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# Cost Analysis of a Condition Monitoring System for Journal Bearings in Wind Turbine Gearboxes

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**Abstract:**

Journal bearings (JBs) have become an established technology in planetary stages of wind turbine (WT) gearboxes, offering high torque density, and reliable operation. Since their introduction into serial production, they have demonstrated robust performance. However, abnormal operating conditions such as contamination, dry running, or elevated local temperatures can cause bearing seizure and costly gearbox failures with extended turbine downtime. Condition monitoring systems (CMS) provide an opportunity to detect critical operating states at an early stage and to initiate countermeasures, thereby preventing catastrophic failures, reducing repair costs, and mitigating yield losses. Despite this potential, no commercial CMS dedicated to WT gearbox JBs is currently available, and existing approaches remain subject to research.

This work investigates the benefit of implementing a CMS for JBs in WT gearboxes regarding economics. First, the study quantifies the costs of gearbox failures, including replacement and yield losses, based on a literature review. Second, it estimates the capital expenditure associated with integrating a CMS. By combining these inputs, a cost model is developed to assess whether the CMS can achieve positive net present value. The model accounts for differences in WT location, failure rates, power ratings, and gearbox configurations, including the number of planetary gears per stage. The paper concludes with a sensitivity analysis of the model and a scenario analysis that shows when the use of a CMS is economically justified. The analysis shows that the CMS application is more beneficial in the offshore sector than in the onshore sector. A maximum acceptable CMS cost value of 1.000 € is set as the limit so that the application makes economic sense in both cases. The analysis shows that the use of CMS only brings economic benefits if the bearing failure rates are significantly higher than 0.0007 /(WT·year).

## 1. Introduction

JBs as planetary gear bearings in wind turbine (WT) gearboxes are an established technology and contribute to gearbox torque density and reliability [1]. They require a reduced installation space in comparison to rolling element bearings due to their compact design and are not subject to fatigue. This has led to the introduction of JBs in serial production of WT gearboxes around the year 2018 [2]. Despite their general robustness under hydrodynamic conditions, abnormal operating states (e.g. oil contamination, dry-running or high local temperatures) can lead to seizure and costly gearbox failures with extended turbine downtimes, significantly impacting the turbine's economic performance. Since planetary gear bearing failures are considered one of the most common reasons for the replacement of an entire gearbox [3], strategies for preventing planetary gear bearing damage promise significant economic benefits.

Condition monitoring systems (CMS) offer the potential for early detection of critical operating conditions. If a critical operating condition were to be detected early by the CMS, potential countermeasures (e.g. derating of the turbine and timely maintenance) can be initiated to prevent

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a catastrophic failure, thereby reducing maintenance costs and preventing unplanned outages. By reducing yield loss and damage-related repair costs through a CMS-based failure prevention, there is an overall potential to reduce the operational expenditures (OPEX) and thus the levelized costs of electricity (LCOE) for wind energy. Currently, there is no commercial CMS that has been specifically developed for the use in WT gearbox JBs. Various CMS approaches for JBs are subject to current research efforts [4, 5], but are not yet technically mature for the application in the field. In addition to further technical development, it is important to consider the economic efficiency of a CMS. Only if the investment costs for a CMS do not exceed its potential benefits can its use be economical and therefore justified.
The aim of this work is a cost model for the estimation of the net present value of a JB-CMS in WT gearboxes, which allows for the identification of scenarios in which the use of CMS is economically beneficial. In a first step the costs resulting from a gearbox failure (replacement costs and yield loss) will be quantified based on a literature review. Secondly, the capital expenditure (CAPEX) for a JB CMS is quantified. The cost model uses the results of the prior two steps and is based on the net present value (NPV) method. Lastly, a sensitivity analysis for the input parameters of the cost model is performed and the analysis of different scenarios is presented.

## 2. State of the art

Several studies exist addressing the potential economic benefit of different CMS for onshore [6] and offshore [7, 8] WTs. These studies compare the potential O&M savings achieved using CMS with the investment costs, focusing on state-of-the-art monitoring systems for gearboxes: MAY et. al. use the NPV method to calculate the annual O&M costs including the expenses for a vibration and oil-condition monitoring system for a WT gearbox. The NPV method is used to discount the O&M costs to the net value of the life cycle costs for a WT lifetime of 20 years. [9] Using the same method NILSSON et. al. analyzed the impact of CMS on maintenance strategies for WTs. It demonstrates that implementing gearbox CMS can enhance maintenance efficiency and reliability, with potential cost reductions of 23% for a single onshore WT and 4.5% for an entire offshore wind farm [10]. None of the aforementioned studies specifically examines a JB CMS. Nevertheless, the approaches they employ are applicable to the subject of this work. Consequently, the cost model discussed below explicitly refers to a JB CMS integrated directly into the gearbox and is likewise based on the NPV method.

## 3. Impact of gearbox failure on O&M costs – literature review

Depending on the location of the turbine, OPEX account for 25-33% of the LCOE [11, 8]. The share of OPEX attributable to the repair of unexpected component damage is up to 73% [11]. The relative number of failures and the resulting costs per failure for various WT components are shown in figure 1. The underlying study considers approximately 4.000 onshore WTs with a power rating below 6 MW [12]. As shown in the figure, one WT component that contributes significantly to the OPEX is the gearbox with the highest cost per failure. Other studies confirm that WT gearboxes cause the highest repair costs in the event of damage [13]. Depending on the size and location of the WT, serious gearbox damage can result in high costs for the replacement due to the accessibility for heavy equipment. The cost for the gearbox replacement $C_R$ of a 3 MW offshore WT can amount to 230.000 € [14]. With a higher power rating of the WT, the costs for a gearbox replacement are significantly higher (e.g. ~ 1 M € for WT with > 5 MW power) due to the high cost $C_{GBX}$ of the gearbox itself [15]. A comprehensive overview over the O&M costs $C_R$ associated with a gearbox replacement are presented in Figure 2. The numbers vary greatly, as some of the underlying studies do not provide complete information on the composition of the costs or detailed information on the wind turbines (e.g., location, power rating).

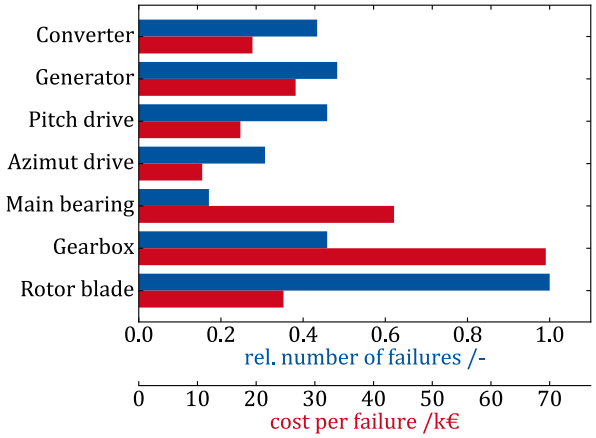



**Figure 1.** Relative number of failures per WT component and mean cost per failure for onshore WTs with a power rating below 6 MW [12]

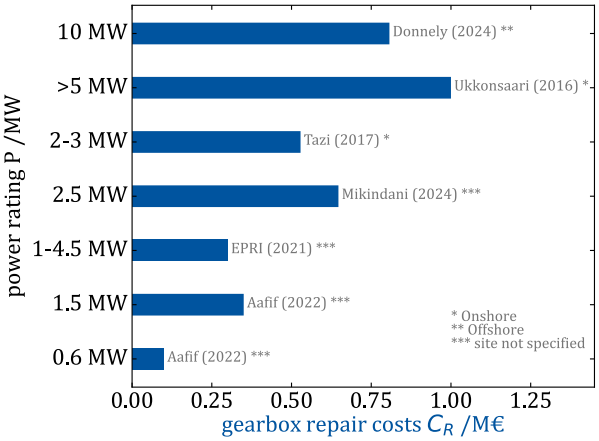



**Figure 2.** Exemplary figures for the O&M costs associated with a gearbox replacement from literature review [16–20, 15]

Since the up-tower exchange of a JB in the planetary gear stage is generally technically not feasible it is assumed in this work, that a JB failure necessitates the replacement of the entire gearbox. Consequently, the aforementioned costs for a gearbox replacement $C_R$ in the event of JB damage are assumed here. A crane (onshore) or jack-up vessel (offshore) is required to replace a damaged WT gearbox. Depending on their availability, the downtime of the turbines can vary greatly. Therefore, it is important to correctly approximate the resulting yield loss. In Figure 3 the results of a literature review for the yield loss are presented. The individual data points (blue squares in Figure 3) have been scaled to a mean turbine downtime $d$ of 240 h of for comparison. This period is often referred to in the literature as the average downtime in the event of a gearbox exchange [21, 22]. However, these numbers may also be subject to significant fluctuations.
Since no numbers for the yield loss from WTs with a power rating greater than 3 MW could be found in the relevant literature, a linear progression is assumed for larger rated outputs. For this study the yield loss $C_{yield}$ (red curve) is assumed to scale linearly with the WT power rating $P$ and an approximation is given in Equation 1 [19].

$$C_{yield} = P \cdot c_P \cdot d \cdot p \qquad \textbf{Equation 1}$$

The parameter assumptions made for the approximation of $C_{yield}$ are given in Table 1. The blue data points in Figure 3 confirm the approximation from Equation 1with sufficient accuracy.

**Table 1**: numerical values used to calculate the yield loss

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Power rating | $P$ | 0.5 - 6 | $MW$ |
| Capacity factor | $c_p$ | 0.3 | $-$ |
| Average downtime | $d$ | 240 | $h$ |
| Electricity selling price | $p$ | 0.082 | $€/kWh$ |

In addition to the repair cost $C_R$ and the yield loss $C_{yield}$ the scenario of a JB failure considered here also incurs the costs for the replacement gearbox $C_{GBX}$. In Figure 4 an overview over the gearbox costs $C_{GBX}$ as a function of rated gearbox torque $T_R$ is provided. The blue data points again stem from literature review for reference. The red dotted line is a linear function fitted to the literature values.

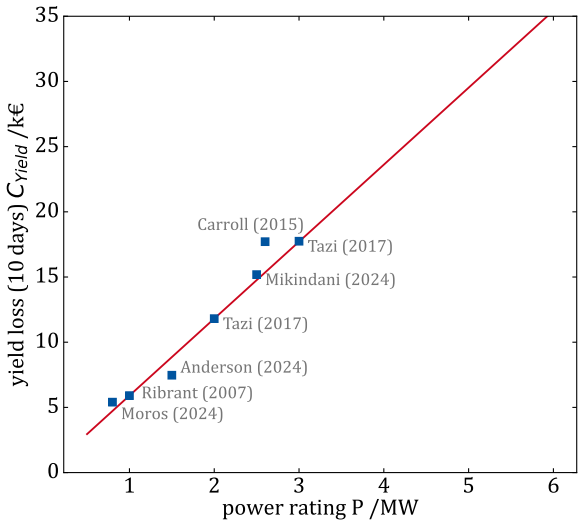



**Figure 3** Approximated yield loss for a downtime of 240 h for turbine power ratings up to 6 MW based on values from literature [19, 23, 24, 20, 25]

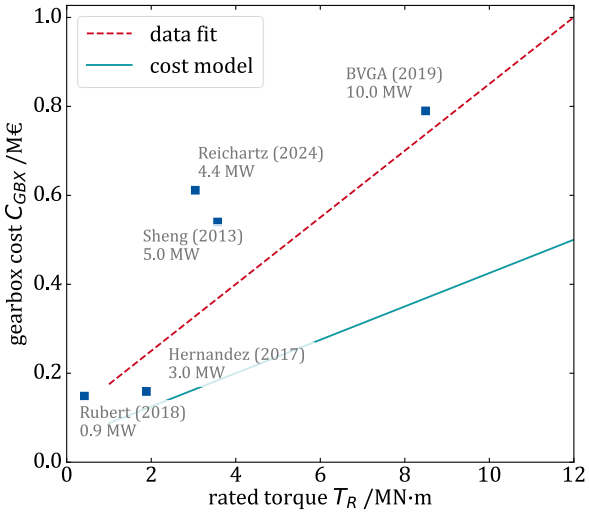



**Figure 4** Approximated CAPEX for a single WT gearbox for rated torque up to 12 MNm compared to values from literature [26–30]

Similar to the above shown yield loss function (Equation 1) a cost model for $C_{GBX}$ is introduced in this work (green curve in Figure 4) with the rated torque $T_R$ assumed to be a function of the rated power $P$ (e.g. 3.9 MNm at 5 MW [31] and 9.9 MNm at 10 MW [32]):

$$C_{GBX} = 40.5\ €/kNm \cdot T_R + 17.000\ € \qquad \textbf{Equation 2}$$

For the sake of simplicity, different types of gearboxes (e.g. 3-point/4-point mounting, with/without helical gear stage, type of oil supply system, etc.) are not differentiated in this work since the resulting cost differences are considered negligible as a first approximation.

As a conservative estimate, the cost model for $C_{GBX}$ (Equation 2) is parametrized to yield 50 % lower numbers than those reported in the literature. This is a conservative estimate that takes the following aspects into account: Individual numbers and models for the costs of WT gearboxes in the literature are often based on a limited amount of publicly available data, which can lead to an overestimation of the actual costs. One contributing factor is the scarcity of transparent, up-to-date cost information, forcing research to depend on a few published data points that may not be representative. Additionally, some works may have considered inflation adjustments of gearbox costs despite industry evidence that costs have decreased over that period due to technological learning, optimized supply chains, and competitive pressures. This can distort the resulting cost functions, particularly for larger power ratings.

With the aforementioned numbers for the repair cost $C_R$, the yield loss $C_{Yield}$ and the cost for an individual gearbox $C_{GBX}$, the total cost of a WT gearbox replacement can be approximated. To evaluate the cost benefit of a CMS for preventing a gearbox replacement due to JB damage, the costs associated with the damage must be compared with the procurement and installation costs for the CMS. In the next section the cost model and its underlying parameters will be introduced.

## 4. Cost model for a JB-CMS

The cost model is structured in two sections: Firstly, the CAPEX for the installation of the JB-CMS are calculated based on the architecture of the CMS inside the gearbox. Secondly, the costs associated with a JB failure necessitating gearbox replacement, and the extent to which these costs can be mitigated using CMS, are approximated using an OPEX model.

### *4.1 Modelling the CAPEX for a JB-CMS*

The costs for the CMS itself can be easily modelled using a bottom-up approach based on the architecture of the CMS: The system considered in this work consists of decentralized measurement units placed in every planet pin in close proximity to the JB sliding surface and a centralized unit receiving the data from the bearings. Due to its highly integrated nature the system can not be retrofitted into an existing gearbox and the costs associated with the installation of the CMS refer to the installation into a gearbox during the assembly at a gearbox supplier. The monitoring technology is based on ultrasonic surface wave and temperature measurements. A technical description and experimental investigations regarding this technology can be found in [5]. Figure 5 shows a schematic overview of a gear stage with planetary JBs. The measurement units (orange rectangles in Figure 5) monitor one individual bearing in a fully autarcic mode (wireless data and power transmission). Each gear stage is equipped with one stationary unit (green rectangle in Figure 5) acting as the data receiver and wireless power transmitter (WPT).

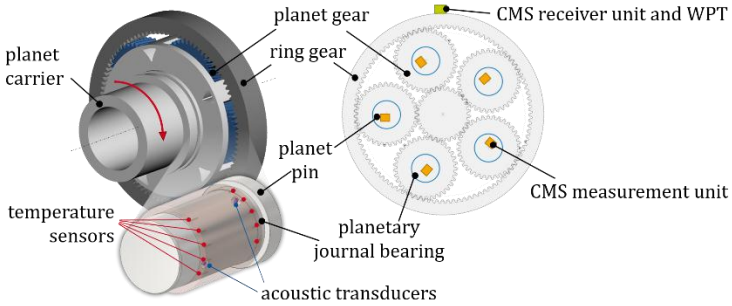



**Figure 5:** Schematic depiction of a planetary gear stage from a WT gearbox with PJBs equipped with a CMS

An approximation of the total CMS cost per gearbox is given in Equation 3. It is assumed that each planetary JB must be monitored individually. The costs for the gearbox CMS therefore scale linearly with the number of planetary gears $n_{Planets,i}$.per gear stage $i$. In addition Equation 3 considers the one-time installation costs $C_{Installation}$ of the entire CMS during gearbox assembly. With the parameter $C_{WPT}$ the costs for the WPT unit are taken into consideration in Equation 3.

$$C_{CMS,WT} = C_{Installation} + \sum_{i=1}^{n_{Stages}} \left(C_{CMS} \cdot n_{Planets,i} + C_{WPT}\right) \quad \textbf{Equation 3}$$

Modern WT gearboxes comprise up to 7 planetary gears per stage [33] and have multiple planetary stages. The cost of a single CMS measurement unit (device placed in the planetary axis) $C_{CMS}$ can only be estimated, since the technology is currently under development. This parameter and its impact on the result will be further discussed below.

### *4.2 Modelling the impact of the JB-CMS on WT OPEX*

In a second step the costs caused by one single JB failure are calculated as the sum of the yield loss $C_{Yield}$, the cost for the gearbox $C_{GBX}$ and the costs associated with the gearbox replacement work itself $C_R$ (including personnel and equipment for the repair work).

$$C_{JB,damage} = C_{Yield} + C_{GBX} + C_R \quad \textbf{Equation 4}$$

In Equation 5 an approximation for the OPEX for one WT caused by JB failures is given with $f_R$ being the JB failure rate per WT per year. The cost for one gearbox replacement $C_{JB,damage}$ caused by an initial JB failure is estimated based on the above shown literature review.

$$C_{OPEX,JB} = C_{JB,damage} \cdot f_R \quad \textbf{Equation 5}$$

The constant failure rate $f_R$ used in this work is a rough estimate. Although several reliability models for rolling element bearings exist (e.g., based on Weibull distributions), the publicly available long-term failure data for WT-JBs are scarce. Therefore, a reliable parameterization of such models is currently not feasible, and a constant failure rate $f_R$ is assumed. This assumption should be revisited once the failure behaviour of WT-JBs is better understood.
It is assumed that the use of the JB-CMS can prevent a significant majority of bearing failures, thereby reducing the above-mentioned operating costs. In this model, the effect of using CMS on the O&M costs is approximated by a reduced bearing failure rate $f_{R,reduced}$. The reduced failure rate $f_{R,reduced}$ is calculated using Equation 6.

$$f_{R,reduced} = f_R \cdot (1 - p_{CMS}) \quad \textbf{Equation 6}$$

The model parameter $p_{CMS}$ represents the true positive rate (TPR) of the CMS indicating the proportion of bearing failure cases that are actually correctly and early identified by the CMS. The parameter $p_{CMS}$ depends on the used CMS method. In this work, the parameter $p_{CMS}$ can only be estimated, as the CMS method under consideration is currently under development and field tests are still pending. Using the reduced failure rate from Equation 6 the reduced annual OPEX can be approximated according to Equation 7.

$$C_{OPEX,JB-CMS} = C_{JB,damage} \cdot f_{R,reduced} \quad \textbf{Equation 7}$$

The annual savings achieved using the JB-CMS $e_a$ are approximated by Equation 8 as the difference between the OPEX incurred as a result of JB damage $C_{OPEX,JB}$ and the O&M costs incurred when using the CMS $C_{OPEX,JB-CMS}$.

$$e_a = C_{OPEX,JB} - C_{OPEX,JB-CMS} \quad \textbf{Equation 8}$$

In a final step, the savings $e_a$ over the entire service life $L$ of the WT are compared with the initial cost for the CMS per turbine $C_{CMS,WT}$ using the net present value (NPV) method according to Equation 9. The NPV method represents the generated change in equity discounted to $t = 0$ by the discount rate $r$ [34].

$$\text{NPV} = -C_{CMS,WT} + \sum_{t=0}^{L} \frac{e_a}{(1+r)^t} \quad \textbf{Equation 9}$$

If the NPV is positive, the use of the CMS over the entire service life $L$ is economical due to a resulting increase in equity or net assets. If the NPV is negative the investment is not economically feasible.

## 5. Results

In this chapter, the results of the NPV analysis are presented and discussed. First, a sensitivity analysis is conducted to identify the parameters exerting the greatest influence on the model output. Subsequently, these parameters are examined in greater detail within both the onshore and offshore scenarios.

### *5.1 Cost model parameter sensitivity analysis*

The model explained above consists of several analytical equations with 15 input parameters in total. There are several uncertainties associated with these input parameters, either due to sparse literature references (e.g. JB failure rate $f_R$, gearbox replacement costs $C_R$) or due to dependence

on the development process of the CMS itself (e.g. costs for the CMS unit $C_{CMS}$, installation $C_{Installation}$ or the wireless power transmission system $C_{WPT}$). To obtain an understanding of the individual parameter influences a sensitivity analysis is performed. For this purpose the sensitivity analysis method according to MORRIS is chosen [35]. The results of the analysis are shown in Figure 6 ranking the parameters based on their effect μ* on the model output (in this case the NPV according to Equation 9).

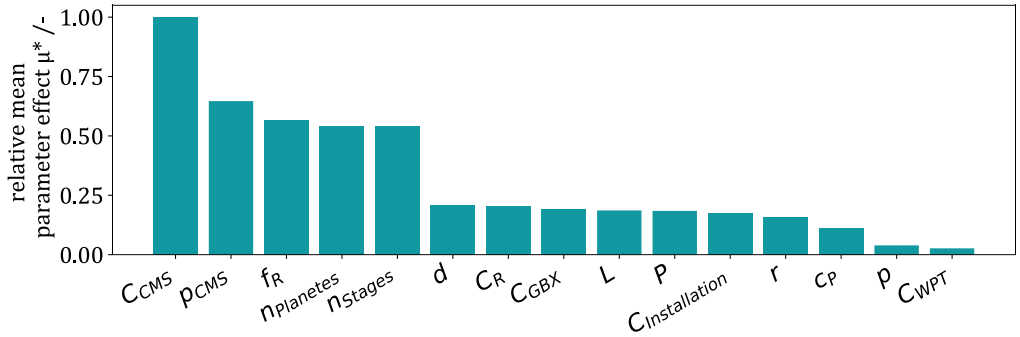



**Figure 6:** Result of the sensitivity analysis: normalized mean parameter effects μ*in descending order

The costs $C_{CMS}$ for one measurement unit and the CMS precision $p_{CMS}$ are the model parameters with the highest effect. The bearing failure rate $f_R$ is the third most relevant parameter followed be the parameters defining the gearbox architecture and thereby size of the entire CMS ($n_{Stages}, n_{Plantes}$). In the following sections the influences of the three most relevant parameters $C_{CMS}$, $p_{CMS}$ and $f_R$ will be investigated further.

### *5.2 NPV results for different failure rates and CMS costs*

For the comparison of the model results for an onshore and offshore WT the values from Table 2 are used to parametrize the cost model. The gearbox cost $C_{GBX}$ is calculated using Equation 2. The resulting NPV for both scenarios is shown in Figure 7 as a function of the failure rate $f_R$ and the cost per CMS unit $C_{CMS}$.

**Table 2:** Parameters for two exemplary WTs

| Parameter | Symbol / Unit | Onshore WT | Offshore WT |
|---|---|---|---|
| Power rating | $P\ /MW$ | 7 | 15 |
| Downtime per failure | $d\ /h$ | 720 [9] | 4000 |
| Gearbox cost | $C_{GBX}\ /M€$ | 0.313 | 0.613 |
| Gearbox replacement cost | $C_R\ /M€$ | 0.3 [10] | 1.0 |
| Number of planet gears | $n_{Planets}/-$ | 7 | 12 |
| Service lifetime | $L/\ years$ | 20 | |
| CMS failure detection rate | $p_{CMS}\ /\%$ | 95 | |
| JB failure rate | $f_R\ /\ 1\ /(WT \cdot year)$ | 0.0001 to 0.002 | |
| Cost per CMS unit | $C_{CMS}\ /€$ | 500 to 5000 | |

For the onshore scenario (Figure 7a) there is a distinct range for $C_{CMS}$ (2000 – 5000 €) where the NPV is negative regardless of $f_R$ showing that the CMS is not economical at all. For the offshore scenario (Figure 7b) this is not the case. This makes the use of the CMS significantly more promising for the offshore WTs. This was to be expected due to the high replacement costs and higher rated power of offshore WTs. In the onshore scenario the NPV result depends more on the failure rate $f_R$ than it does for the offshore scenario. This is due to the high costs for the gearbox and thus the CMS for the offshore WT dominating the NPV here.

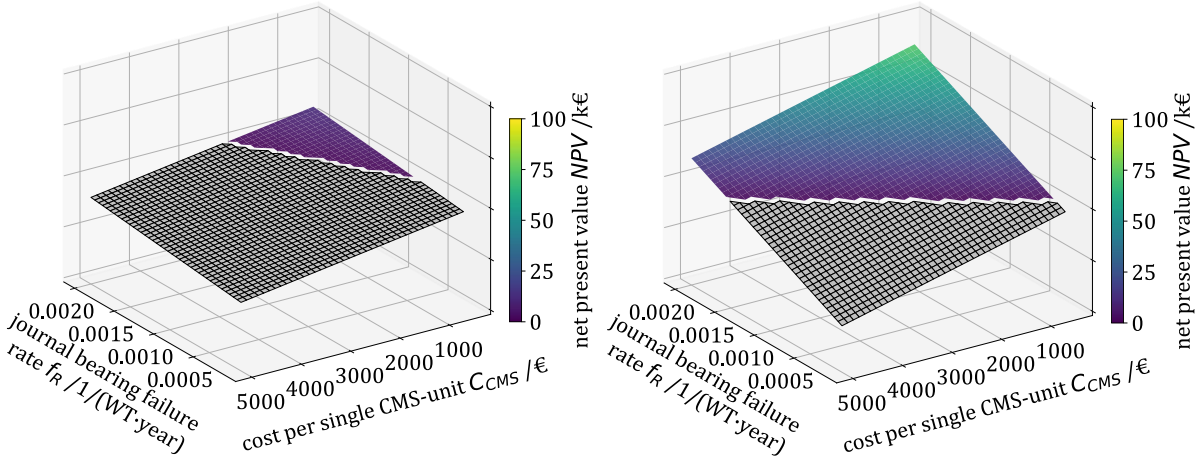



**Figure 7:** Results for the NPV for a JB-CMS as a function of the bearing failure rate and cost for a single CMS unit for two scenarios: (a) 7 MW onshore wind turbine and (b) 15 MW offshore wind turbine

Since there exists a high uncertainty to $f_R$ the economic benefit for the onshore WT is only guaranteed if the CMS costs are well below 1000 € (can be higher for the offshore scenario). For a failure rate below 0.0007 $/(WT \cdot year)$ (onshore) and 0.0002$/(WT \cdot year)$ (offshore) the NPV is negative regardless of $C_{CMS}$. These results are generated based on the assumption of a constant failure detection rate $p_{CMS} =$ 95 %. According to Figure 6 $p_{CMS}$ has the second highest influence on the NPV result. In the following, this parameter influence will be investigated further.

### *5.3 Influence of the CMS failure detection rate on the NPV*

The precision of a CMS $p_{CMS}$ is known to have a significant influence on the achieved O&M savings [9] (second most important parameter according to Figure 6) and an imperfectly operating CMS can jeopardize its economic benefit entirely [6]. To account for this effect a further investigation is presented in Figure 8. The resulting NPV for the onshore and offshore scenario is shown as a function of $f_R$ and the CMS failure detection rate $p_{CMS}$ (further parameters according to Table 2)

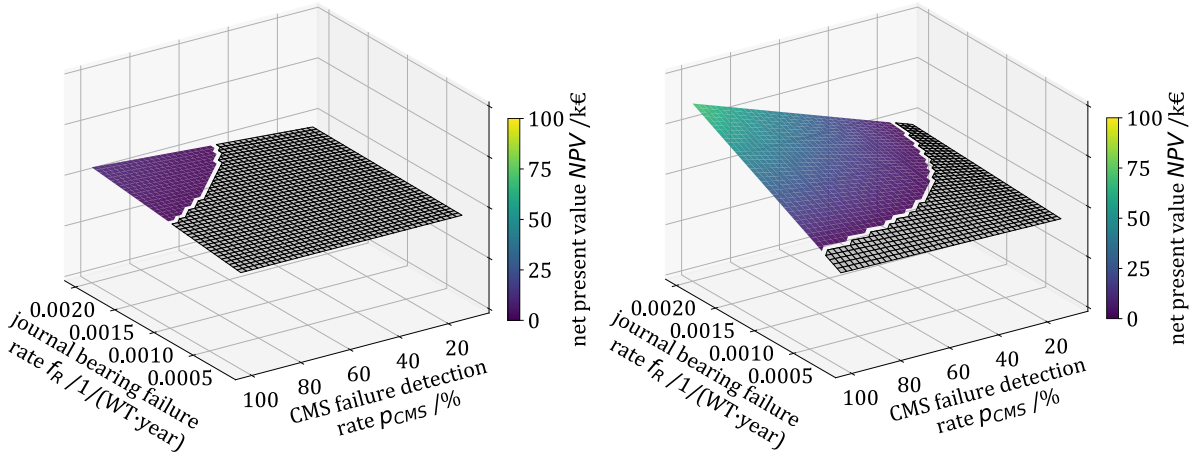



***Figure 8:*** *Results for the NPV for a JB-CMS as a function of the bearing failure rate and CMS failure detection rate for two scenarios: (a) 7 MW onshore wind turbine and (b) 15 MW offshore wind turbine*

Based on the results from Figure 7 for $\boldsymbol{C_{CMS}}$ a value of 1000 € is assumed. The NPV model shows that for both scenarios there is a limit to $\boldsymbol{p_{CMS}}$ below which an economic benefit is no longer

guaranteed (51 % onshore and 19 % offshore). If the system is to be used in both scenarios, $\boldsymbol{p_{CMS}}$ must not be below 51 %. This value refers to the absolute allowable minimum for $\boldsymbol{p_{CMS}}$, assuming that the JB failure rate is at its highest (0.002 /(WT·year)). For real-world CMS applications, the highest possible failure detection rate should always be aimed for $\boldsymbol{p_{CMS}}$, with realistic target values for a CMS between 90 % and 95 %.

## 6. Discussion and outlook

This work presents a cost model for the NPV of a JB-CMS. The model compares the savings in O&M costs using a CMS with the costs for a JB-CMS. The O&M costs are approximated using values from literature. The effect of model parameters on the NPV result is analyzed using a sensitivity analysis. The costs for the measurement units and the CMS failure detection rate are identified as the two parameters with the highest effect. These parameters depend on the technology itself, and therefore can be positively influenced during the development of the CMS. For the costs of the measurement units a value < 1000 € was found to be feasible in the onshore scenario. In the offshore scenario higher CMS costs are justifiable. The third most influential parameter is the bearing failure rate. This parameter is subject to a high degree of uncertainty, as public information on JB failures is scarce. The scenario analysis shows that the use of CMS only has economic benefits if the bearings failure rates are significantly higher than 0.0007 /(WT·year).
Further, the results show that the failure detection rate of the CMS significantly influences the achieved NPV. A detection rate of 51 % was determined as the minimum value necessary to achieve a positive NPV.
A central aspect of the continued development of the CMS will be the systematic integration of the underlying cost model. This approach will enable optimization not only from a technical perspective but also with respect to economic considerations. One limitation of the model is that it does not account for the costs of maintaining the CMS itself, software license fees, or the degradation of the CMS over time. Incorporating these aspects in future work could further improve the model.
The operational response following the alarm of a JB-CMS is currently uncertain. In practice, operators may temporarily derate the WT until inspection or maintenance is carried out. This operational strategy has the following economic implications: false alarms may lead to unnecessary derating and associated yield losses. In the case of an actual fault, the WT is derated prior to maintenance, resulting in production losses. The cost model must be further extended to capture these effects as well.
In summary the assumptions underlying the model must be continuously reviewed and updated as soon as new insights or changing conditions emerge. In this way, the cost model can serve as a robust basis for informed decision-making in the long-term technical evolution of the system.
In addition, as described earlier, the CMS considered here is not intended for retrofitting into existing wind turbine gearboxes. Consequently, the economic potential is limited to new installations. Nevertheless, assessing the economic potential of retrofit solutions would be highly relevant and should be considered in future research.

## Acknowledgements

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