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Reducing cost uncertainty in the drivetrain design decision with a focus on the operational phase

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Abstract

In order to identify holistically better drivetrain concepts for onshore application, their operational behaviour needs to be considered at an early design phase. In this paper, a validated approach for estimating drivetrain concept-specific risk of unplanned maintenance based on open access data is presented. Uncertain influencing factors are described with distribution functions. This way, the poor data availability in the early design phase can be used to give an indication about the concept's choice influence on the unplanned operational turbine behaviour. In order to get representative comparisons, Monte Carlo method is applied. This makes it possible to model the life of a fictional wind turbine based on the derived distributions. Technical availability and drivetrain influenced unplanned maintenance effort are defined as evaluation criteria. The latter is constituted by labour, material, and equipment expenses. By calculating the range of fluctuation of the evaluation criteria mean values, this approach offers an indication about the inherent risk in the operational phase induced by the drivetrain concept choice. This approach shows that open access data or expert estimations are sufficient for comparing different drivetrain concepts over the operational phase in an early design stage. The approach is applied on the five most common state-of-the-art drivetrain concepts. The comparison shows that the drivetrain concept without a gearbox and with a permanent magnet synchronous generator performs the best in terms of absolute unplanned maintenance effort over the lifetime as well as on the inherent risk. For future research, the influence of the maintenance strategy as well as site and park specific impacts on the unplanned concept behaviour should be included. For adapting this method to new concepts, a physically based approach could be developed which would make it possible to estimate probability distributions for the uncertain factors. Nevertheless, this approach will help to identify holistically better drivetrain concepts by being able to estimate the inherent risks in the operational phase.

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1. Introduction

Decreasing subsidies, fierce competition from fossil power stations and photovoltaics puts the wind industry under high development and cost pressure. The wind turbine drivetrain as the sum of the energy converting components between hub and transformer has a significant influence on the turbine's properties and behaviour. The nacelle and its components can account for up to 50 % of the investment cost of a turbine (Mone et al., 2015). More importantly, over 80 % of the unplanned failures of a turbine can be traced back to nacelle components (Reder et al., 2016). It is estimated that cost arising during the operational phase can accumulate up to the initial investment cost (Luers et al., 2015). Today's market presents a variety of drivetrain concepts. However, no statement about the best concept is yet possible. Especially the concepts performance in the operational phase is hard to estimate upfront. Its components are designed for a 20 years lifetime with not fully known load cases, maintenance, and mounting accuracy. These are especially not known during the conceptualization phase. In the best case, innovation in the wind turbine drivetrain aims to provide holistically superior products. The greatest influence on the products success can be exerted in the early phases of product development as this is when its cornerstones are set (Ehrlenspiel et al., 2014). Furthermore, effort for design modification rises exponentially with the products maturity level (Ehrlenspiel et al., 2014).

To identify superior products in an early phase of the product development, a concept-specific estimate about the unplanned maintenance effort and inherent risks is required. This leads to the questions of how do the drivetrain concept characteristics influence the operational phase of an onshore wind turbine and how can this be modelled in an early design stage? This paper aims at providing information about the expected drivetrain component and concept operational behaviour as well as a statement about the certainty of this behaviour. The outcomes of this paper provide a turbine designer with tools to identify holistically better drivetrain concepts for onshore application.

In the following, an approach for estimating drivetrain concept-specific inherent risk of unplanned maintenance effort and technical availability is developed and presented. In Section 2, a literature review is given. Section 3 presents the papers object of reflection. Section 4 introduces the general model approach. In Section 5, the developed model and its underlying assumptions are introduced. The required validation is stated in Section 6, and, in Section 7, a concept comparison is conducted. Finally, Section 8 concludes the work and gives an outlook.

2. Literature review

Some drivetrain concept comparisons focusing on the operational phase are available in literature. Most of them derive statements based on the evaluation of empirical databases, which are unfortunately not open access (Carroll et al., 2014b). Thereby, failure modes and effects analysis and derivatives (Cevasco et al., 2018; Ozturk et al., 2018) as well as Monte Carlo simulations (McMillan and Ault, 2010; Dalgic et al., 2015) are the most commonly used methods. They highly rely on empirical databases which are not available in the early phase of product development. Alternatively, other authors use fixed average failure rates from one source to model the components operational behavior (Carroll et al., 2014a; Carroll et al., 2017).

As shown by Carroll et al. 2015, the representativeness of analyses based on fixed average failure rates from one source is questionable (Carroll et al., 2015a). In addition, available concept comparisons mostly lack an indication about the certainty of results. In an uncertain situation it helps to at least have an indication about the level of uncertainty and its source(s). Statements about the lifetime behaviour as well as scalability is mostly not in the scope of previous investigations. Hence this publication presents an approach for deriving scalable and more representative estimations about the concept-specific operational behaviour of a drivetrain based on publicly available data.

3. Object of reflection

This paper aims to quantify the influence of the drivetrain concept choice on the operational expenditures over the turbine's lifetime as well as on the turbine's technical availability. The focus lies on the consideration and quantification of uncertain aspects of unplanned operational effort. In this approach, drivetrain is seen as the sum of the energy converting components between the turbine's hub and transformer. This means the operational behaviour of the chosen suspension system, gearbox, generator and converter design are considered. Figure 1 gives an overview about aspects generally influencing the operational expenditures of a turbine. They are divided into aspects being directly influenced by the drivetrain concepts choice as well as aspects being uncertain.

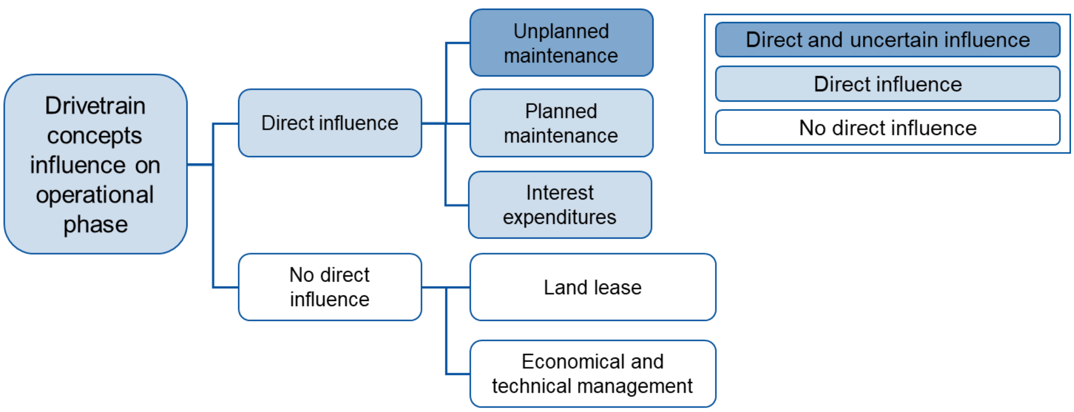

Figure 1: Factors influencing the operational phase of a wind turbine

The focus of this investigation lies on drivetrain-influenced uncertain aspects. Unplanned maintenance is the most prominent factor which is uncertain and directly influenced by the concept choice. Therefore, it is solely taken into account in this approach. Unplanned maintenance is defined as an unpredictable component breakdown which urgently needs unscheduled activities. The unpredictable component breakdown makes this aspect a highly uncertain and risk-inherent situation. It can have a multitude of influencing factors like the component design, unknown loading conditions, system interaction, manufacturing, and mounting accuracy. When trying to find help in literature, data is often anonymized and therefore samples cannot be characterized in a sufficient way (Cevasco et al., 2018). More importantly different studies come to contradictory statements about the components failure behaviour (Ozturk et al., 2018; Carroll et al., 2017). Unplanned maintenance includes

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unscheduled activities that need to take place in case of a component breakdown. The needed actions and the related effort are mostly uncertain and again are influenced by a multitude of factors. Failure type, accessibility, weather, spare part, technicians, and equipment availability can influence the unscheduled activities. Once more literature studies seldomly provide information about durations (downtimes, repair times) and reasons for the extent of the activities. Samples are defined in an unsatisfactory way. These complex and uncertain features make it impossible to precisely calculate the unplanned maintenance effort and availability of a drivetrain concept in an early design phase with respectable effort. Still this is a major characteristic of a drivetrain concept which has to be considered in the concept decision.

The early design phase in this paper is defined as the phase in the product development process where design decisions for the concept are made (cf. step three of VDI 2221 (VDI, 1993)). This phase is characterized by a high degree of complexity, uncertainty and information deficits. In the status quo, this highly important decision is mainly based on experience of the deciding engineers. This can be especially critical when evaluating completely new ideas differing in many aspects to the former product generation. Known in this decision are the rated power of the turbine, the rotor diameter, the wind class it is developed for and, the possible drivetrain concepts.

4. Model approach

This Section presents the used approach for estimating drivetrain concept-specific unplanned maintenance effort and technical availability in an early design stage. The approach needs to fulfil the following requirements:

- Deal with the poor availability of concept-specific information in literature and early design stage
- Allow estimates about the technologically inherent impact the drivetrain concepts choice has on the operational phase
- Consider and evaluate the most relevant influencing factors in the operational phase
- Be applicable to state-of-the-art drivetrain concepts
- Be scalable in rated power
- Be applicable to incremental inventions and new concept ideas

This approach is based on publicly available studies about the drivetrains operational phase. As mentioned in Section 3, these studies sometimes come to contradictory statements and are not always transparent about the cause of failure or downtime. Therefore, the model is based on several assumption. First assumption is, that not all influencing factors leading to a failure can be depicted and though modelled individually. Failure detectability, weather or site-specific impacts as well as the maintenance strategy itself are not considered directly. Furthermore, it is assumed, that all available study results from literature represent realistic component behaviour, as it is mostly not comprehensible what conditions the turbine experienced. The next assumption is, that this behaviour is mainly influenced by technological choice. It is assumed that these influencing factors are randomly distributed. Failure rate, downtime, failure severity, and duration of repair and replacement are modelled as uncertain factors. In order to include all available information, continuous distributions are chosen to fit the observed data for depicting the uncertain factors if possible. Parameters for fitting the distributions are estimated based on maximum likelihood method.

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It is assumed that the entire drivetrain consists of repairable assemblies, which means each assembly can sustain more than one failure and is 'as good as new' after repair or replacement. In reality, repair never reaches the reliability of a new component. Still, this assumption makes it possible to model the life of a fictional wind turbine based on the derived distributions.

A statistical approach, Monte Carlo method, is utilized for deriving representative results as it makes it possible to calculate a multitude of fictional turbine lives. It has the ability to conduct a high number of random experiments based on uncertain influencing variables. Basis for this method is the law of large numbers. It says that, by performing a large number of experiments, the mean of the results will get close to the expected value. This approach is suitable for the present problem as it is constituted by different uncertain factors that can be described by continuous distribution functions. Furthermore, this method offers the possibility to not just get insights on the expected value but also about the results occurrence probability. Inverse-Transform sampling method is used for generating random numbers with a defined distribution. This way, a sufficient number of fictional wind turbine operational lifetimes are simulated for every component based on the distributions derived from literature data. This is done for all relevant components.

In this approach, technical availability (AV [%]) is influenced by uncertain factors including mean time to failure and duration of the repair, replacement or downtime, c.f. Formula (1):

$$AV(i) = \frac{\sum_{s=1}^{3}\sum_{j=1}^{4}\sum_{d=1}^{4} do_{j,d,s} * f_{j,d,s}(i)}{8760\,\frac{h}{a}} \qquad (1)$$

In this Formula, *j* indicates the component type, *d* the specific design of the component, and *s* the failure severity. The amount of failures in the specific year *i* is represented by *f* $[\frac{failure}{a}]$. The downtime each failure leads to is represented by *do* $[\frac{h}{failure}]$ in year *i*. Technical availability is therefore calculated as the percentage of the time of the year where the turbine could theoretically provide electricity if wind conditions are met.

$$OME(i) = \sum_{s=1}^{3}\sum_{j=1}^{4}\sum_{d=1}^{4} f_{j,d,s}(i) * (LE(dr_{d,j,s}, w, nt_s) + ME(m_{d,j,s}(i)) + EE(we_{j,d,s}, c_{j,d,s})) \qquad (2)$$

Estimating the drivetrain influenced unplanned maintenance effort (OME [€]) is a bit more complex cf. Formula (2). It is constituted by labour, material and equipment expenses. Labour expenses (LE) is influenced by the uncertain factor duration of repair or replacement as well as the number of technicians (nt) which is failure severity dependent (s) and the wage of a technician (w). While material expenses (ME) is determined taking the severity of the failure and component specific investment cost into account (m). Furthermore, the component specific weights (we) combined with a crane function (c) account for equipment expenses (EE). Having included component specific mass and cost makes this approach scalable in rated power and rotor diameter.

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5. Model implementation

The following Section gives insights on how the model idea is implemented. Some general assumptions are presented in the beginning before the model procedure is introduced. Failure rate, downtime, failure severity, duration of repair and replacement are modelled as uncertain factors. Collected data about these factors is allocated to the different components and their design. Design unspecific information is assorted to the component in general. This unspecific information is later considered for all component designs. This allows to make the most out of the available data while not favouring one design or distorting the result. Figure 2 shows an overview of the models structure and the underlying assumptions. Model input are the component design, rated power, and the rotor diameter. One model iteration represents the operational behaviour of a drivetrain from installation until end of its design lifetime.

For every operational year component failure occurrence and failure time are calculated. It is assumed that the components failure behaviour follows a Weibull distribution. This is a common assumption for technical systems. Weibull distribution makes it possible to reveal the main nature of the failure being premature, random, or due to wear out. Weibull parameters for the failure behaviour of the different components are determined based on mean times to failure. Mean time to failure as the reciprocal of failure rates is derived from available failure rates from literature (for sources see Table in Figure 2). Maximum likelihood method is applied for deriving Weibull parameters for mean time to failure. It is assumed that failure rates for the different component designs already consider subsequent faults due to the chosen system. Therefore, components can be modelled independently from each other.

In case of a failure, its severity needs to be determined. Referring to Carroll et al., failure severity categorizes failures due to their impact on material cost (Carroll et al., 2014b). It is distinguished between minor repair, major repair, and major replacement. The first row in Table 1 gives the definition of the failure severity types. Failure severity is considered with a uniformly distributed random number and a percentual distribution determined from (Carroll et al., 2015a). Unfortunately, this distribution is deduced from an offshore database.

Table 1: Failure severity distinction based on Carroll and model implementation (Carroll et al., 2014b)

Failure severity distinction	**Minor repair**	**Major repair**	**Major replacement**
Definition (Carroll et al., 2014b)	material cost up to 1,000 €	material cost between 1,000 € to 10,000 €	material cost over 10,000 €
Material expenses	0	Random number between 1,000 € – 10,000 €	Component investment cost
Labour expenses	f (Repair time)	f (Repair time)	f (Replacement time)
Equipment expenses	-	-	Additional crane

Failure severity affects downtime. Downtime due to minor repair is modelled with a constant value. For major repair and replacement, downtime is assumed to follow a normal distribution. Distribution parameters are derived from literature (compare Table in Figure 2). The accumulated downtime over the drivetrains design lifetime allows now an estimate about the effect of the unplanned drivetrain failures on technical availability (AV).

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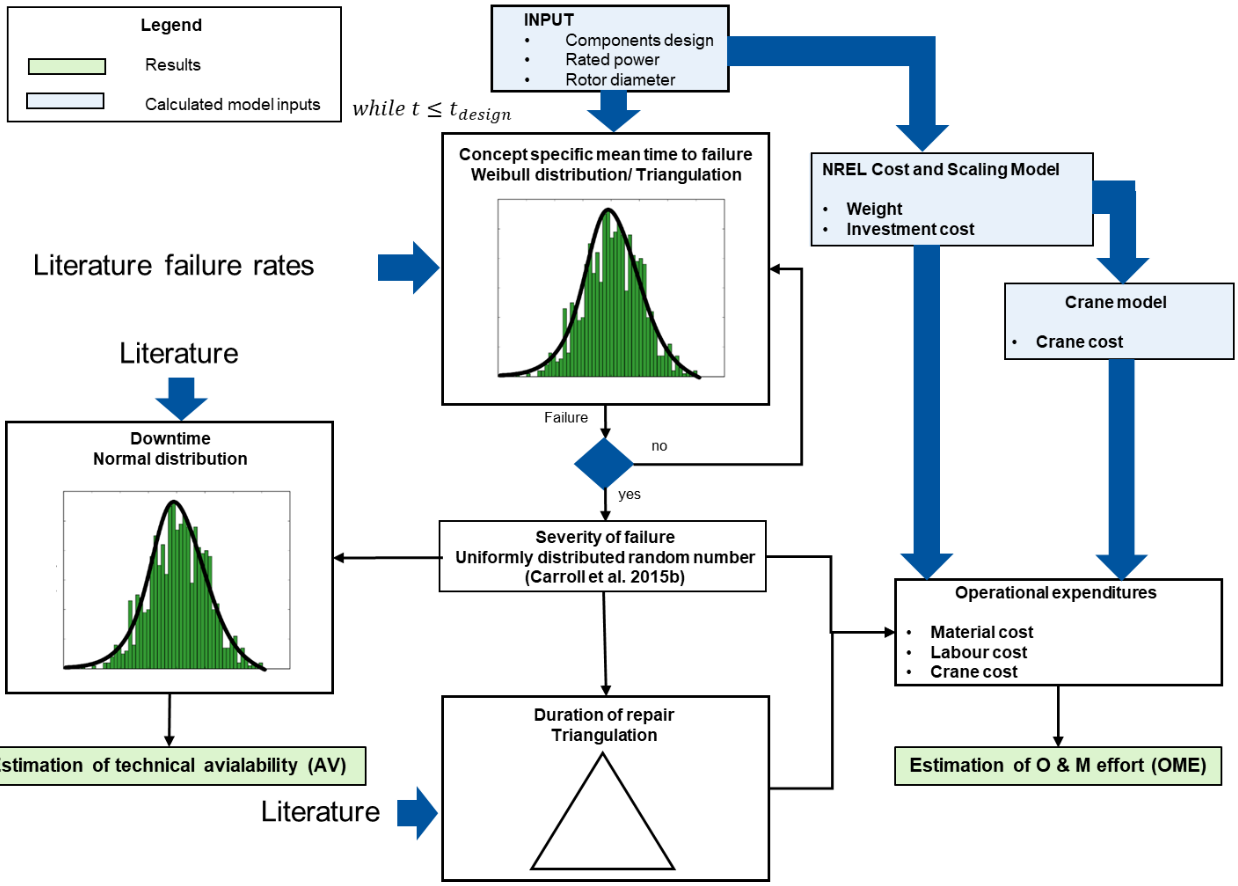

Uncertain factor	Model implementation	Source
Failure rate	Weibull distribution/Triangulation	(Fischer and Wenske, 2015; Fischer et al., 2015; Ozturk et al., 2018; Shafiee and Dinmohammadi, 2014; Ribrant Johan, 2006; Dinmohammadi and Shaffiee, 2013; Arabian-Hoseynabadi et al., 2010; Carroll et al., 2017; Berger, 2016; Reder et al., 2016; Carroll et al., 2016; Dinwoodie* and D. McMillan, 2012; Pinar Pérez et al., 2013; Wilson and McMillan, 2014; Carroll et al., 2014a; Tavner and Spinato, 2008)
Downtime	Normal distribution	(Fischer and Wenske, 2015; Samet Ozturk, Vasilis Fthenakis and Stefan Faulstich; Ribrant Johan, 2006; Carroll et al., 2017; Reder et al., 2016; Dinwoodie* and D. McMillan, 2012; Pinar Pérez et al., 2013; Carroll et al., 2016)
Failure severity	Uniformly distributed random number	(Carroll et al., 2015b)
Duration of repair	Triangulation/constant	(Carroll et al., 2016; Carroll et al., 2017)

Figure 2: Overview of model structure

170 Referring to Formula (2) the estimation of O&M effort (OME) is constituted by material, labour, and crane expenses (compare Table 1). Minor repair is repair which leads to material cost up to 1,000 €. In this model material expenses are neglected for minor repair due to their small amount. Major repair is implemented as a random number between 1,000 – 10,000 €. According

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to Carroll major replacement is a replacement which leads to material cost over 10,000 €. In the model, it is assumed that the entire component needs to be exchanged if this failure type occurs. Material expenses are therefore modelled as the investment cost of the failed component. Component and design specific investment is calculated based on rated power and rotor diameter using the NREL Cost and Scaling Model (Fingersh et al., 2006).

Labour expenses, another stake of OME, is mainly influenced by the duration of the action. Failure severity and component specific actions duration for major repair and replacement are modelled with the help of a triangulation. Here the modus is assumed to equal the mean. For minor repair, a fixed action duration per component is taken into account based on (Carroll et al., 2017). Repair is done by two technicians. Replacement measures require three technicians due to safety reasons. A constant hourly wage is assumed.

Finally, the equipment expenses need to be estimated. It is assumed, that no additional crane is needed for minor and major repair as the onboard equipment can be used. An additional crane is used to enable the component exchange for major replacements. For the crane cost estimation, a parameterized model is developed which chooses the needed crane based on component weight and hub height, which the component needs to be lifted on. Crane data is based on Liebherr cranes (Liebherr). Component weight is estimated based on the NREL Cost and Scaling Modell (Fingersh et al., 2006). For some components an exchange is only possible if further components are dismounted, this fact is considered in the crane decision. The crane is leased for the time the replacement takes place. This way an estimate about the drivetrain-influenced unplanned maintenance effort (OME) is possible.

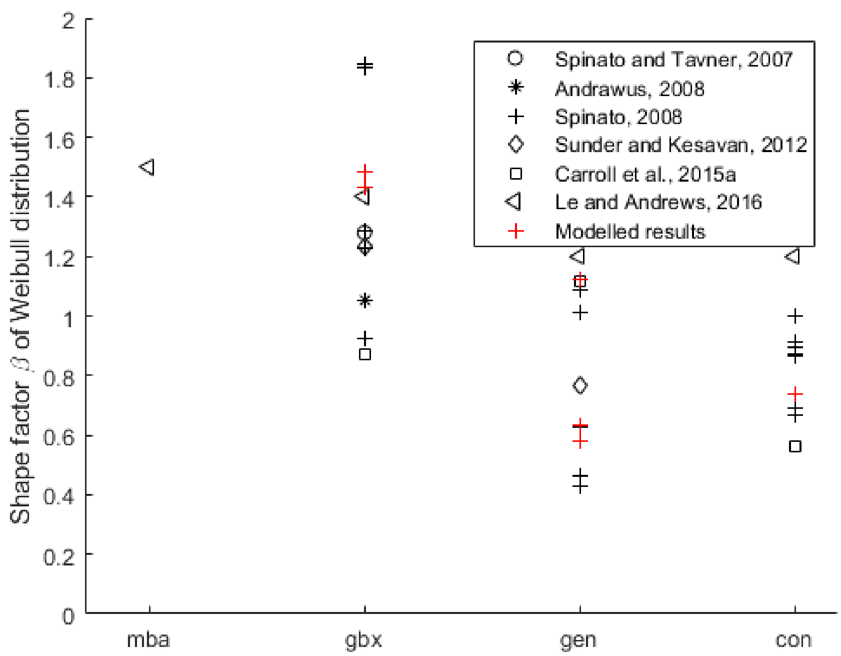

Figure 3: Components failure behaviour from literature and model results described by the Weibull shape factor (Spinato and Tavner, 2007; Andrawus, 2008; Spinato, 2008; Sunder and Kesavan, 2012; Carroll et al., 2015a; Le and Andrews, 2016)

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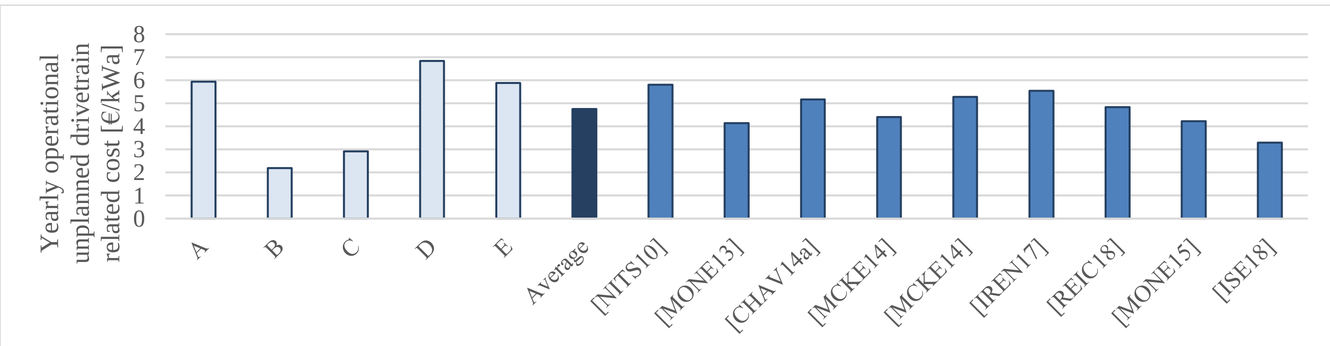
6. Model validation

The verification and validation are done by comparing modelled values with published data combined with a general reasonability check. In the beginning, the failure behaviour is in the focus. The following components in the following designs are in the scope: moment, trunnion, 3-point and 4-point suspension system, two and three-stage gearbox, permanently magnet synchronous generator (PMSG), electrically excited synchronous generator (EESG) and doubly fed in duction generator (DFIG) as well as partiall and fully rated converter. Initial null hypothesis is that all components failure behaviour can be described by a Weibull distribution. Due to the small sample size, an Anderson-Darling goodness of fit test is conducted. This test is applicable to samples with a minimum size of four. Null hypothesis for a Weibull distribution is not rejected for the two stage gearbox and the three stage gearbox with a three point suspension system, all generator types and the partially rated converter with a five percent significance level. Though they are modelled by a Weibull distribution. The three-stage gearbox with a four-point suspension system follows a log-normal distribution again confirmed by an Anderson-Darling goodness of fit test. For all main bearing arrangement designs as well as the fully rated converter, this test is either not applicable or the null hypothesis is rejected. Therefore, a triangulation is applied. An Anderson-Darling goodness of fit test supports the assumption that components downtime can be described by a normal distribution. Unfortunately, no design specific modelling for downtime is possible due to a lack of data.



Concept	**A**	**B**	**C**	**D**	**E**
Suspension system	Moment	Moment	Trunnion	3-point	4-point
Gearbox	2 stage	-	-	3-stage	3-stage
Generator	PMSG	PMSG	EESG	DFIG	DFIG
Converter	Fully rated	Fully rated	Fully rated	Partially rated	Partially rated

Figure 4: Scaled Meta study about drivetrain influenced unplanned maintenance effort and model results [€/kWa]

There are a few publications available in literature where the failure behaviour of different wind turbine drivetrain sub-assemblies has been empirically evaluated and described by a Weibull distribution. Figure 3 shows the shape factor of the Weibull distribution for different components failure behaviour from literature and modelled. A first look reveals a wide spread in the shape factor in literature not indicating an ambiguous failure behaviour. It needs to be considered that the Weibull shape factors are not distinguished into the components design. Model results are component design specific and show different behaviour for the different designs which is in line with literature values. This way the chosen distributions and distribution parameters are confirmed.

Not only the failure behavior shall be validated but also the general model results, meaning the modelled mean drivetrain influenced unplanned maintenance effort and its technical availability. Literature does not directly provide these numbers. Yearly operational cost can vary between 2 – 4.2 % of the initial investment cost of the turbine (Nitsch et al., 2010; ISE Fraunhofer, 2010, 2012, 2013; Fichtner / Prognos, 2013). Two further created Meta studies indicate that operational expenditures over the year vary from 30 to 52 €/kWa or 0.5 – 2.68 ct/kWh (Nitsch et al., 2010; Mone et al., 2013; Chaviaropoulos and Natarajan, 2014; McKenna et al., 2014; IRENA - International Renewable Energy Agency, 2018; Reichenberg et al., 2018, 2018; Fraunhofer ISE, 2018). These Meta studies give the impression that operational expenditures vary substantially. Unfortunately, the sources do not indicate their samples in a sufficient way. Therefore, only a scale comparison can be conducted for validation. 44 – 55 % of yearly operational expenditure is associated with maintenance and repair (Luers et al., 2015). For the comparison planned maintenance effort, and unplanned effort for other turbine components needs to be excluded. This leads to the assumption that a quarter of the maintenance and repair expenses are caused by unplanned drivetrain failures. A corrected Meta study is shown in Figure 4. In addition to the literature values, this Figure also depicts the calculated values for the different drivetrain concepts (A – E). All concepts are designed for a rated power of 3 MW and a rotor diameter of 120 m. With an average mean value of 4.75 €/kWa the modelled results are in between the Meta study results varying between 3.3 €/kWa and 5.808 €/kWa. Furthermore, the industry standard of a technical availability above 97 % is achieved for all analysed concepts. So, the general model results are reasonable.

7. Concept comparison

The validation section shows that there are significant differences in the drivetrain influenced unplanned maintenance effort. This Section allows to better understand underlying reasons for these differences. First of all, the component design specific failure behavior is evaluated. Figure 3 presents the Weibull parameters for the different components in their different designs. It is visible that the PMSG, EESG and partially rated converter follow mainly early failure behaviour. Statistically, one failure will occur during their lifetime. Whereas the two-stage gearbox, the three-stage gearbox with a three-point suspension system, and the DFIG can mainly be attributed to wear out behaviour. For these component designs statistically two failures will occur over their lifetime, indicated by their scale factor.

Table 2: Modelled Weibull parameter for failure behaviour of different drivetrain components

	2-stage gbx	3-stage gbx & 3-point suspension	PMSG	EESG	DFIG	Partially rated converter
Shape factor	1.4311	1.4846	0.57877	0.63376	1.1203	0.73571
Scale factor	9.195	8.4066	14.5737	13.9907	9.3895	13.3346

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Figure 5 gives an overview about the calculated mean drivetrain influenced unplanned maintenance effort over the entire turbines lifetime for 1,000,000 iterations split into the labour, material and crane expenses share. The direct drive concepts (B & C) score best. Mainly due to the reason, that they lack a gearbox. Main source for expenses for the direct drive concepts is the generator. Here the EESG performs worst. Failure rate wise PMSG and EESG seem to be on the same level, this is derived from the same labour expenses level and the Weibull parameters. Still material expenses are higher for the EESG as it is modelled more expensive in the NREL CSM. It is furthermore, heavier than the PMSG resulting in higher crane expenses. Despite of its higher failure rates, the DFIG results in the lowest unplanned operational effort. Looking into the behaviour of the component converter it is visible, that the converter has a minor influence on the overall expenses. Reason is the low amount of needed replacements which usually lead to high expenses. This is in line with literature which says that converter failures can often be solved remotely or with low effort. No direct influence for the main bearing arrangement on the unplanned operational expenses is calculated. This can be explained by the mean time to failure used for the triangulation which is in the scale of 10^6 years. Looking at the gearbox it is apparent, that this is the componentent responsible for most of the unplanned operational expenditure of the drivetrain. Due to less high rotating components, the two-stage gearbox is more reliable than both three stage versions. Furthermore, the exchange of a two-stage gearbox is less expensive as the gearbox is lighter and has lower investment cost. A distinction between three stage gearbox with a three point and a four-point suspension is discernible. Due to the non-torque loads entering the gearbox with a three-point suspension system, it is less reliable and leads to higher unplanned operational effort.

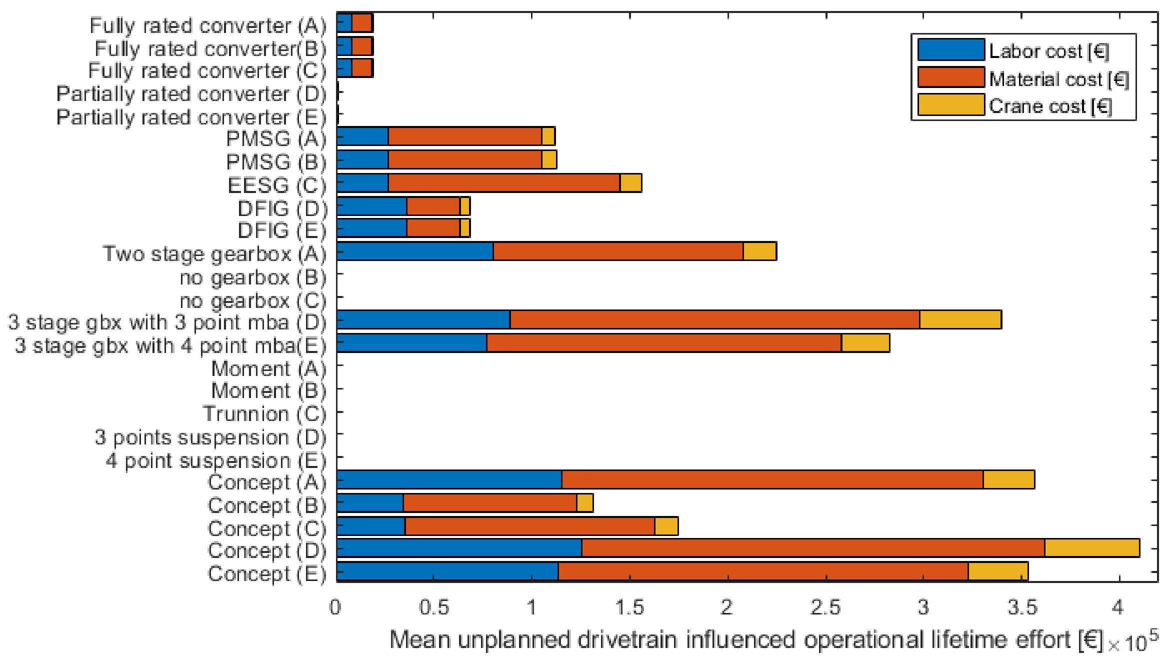

Figure 5: Drivetrain concept comparison

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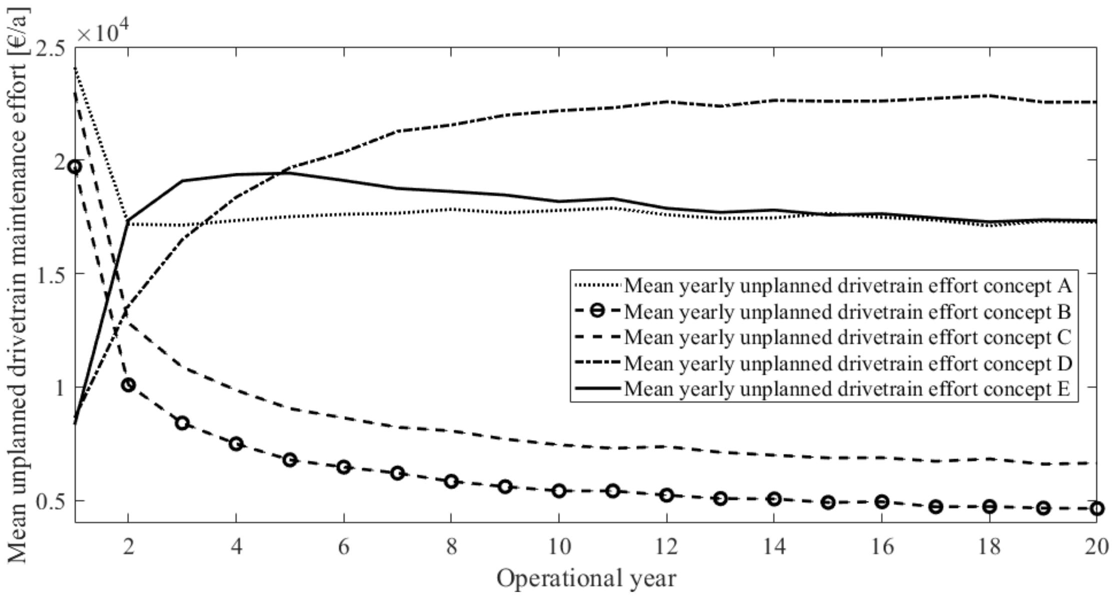

Figure 6: Mean unplanned yearly drivetrain related maintenance expenses for 1,000,000 iterations

Figure 6 gives an overview about the mean unplanned maintenance effort of drivetrain concepts and its development over their lifetimes. For the direct drive concepts, the early lifetime failures of the generators dominate their behaviour. The two-stage gearbox concept with PMSG follows this early failure behaviour on a higher level. For the other concepts with gearbox, wear out behaviour is dominant. Still mean values do not allow a statement about the results certainty. In order to allow a statement about the certainty of this behaviour the range of fluctuation is calculated for a worst-case scenario. The range of fluctuation is defined as the component's individual yearly standard deviation of the components unplanned maintenance effort divided by the mean of the unplanned components maintenance effort c.f. Formula (3):

$$range\ of\ fluctuation(i) = \sum_{j=1}^{4} \frac{\sigma_j(i)}{\mu_j(i)} \tag{3}$$

Worst case is defined, that the range of fluctuation is calculated for each component individually and then added. This analysis is based on 1,000,000 iterations. Range of fluctuation is an indicator of inherent risk. From an inherent risk point of view, the direct drive concepts perform the best compare Figure 6. Still worst case can be 10 – 20 times the yearly mean unplanned maintenance effort. Risk rises until the end of the drivetrain's lifetime. The two three stage gearbox concepts also perform worse from a risk inherent perspective. Especially concept D can have 560 times the mean yearly operational value in a worst-case scenario in the early lifetime. Concept E can result in expenses over 300 times the mean yearly value. For better vividness, the plot is cut at a range of fluctuation of 100. It needs to be kept in mind that the failure behaviour for gearboxes is derived from a lot more data points than the behaviour of the other components. This can lead to a higher deviation as more possible applications are covered. A solely technical cause is questionable.

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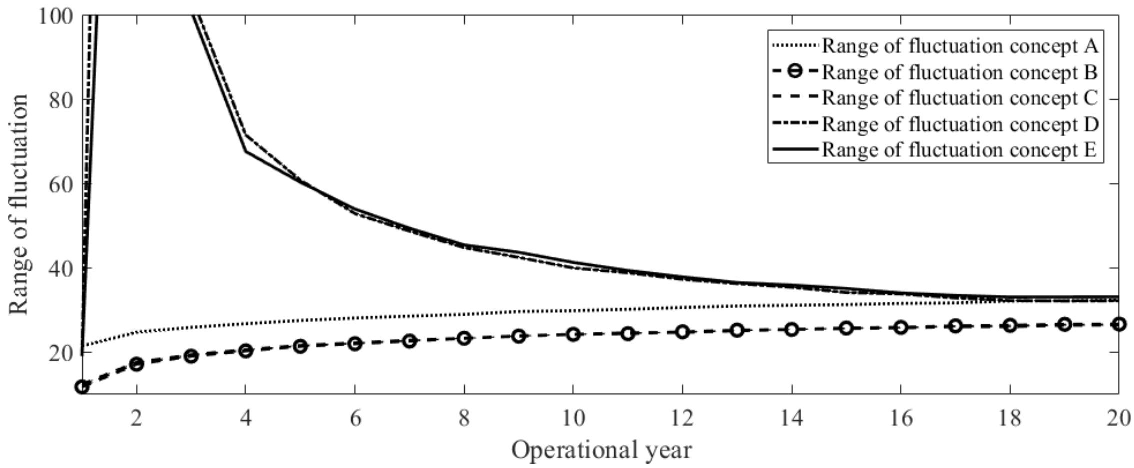

Figure 7: Yearly range of fluctuation of mean lifetime operational behaviour of different drivetrain concepts

8. Conclusion

In order to identify holistically better drivetrain concepts for onshore application, its operational behaviour needs to be taken into account in an early design phase. In this paper, a validated approach for estimating drivetrain concept specific risk of unplanned maintenance effort and technical availability based on open access data is presented. By describing uncertain influencing factors with distributions, the poor data availability in literature and in the early design phase can be used to get an indication about the concepts choice influence on the unplanned operational turbine behaviour. This approach furthermore allows to include information about the concept's behaviour from different applications and different sources. If data availability is low, a triangulation can be applied. By using triangulation incremental innovation and completely new concept ideas can be evaluated as well. In order to get representative comparisons Monte Carlo method is applied. This way a multitude of drivetrain lifetimes can be modelled following the distributions behaviour. The most relevant influencing factors are considered by modelling failure rate, downtime, failure severity and duration of repair and replacement as uncertain factors. Technical availability and drivetrain influenced unplanned maintenance effort are defined as evaluation criteria. The latter is constituted by labour, material and equipment expenses. By calculating the range of fluctuation of the results, this approach offers an indication about the inherent risk in the drivetrain influenced unplanned maintenance effort which is a central criterium. Scalability is given, as material and equipment expenses are scaled with turbine rotor diameter and rated power. This approach shows that openly accessible data or expert estimations are sufficient for comparing different drivetrain concepts over the operational phase in an early design stage. It shows, that most of the component designs failure behaviour can be described by distributions, mainly Weibull distributions. A component design distinction of state-of-the-art concepts is possible this way.

The application of this approach on five state-of-the-art drivetrain concepts for a 3 MW, 120 m rotor diameter turbine shows that direct drive concepts lead to the lowest drivetrain influenced unplanned maintenance effort over the lifetime. Despite of the higher effort for their generator and converter designs they are superior as they can operate without a gearbox. As the EESG investment is more expensive and heavier than the PMSG for the same application, a direct drive with a PMSG is the winner in this comparison. This indication is confirmed when looking on the inherent risk of deviations from these estimated mean values. This concept has the lowest risk of deviating from the estimated unplanned maintenance effort. Concluding the drivetrain concept without a gearbox and with a PMSG performs the best in this comparison in terms of absolute expenses over the lifetime as well as on the inherent risk.

Still it has to be considered, that this analysis is based on sometimes very old and maybe outdated data especially when describing the failure behaviour. Furthermore, the extend of the databases for different component design deviates a lot which might bias the result. Unfortunately, a component design specific distinction of the failure severity is not possible based on open access data up to now. For adapting this method to new concepts, a physically based approach could be developed which would make it possible to estimate probability distributions for the uncertain factors. Another possible direction for research is to include the influence of the maintenance strategy as well as site or park specific impacts in the evaluation. Moreover, this approach only takes the operational phase into account. For identifying holistically superior drivetrain concepts, the entire drivetrain lifecycle needs to be considered. The authors intend to develop approaches for estimating the concepts behaviour in all lifecycle phases of the drivetrain which can deal with the poor data availability in the early development phase. This way they will be able to evaluate different trade-offs within the drivetrain design. Nevertheless, this approach can already assist in the drivetrain concept decision making by being able to quantify the inherent technological risks in the operational phase.

9. Author contributions

Freia Harzendorf did the conceptualization, data curation, formal analysis, methodology development, validation, writing and editing of this paper. Funding acquisition has been done by Prof. Schelenz and Prof. Jacobs.

10. Competing interests

The authors declare that they have no conflict of interest.

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