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Spare Parts Planning for Offshore Wind Turbines subject to Restrictive Maintenance Conditions

Kirsten Tracht[a], Jan Westerholt[a], Peter Schuh[a,]*

[a]University of Bremen | Bremen Institute for Mechanical Engineering, Badgasteiner Strasse 1, 28359 Bremen, Germany
* Corresponding author. Tel.: +49 – 4121 – 218 64832; fax: +49 – 4121 – 218 64848; *E-mail address*: Schuh@bime.de.

Abstract

The use of offshore wind energy is supposed to play a significant role in future energy supply. Because offshore wind farms will be built in greater water depths and distances to shore according to other already realized offshore projects, maintenance is far more influenced by different restrictive factors. Limited availability of vessels, dependency on meteorological surrounding conditions, such as wind speed and weave height, as well as a complex logistical process chain require adjustment of up to now implemented maintenance concepts. In this context ensuring a reliable and cost-effective supply of spare parts is of great importance. This paper describes an approach for spare parts planning by considering restrictions that exist in the field of offshore maintenance. The model developed is used to show how restrictive factors influence maintenance and operation costs and how spare parts supply processes can be adopted. Scenario analysis will be used to estimate time of preventive maintenance activities and to investigate stock out costs caused by the restrictive accessibility.

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Keywords: spare parts; wind turbines; maintenance; demand prediction

1. Introduction

In the future, offshore wind turbines are supposed to play a significant role in energy supply [1]. This makes a reliable and safe operation necessary for which availability of wind turbines is essential. To achieve a reliable and safe operation of wind turbines, and machines in general, maintenance processes are conducted. Most repair tasks performed during maintenance rely on spare parts. Its supply offers high potential in cost savings; especially in case of expensive and large spare parts. This is because of the fact, that inventory costs are high and only specific transportation resources can be used to supply maintenance sites. Above that, maintenance of offshore wind turbines is exposed to harsh operating conditions, which lower wind turbine accessibility. In particular, accessibility of wind parks built in great water depth and distances to shore are greatly influenced by restrictive factors.

Today, experience of wind turbine operation and maintenance is primary transferred from onshore industry and accessibility is not considered in spare parts supply, even if restrictive factors can prohibit an installation of spare parts, so that the date of demand is postponed.

Within this paper, restrictive factors caused by operating conditions are investigated and a model for spare parts supply is presented. The model integrates accessibility of wind turbines, and herewith restrictive factors, with the aim of minimizing maintenance costs.

2. Maintenance of Offshore Wind Turbines

2.1. Maintenance Strategies

Maintenance strategies of the offshore-industry are mainly based on strategies known from onshore wind turbines. Though, they have been adopted to meet the harsh requirements in the field of offshore operation [2].

To reduce unscheduled downtime, maintenance operations are either performed preventively, based on the condition of the system, or correctively. In case of unplanned failures, corrective maintenance actions have to be conducted. All maintenance strategies are defined in EN 13306:2010 ISO [3].

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In contrast to maintenance actions of onshore wind turbines, that take place every six month, maintenance operators try to reduce the amount of inspections in the field of offshore wind turbines. Hence, preventive maintenance activities are reduced to one per year. The reasons for that are higher transportation costs and a reduced probability of wind turbine accessibility because of weather dependencies [4]. Maintenance tasks during preventive maintenance actions are performed regarding a maintenance plan, which has been defined by the wind turbine producer. A preventive maintenance plan includes activities like an oil change, visual inspections of key elements within the power train, functional checks of the crane and the lightning protection system as well as an inspection of rotor blades. [2, 5]

In addition to that, offshore wind turbines need to be checked thoroughly in periodical intervals (every four years). Institutions like the Germanischer Lloyd take care of the more comprehensive periodic inspections. [6].

Regardless of the maintenance process technicians need to get on and off the wind turbine. However, the restricted accessibility can prohibit maintenance processes and prolong downtimes. Therefore, operators usually try to avoid corrective maintenance processes and herewith shorten the mean time to repair by means of planned preventive maintenance activities. The impact of this strategy on spare parts planning will be shown in the model.

2.2. Spare Parts for Maintenance Activities

Spare parts are used to replace defective or worn out parts. Spare parts can be subdivided in repairables and consumables [3]. Spare parts considered in this article are repairables. Usually these parts are complex and expensive [7]. As a result procurement costs are high and inventory levels are low. The aim of the spare parts management is to provide spare parts when they are required in maintenance processes and to keep inventory cost low at the same time.

While approaches for spare parts planning, based on inventory or capital commitment costs are well known, algorithms that take into account maintenance processes are not widely spread. Liao and Wang for example, considered maintenance processes for machine tools and therewith improve prediction accuracy with the result of reduced inventory levels. [8, 9, 10]

Above that, Stolletz implemented lost earnings for defective machines. These were compared to the costs of stock keeping [11]. Wang used the estimated remaining useful lifetime for scheduling of maintenance activities to an economically reasonable point of time for spare parts planning. Next to that Liao and Vaughan used stock out costs for inventory planning. Therewith, costs for maintenance processes of tool machines have been lowered. [8, 9] Despite the enhanced models, inventory management under consideration of restrictions during maintenance processes has not been investigated.

2.3. Restrictions in Maintenance Feasibility

Planning and scheduling of extensive maintenance activities, such as the exchange of main components like gearboxes and rotor blades, can be considered as one of the most difficult tasks in maintenance of offshore wind turbines. The main challenges appear in consequence of different uncertainties related to the necessity of the maintenance activity, mainly determined by the probability of failure and its potential consequences and the feasibility of the maintenance activity, which is reliant on different restrictive factors, such as meteorological surrounding conditions and the access to required maintenance-resources. Weather conditions influencing maintenance activities are the sea state, in particular the significant wave height and also wind conditions. When considering restrictive factors, spare parts determine the transport resources for example. Small parts can be carried by helicopter that is not influenced by wave height, but by visibility conditions. Large components like gear boxes or blades are carried by a crane ship or a jack-up barge. Wind conditions as well as the sea state could prohibit any maintenance activity.

3. Model

In the following the model will be presented that considers a spare part to exemplify how the approach can be implemented in general.

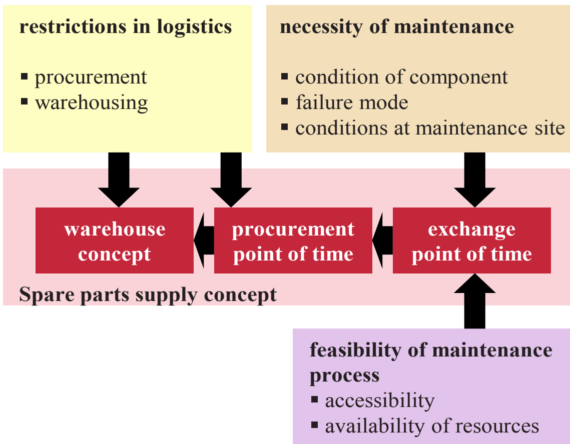

Fig. 1. Spare parts planning model

Figure 1 clarifies how maintenance restrictions or availability of resources can influence spare parts planning. The design of a warehouse concept will not be considered in this paper.

Nearly all maintenance restrictions shown in the previous chapter apply on gear boxes of offshore wind turbines. In addition to that, the following decisive arguments for the consideration of the gear box as an example are presented.

- The gear box is one of the most expensive parts of a wind turbine, next to rotor blades or the tower. It has a cost share of the wind turbine of around 13 percent [14]. Therefore, it causes high inventory costs. Furthermore, the wind turbine is unable to operate if a failure causes a malfunction in the gearbox. Thus, availability of material and low inventory levels are targeted.
- A gear box can only be replaced with a jack-up barge or a crane ship. Using these transport and assembly resources causes high chartering costs, which leads to high maintenance costs.
- Failures are either random or caused through continuous wear. The health of a gear box is mainly influenced by wear. Therefore, failures can be predicted with the help of a failure distribution.
- Long lead times of gear boxes are a challenge in procurement. Due to its dimensions and weight, transportation processes are the main issues for maintenance providers.

3.1. Cost Functions and Relaxations

In the following acronyms (table 1) and the mathematical framework of the model is described.

To implement restrictive maintenance conditions, the model is based on analytic Equations. These are used to calculate maintenance and operation costs. The result obtained with the integrated spare part model is ideal, if the sum of all occurring costs during the wind turbines life time, like costs for inventory, capital commitment costs, costs for maintenance tasks and default induced downtime costs are minimized (Equation 1).

$$C = C_i + C_m + C_{acc}(wt) \qquad (1)$$

Inventory costs during time of non-feasibility are calculated as shown in Equation 2. In Equation two, inventory costs are calculated for one year.

$$C_i = C_{so} + (R_{icc} + C_{sdr}) * (Sq - x_{pm}) * C_{sp} * \frac{T_d}{365} \qquad (2)$$

Tab. 1. Acronyms

A_{mt}	availability of maintenance technicians
A_{sp}	availability of spare parts
A_{ta}	wind turbine accessibility
A_{tr}	availability of transport resources
C	sum of all operation costs
C_{acc}	capital commitment costs
$C_{acc}(wt)$	capital commitment costs of the wind turbine
C_{cm}	corrective maintenance costs
C_d	default induced downtime costs
C_g	cost of gear box
C_i	inventory costs
C_{inv}	costs for investments (e.g. spare part, wind turbine)
C_m	total cost for maintenance
C_{mt}	cost for maintenance technicians
C_{pm}	preventive maintenance costs
C_{sdr}	stock keeping direct cost ratio
C_{so}	stock keeping overhead cost
C_{sp}	spare part costs
C_{tr}	cost of transport resources
d_f	failure density function
F_{fn}	feasibility of maintenance tasks at the time of t
f_{ft}	feed in tariff
h_{fld}	lost full load hours during downtime
k	amount of predicted failures
k_s	shape parameter (weibull distribution)
kW	kilo watts
kWh	kilo watt hours
n	number of experiments or wind turbines
P_f	probability of failure at the time of t
P_s	probability of survival at the time of t
P(k;n,p)	Binomial probability mass function
P(k;n,p)	Binomial cumulative distribution function
R_{icc}	imputed capital commitment interest rate
Sq	stock quantity
t	time
t_{ce}	point of time of corrective spare parts exchange
T_d	downtime
T_{nf}	time of non-feasibility
T_{lg}	characteristic life span of gear box
T_{lt}	life span of a wind turbine
T_{mttr}	mean time to repair
t_{pe}	point of time of preventive spare parts exchange
μ	expected value of binomial distribution
W_{pt}	nominal power of the wind turbine
wt	wind turbine
x_{cm}	number of corrective exchanges of spare parts
x_{pm}	number of preventive exchanges of spare parts

Maintenance costs consist of costs for preventive and corrective maintenance activities (Equation 3). These are influenced by spare part procurement cost, the time to repair and a time depended factor for maintenance tasks, which includes variables, like cost for maintenance technicians, transport resources and loss of earnings.

$$C_m = x_{cm} * C_{cm} + x_{pm} * C_{pm} \tag{3}$$

In case of a failure that is repaired correctively, corrective maintenance cost are calculated as follows:

$$C_{cm} = C_{sp} + C_{mt} + C_{tr} + C_d + C_{acc}(t_{ce}) \tag{4}$$

In case of a spare part demand, costs for the specific spare part have to be used. The costs for preventive maintenance tasks are defined in Equation 5.

$$C_{pm} = C_{sp} + C_{mt} + C_{tr} + C_d + C_{acc}(t_{pe}) \tag{5}$$

During downtime a loss of earnings takes place (Equation 9). The higher the nominal power of the wind turbine and the higher the amount of full load hours is, the higher will be the loss of earnings of a dysfunctional wind turbine. The downtime of a machine is heavily dependent on the feasibility of maintenance tasks. Non-feasibility due to restrictive factors is implemented in the framework by means of binary variables. The variable changes its value regarding weather conditions and availability of resources. As a relaxation every variable in Equation 6 can be 0 or 1. Hence, feasibility is either given (1) or not (0). This assumption could be replaced with steady values between 0 and 1. To show the functionality of the model, the relaxation of binary values will be used in this paper.

$$F_{fn}(t) = A_{ta} * A_{tr} * A_{mt} * A_{sp} \tag{6}$$

Within the model it is assumed that a repair process cannot be performed within a period of time in which the binary variable equals zero. An inhibited maintenance task leads to downtimes until the next period without restrictions in accessibility. As a consequence, a high amount of lost earnings could occur when restrictive factors are present during a wind turbine failure. After a period of non-feasibility wind turbines are not repaired in sequence but parallel, with the result that downtime after non-feasibility equals repair time. If feasibility is given during a breakdown of the system (Equation 7), downtime of the wind turbine is shorter than in case of non-feasibility (Equation 8).

$$T_d(F_{fn} = 1) = T_{mttr} \tag{7}$$

$$T_d(F_{fn} = 0) = (T_{nf} + T_{mttr}) \tag{8}$$

$$C_d = T_d * h_{fld} * f_{ft} * W_{pt} \tag{9}$$

Capital commitment costs occur during the life time of a wind turbine as well as in case of spare parts exchange. In case of spare part exchange, capital commitment costs are calculated from the point of time of exchange (Equation 10).

$$C_{acc}(t) = C_{inv} * (1 + R_{icc})^{(T_{lt} - t)} - C_{inv} \tag{10}$$

The investment costs (C_{inv}) are represented by the cost for a wind turbine and in case of a spare part exchange, by the cost of the spare part.

3.2. Failure Prediction for Demand Planning

Due to the fact, that failures cannot be predicted as a definite event, the probability of failure needs to be included in the model (Equation 11). Because gear boxes are subject to mechanical wear it can be assumed that the Weibull distribution estimates the probability of failure properly [2]. Its cumulative distribution function is defined as follows:

$$P_f(t) = 1 - e^{\left(\frac{t}{T_{lg}}\right)^{k_s}} = 1 - P_s, t \geq 0 \tag{11}$$

The related density function is calculated by the first derivation of Equation 11. According to the Weibull distribution the characteristic lifespan is defined as the time to which 63.3 percent of all units failed [12]. The parameter k_S is used to estimate variance and slope of the density function.

$$d_f(t) = P_f{}'(t) = \frac{\delta P_f(t)}{\delta t}$$

$$= \frac{k_s}{T_{lg}} \left(\frac{t}{T_{lg}}\right)^{(k_s - 1)} e^{-\left(\frac{t}{T_{lg}}\right)^{k_s}}, t \geq 0 \tag{12}$$

Spare part planning is based on the amount of demand during a period of time. The period of time is defined by the lead time of a spare part because it represents the time needed for replenishment. In that standard scenario downtime would equal lead time in case of an empty inventory, if a spare part is needed for maintenance. Due to the fact, that maintenance feasibility is not given during a defined time window, the period of time for demand estimation is replaced in this paper. If time of non-feasibility is longer than lead time, spare parts planning needs to consider demand during the time of non-feasibility. For that reason, the probability of failure (Equation 12) is implemented into a Bernoulli process. A relaxation within the model is a constant failure probability during non-feasibility. The constant probability and the independence of failure processes of different wind turbines allow the usage of a Bernoulli process for demand prediction. Performing *n* Bernoulli processes is expressed with the help of the

Binomial distribution (Equation 13). Its probability mass function represents the probability of getting exactly *k* events after *n* experiments.

$$p(k;n,p) = \binom{n}{k} p^k (1-p)^{n-k} \qquad (13)$$

Equation 13 is used to estimate the probability of appearance of a specific amount of demand *k* in a wind park that has *n* wind turbines. The probability of 0 or less than *k* demands can be estimated with the cumulative distribution function in Equation 14.

$$P(k;n,p) = \sum_{k=0}^{k} \binom{n}{k} p^k (1-p)^{n-k} \qquad (14)$$

Replacing the amount of demand *k* in Equation 14 with the stock quantity minus one (*Sq-1*), the service level of the inventory considered is calculated. The probability of a specific number of demands during non-feasibility, for example expected value (μ) and standard deviation of the binomial distribution are used to estimate demand during time window of non-feasibility.

4. Model Validation

4.1. Scenario Description

The model has been tested with a single item, single echelon scenario. It contains a wind park with 100 wind turbines in great distance to shore, which is operating since eight years. In the scenario the relaxation of constant wind force throughout one year is assumed. All parameter used within the scenario are defined in table 2.

Tab. 2. Parameter values of the scenario

Parameter	value	Parameter	value
W_{pt}	5,000 kW	C_{tr}	150,000 Euro/ day
f_{ft}	0.15 Euro/ kWh	C_{mt}	10,000 Euro/ day
T_{lt}	20 years	C_{sp}	800,000 Euro
T_{lg}	10 years	T_{mttr}	8 days
k_s	2	R_{icc}	0.03/ year
n	100	C_{so}	100,000 Euro/ year
T_d	150 – 270 days	C_{sd}	0.005/ year

The characteristic lifespan of the gear box that is used as a spare part in the model is ten years [13]. The lifespan is taken over from a gear box of an onshore wind turbine, because lifetime data of offshore components have not been published yet. Equation 8 and 9 are used to estimate the density function and the failure rate. Parameter values of table 2 are either estimated or taken from expert interviews that were multiplied with a factor to warp real values.

4.2. Restricted Accessibility Scenario

To analyze the influence of restrictive conditions, feasibility of maintenance activities can be controlled for every month of the year in the model. The spare part (gear box) can only be exchanged, if maintenance feasibility is given. If there are no restrictions, the decision of instant of gear box exchange only depends on the cost of corrective maintenance processes in contrast to capital commitment costs and preventive maintenance costs (Equation 4 and 5).

In case of non-feasibility, the number of failure during that period increases with its duration. In a worst case scenario some wind turbines would be unable to operate during the whole time span of non-accessibility. Hence, loss of earnings is maximal.

If spare parts are in stock, they can be used to perform preventive maintenance processes. These have to be conducted before the time span of non-feasibility begins. The required inventory level at the beginning of non-feasibility is calculated with the help of Equation 14, which estimates the number of expected spare part demands during the period of non feasibility. For fulfilling 97 percent of all demands during non-feasibility, the number of spare parts in stock is plotted in figure 2.

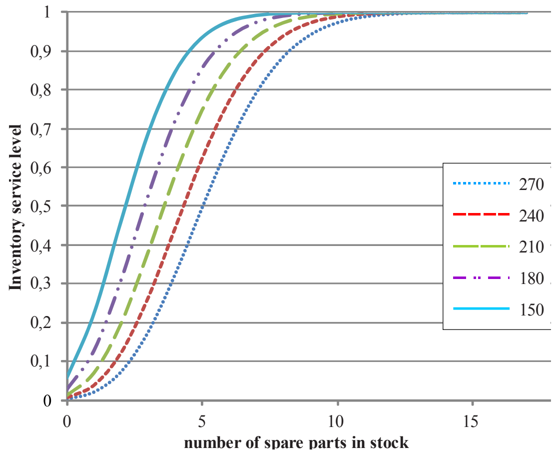

Fig. 2. Inventory service level

Table 3 shows the calculated number of spare parts needed in stock as well as the expected number of demand (μ) of the binomial distribution during non-feasibility (Equation 13 and 14)

Tab. 3. Service level and stock within scenario

days of non-feasibility	μ of demand	inventory level (pcs.)	expected service level (%)
150	2,82	7	0,97
180	3,54	8	0,97
210	4,25	9	0,97
240	4,96	10	0,97
270	5,68	11	0,97

In the scenario, the amount of preventive component exchanges has been varied. Figure 3 shows the comparison of preventive and corrective cost of the scenario that has 150 days of non-feasibility. Costs for 3 demands (expected value) during time of non-feasibility as well as costs for 6 demands (expected value plus standard deviation) are presented to illustrate the influence of demand height during the time window of non-feasibility.

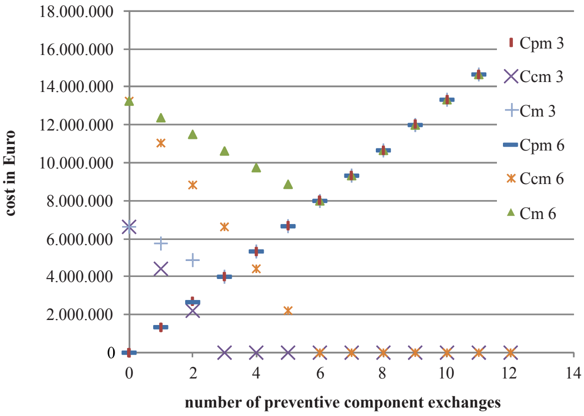

Fig. 3. Costs in case of 150 days of non-feasibility

It can be observed, that the most economic amount of preventive component exchanges equals the amount of demand predicted by the binomial distribution that describes the probability of failures under consideration of the Weibull hazard rate. Even if failures cannot be predicted as a definite event in maintenance practice the amount of demand calculated with the framework gives a valuable indicator for spare parts planning and preventive maintenance activities.

For example, if condition monitoring systems show noticeable problems, the corresponding spare part should be replaced before time window of non-feasibility. As a consequence, inventory level of spare parts can be lowered to the expected value of demand to reduce inventory costs without venturing stock out events.

5. Conclusion

The results of the analysis, conducted with the model, emphasize that restricted accessibility has an impact on scheduling of preventive maintenance and, herewith, influences the date of spare parts demand. For procurement processes of spare parts, the time of non-feasibility needs to be considered to avoid unnecessary machine downtime and to lower inventory cost by reducing the inventory level. This novel planning approach will also offer the opportunity of utilizing transport resources and maintenance technicians to capacity. Thereby, maintenance costs can further be reduced and profitability of wind turbines improved.

In further investigations relaxations within the approach, like constant wind force throughout one year as well as dynamic stock levels during time window of non-feasibility will be removed to further improve spare parts planning. Fundamental changes of results are not expected. Instead, it is assumed that implementing parameters that aren't considered today, will lead to variations in the number of recommended exchanges before time window of non-feasibility, which will influence inventory levels. With this, spare part inventory levels will be estimated more accurate.

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