concept phase with tasks like the development of a concept, which ensures the confidentiality of data and analyses. It is an essential characteristic of the project that only anonymous and non-confidential results are made available to the public.

However, operators of wind farms have started to document assets, maintenance measures and failures using standardised structures [16, 17, 18]. A group of planners and operators have already confirmed to support this new German programme for monitoring the development of offshore wind energy use as well as improving availability of offshore wind farms. The project is designated to start the operational phase together with first German offshore wind farms. It will enhance the database, already existing for onshore application. Thus, future analyses of failure rates, downtimes and causes can be based on much more detailed information and on an enhanced statistical basis.

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