A Reliability Case Study of the Impact of Tribology on Wind Turbine Gearboxes

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Abstract

This work shows the impact of reliability influencing factors related to tribology on the monetary saving potential. The gearbox reliability was evaluated using an extended Fault Tree Analysis (FTA) with added connections focusing on the tribological influences on the failure rate. A modified Failure Mode and Effect Analysis (FMEA) without accurate reliability connections related to tribology was evaluated for comparison. A 10% improvement in all tribology-related factors in the extended FTA yields 14.96% higher annual failure cost savings, which relates to reduced costs of 22937 €/turbine/year for a 2.5 MW reference turbine. The extended FMEA estimates the saving potential to be 4.99%. The study demonstrates the importance of integrating tribology expertise and cooperation between park owners, manufacturers, suppliers, and academia. Our results demonstrate that even marginal tribological improvements significantly increase wind turbine reliability and monetary savings confirming that tribology, despite being overlooked, is a powerful reliability enhancement tool.

1. Introduction

The share of renewable energy has to increase to face the climate crises and reach the related national and global agreements [1]. To achieve this, we need to increase the availability and reliability of renewable energy by improving state-of-the-art technology and introducing new technologies. During the last decades, wind turbines have grown steadily, both in numbers and in size, and their performance improved continuously [2]. The worldwide installed wind turbine capacity, recently reported, is 743 GW [3], with an annual electricity production of 1591 TWh [4].

The performance and economics of energy systems are often measured by using the levelised cost of energy, representing the average merits per unit of electricity, including building and operating the system. A comparison of the levelised cost of energy of different energy systems allows an economic categorisation of such systems to be made [5]. The system performance can be enhanced through various measures like increasing the power output, decreasing the production, installation and operating costs, and improving availability. Due to the importance of performance, most research on wind turbines aims to contribute to one of the above-listed measures. As operating costs and wind turbine availability are highly affected by the reliability of subsystems and components, a substantial amount of publications covered this topic, for example, [6, 7, 8, 9, 10].

Failure rate statistics help to understand the failure rates of different subsystems. Even if the taxonomy differs between the publications, the subsystems can be approximately divided into blades, generator, gearbox, and tower. An analysis of 1500 wind turbines showed that the generator, gearbox, and blades were responsible for the highest failure rates in wind turbines that were smaller than 1 MW [11]. Seventy-two wind turbines located in Finland were reported to have the highest failure rates of the gearbox and the generator [12]. The highest failure rates for generators, gearboxes, and blades were also detected by analysing the data for 350 wind turbines in Europe over five years [13]. Differences between onshore and offshore wind turbines were reported in [14]. Most studies recognised high failure rates of the wind

turbine gearbox. Due to the complexity of maintenance and repairs in the gondola, these failure statistics go hand in hand with extended turbine downtime. The gearbox handles complex load situations and allows power transmission from the hub to the generator. Typically, power transmission in the gearbox is done by a combination of planetary and parallel stage gears.

Several publications highlighted the failure rates of bearings in wind turbine systems [15, 16, 17]. A good overview of component-based failure analysis for wind turbines can be found in DAO ET AL. [18]. In the study of Swedish wind farms in 2007, the gearbox was revealed as a critical component [19]. The gearbox was responsible for 9.8% of all failures, which led to 19.4% of the total turbine downtime. The average downtime due to bearing damages was around 562 hours. 87.8% of bearing failures were caused by wear. Most of the bearing issues can be related to tribological problems.

In 1966 the "JOST-Report" introduced the term "tribology" and revealed that the costs of friction and wear for the British economy were equal to 1.1–1.4% of the gross domestic product [20]. As a result, the government-financed several research centres to develop technologies for reducing friction and wear. Since then, the term tribology has been used for the science of friction, wear, and lubrication [21]. Today power densities of modern machines are much higher, and their operating conditions are more complex, not least due to the electrification of the automotive industry and rapid growth of green power production, which lead to new tribological challenges [22].

The importance of wind turbine reliability and tribology are well known, but a connection between them was surprisingly overlooked in the published literature. Investments to enhance tribological solutions in the wind systems have also been difficult to justify economically.

In this work, we demonstrate the impact of tribology on wind turbine gearboxes. Available wind turbine failure data are analysed from a tribology perspective. The analysis sheds light on the difficulties with the interpretation and use of such data. Hybrid Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA), including the implementation of failure cause relation and cost of failure, are accomplished in a case study. The work is the first study that entirely focuses on the tribology-related failure rates in wind turbine gearboxes and highlights the saving potential for the wind power industry. The result is a quantified statement of the tribological impact on wind turbine gearbox reliability.

2. Methodology

We use failure data and simulation models to deliver a probabilistic perspective on the impact of tribology in wind turbine gearboxes.

The model methodology is shown in Fig. 1. We use a standard reliability failure model that can relate assembly failure rate to failure cause (section 2.3). This model is coupled with a reliability influencing model (section 2.4), which relates failure causes to the underlying factors. The failure rate of the assembly is multiplied by the cost of failure (section 2.5) to achieve the probabilistic gearbox failure cost. The basis of the simulations is to induce a particular deviation of the initial failure cause or reliability

influencing factors of one or more components, which can be freely selected in the simulation environment. For our research, failure rates and influencing factors that can be improved with tribology-based solutions are in the foreground. The deviations in the case study are chosen based on our experience and available scientific literature. In our study, we show the impact on annual savings that would result from the improvement of all tribological influences. Complementary, we analyse the impact of the parameter Bearing Lubrication Quality on annual savings.

All dependent parameters in the reliability influencing model are changed by the same amount. For example, a 2% change in a specific reliability influencing factor changes each dependent failure cause by 2%. These failure causes are used to calculate the gearbox failure cost. The results are applied to a 2.5 MW turbine to show the economic impact that can be achieved by implementing tribological improvements.

2.1. Wind turbine gearbox

The design and components of wind turbine gearboxes depend on the type of wind turbine and the drivetrain configuration [23]. Gearboxes in wind turbines usually include a planetary stage, followed by a planetary or parallel stage. A typical 2 MW wind turbine gearbox may have 20 bearings and nine gears [24]. A schematic representation of a gearbox is displayed in Fig. 2. This gearbox has a planetary stage (PL), a low-speed stage (LS), an intermediate-speed stage (IM), and a high-speed stage (HS) with the related bearings, shafts, and gears. A complete gearbox lubrication system includes components like a lubricant, seals, a pump, filters, and pipes and is sometimes considered a part of the gearbox assembly.

Gearboxes are highly loaded components making them susceptible to failures. Figure 4 shows different wind turbine assemblies' average failure rates across databases. With less than 0.5 annual failures per turbine with some outliers even higher than 1.0, the gearbox seems to be not the most significant source of failures. But if the linked downtime per failure, see Fig. 5, is taken into account, it becomes apparent that a gearbox failure can lead to more than 200 hours of annual downtime. This is a significant factor.

2.2. Wind turbine failure data

Detailed investigations of modern wind turbine failure statistics were provided in [19]. They summarised failure data from Swedish, Finnish, and German wind turbines from 1997 to 2005. The ReliaWind project is another source of wind turbine failure statistics from northern Europe. The project includes onshore data from Windstats Germany, Windstats Denmark, and LWK Germany databases [25]. The DOWEC project was established in the late 20th century to provide insights into the feasibility of offshore wind turbines [26, 27].

All open-access databases that are frequently used in the scientific literature are consolidated in Table 1 by using information from [18, 28]. From this table, several observations can be made:

- Most databases are at least a decade old. Most databases consider turbines with a rated power lower than 3 MW.

- Most databases consider onshore turbines. Another point to consider is variations in wind turbine failure information. Subsystem-wise failure information is shown in Fig. 3. Note that not all studies have assembly-wise bifurcated failure data. Hence not all the studies mentioned in Table 1 can be used for the plots. For example, not enough downtime data is available for Nacelle or Tower system to generate a box plot in Fig. 4. The gearbox causes the highest mean downtime with a distinctly high outlier. Some of the underlying reasons for the problems with failure databases are:

- Failures of wind turbines are heavily influenced by the location and environmental conditions [55] as well as turbine design [56]. Local wind speed can also significantly affect the failure rate of wind turbines [57].

- Taxonomy across these failure data sets is not consistent, even to the point where a failure definition can differ across databases [58].

- Most failure reports are still based on manual record-keeping. This is susceptible to human errors and subjective differences. [59]

- Most failure data do not include information about the manufacturer and model of the wind turbine. Market competition makes disclosure of such information problematic for manufacturers.

- The reliability data sets are derived from the on-site failure reports, which at most provide information about the system that failed but not the cause or the exact component behind it.

- Most wind turbine failure data are generally 10 to 20 years old.

Accessible data sets for the analyses of tribological components are rare. An alternative approach to deal with this problem was reported in [60]. Accessible data sets for the analyses of tribological components are rare. An alternative approach to deal with this problem was reported in [60]. It was shown that at least for well-studied and understood core mechanical assemblies, like gearboxes and blades, reliability data for their constituent components could be generated using industry standards, data sheets and failure information of similar parts in other machinery [60]. None of the data sets in themselves provides component-level failure information required to investigate tribology-induced failures.

Table 1. Summary of wind turbine failure databases

DataBase	Country	No. of WTs	Location	WT Rating(MW)	Years	Failure Rate	Source
CIRCE	Spain	4300	Onshore	0.3-3	3 y, ~2013	0.481	[29, 30]
CREW	USA	800-900	Onshore	0.05-3	2011-2015	-	[31, 32, 33]
CWEA	China	640	Onshore	1.5-6	2010-2012	7.167	[34]
East China	China	108	Onshore	1.5-2	2009-2013	-	[35]
EPRI	USA	290	Onshore	0.04-0.6	1986-1987	10.195	[36]
Huadian	China	1313	Onshore		2012	0.846	[37]
India	India	15	Onshore	0.225	2000-2004	-	[38]
LWK	Germany	643	Onshore	0.225-1.8	1993-2006	1.855	[39]
NoordzeeWind	Netherlands	36	Offshore	3	2007-2009	-	[40, 41, 42]
Round 1 UK	UK	120	Offshore	2-3	2004-2007	-	[43]
SE China	China	134	Onshore	1.5	2011	-	[44]
SPARTA	UK	1045	Offshore	2-6	2015-2016	15.84	[45]
Strathclyde	Europe	350	Offshore	2-4	5 y	8.273	[13, 46]
Sweden	Sweden	723	Onshore	0.055-3	1997-2005	-	[47, 19, 48]
VTT	Finland	72	Onshore	0.075-3	1996-2008	1.45	[48, 49, 50]
Windstats (DK)	Denmark	2345	Onshore	0.1-2.5	1994-2004	0.434	[51, 39, 52]
Windstats (GR)	Germany	4285	Onshore	0.1-2.5	1995-2004	1.796	[51, 39, 52]
WMEP	Germany	1500	Onshore	0.03-1.8	1989-2006	2.606	[53, 54]

2.3. Failure model

As shown in the previous section, the selected data significantly influences simulation results, and tribological failure analysis requires detailed data that are rarely publicly unavailable. Hybrid reliability tools such as FMEA and FTA can utilise expert knowledge in conjunction with numerical data to extrapolate information about the system. While several methodologies allow a combination of numerical and qualitative data to obtain sufficient estimations, FMEA and FTA provide the best accuracy for the limited data [61].

FMEA was used in a wind turbine reliability study as reported in [62]. This highly efficient reliability tool enabled the inclusion of the cause of failure in reliability studies, a feature that was previously limited to assembly-level failure. An improvement in terms of a quantitative approach to FMEA was introduced later, with numerical turbine failure data, number of turbine faults reported and cost of failure replacing qualitative ranking. The output of this methodology was a very practical value of the probabilistic failure cost of wind turbines [63]. This work was further expanded in [64] with a detailed breakdown of wind turbine failure modes, presenting a comparison between the critical assemblies in offshore and onshore wind turbines. Similar work with FMEA was carried out in several other studies with some variations [65, 61, 66]. FTA methodology was also used to calculate wind turbine reliability by breaking down the wind turbine into sub-assemblies and further down to its components to investigate the primary cause of failure [67].

In order to be able to analyse tribological problems in a gearbox, an extensive data set and a link between failure and cause is required. Research work reported in [24] and [68] provides a reliability estimation model based on FMEA and FTA, respectively. The models take into account the failure causes of corresponding components of wind turbine assemblies. This is the approach we use in our study, as both sources provide the required level of detail and contain data that are necessary for the targeted tribological focus. We use both models to demonstrate how the disparities caused by different data sources and assumptions may influence the results.

- Bottom - Up approach: FTA

This approach is adapted from [68]. The approach starts by developing a wind turbine Gearbox Fault Tree (Fig. 5a), which breaks down the overall gearbox failure into its basic failure events. Similar to [60], experimental data, data from similar systems, and estimates are used to obtain the failure rate of basic events that are not available otherwise. These quantitative basic event failure values are then, with the help of Bayesian probability, used to calculate the top event, which is the gearbox failure rate.

- Top-Down Approach: FMEA

Wind turbine FMEA analysis [24] focused on the gearbox and included expert knowledge to qualitatively state the probability of the contribution of a particular failure mode to the total failure of the sub-assembly. Furthermore, a similar approach was undertaken to generate weights for the influence of

failure causes on the failure mode. Using these probabilistic weights, it is possible to point out the contribution of a particular failure cause to the overall failure of the gearbox and sub-assembly failure data. The contributions of failure causes are calculated based on [60].

2.4. Reliability influencing factors

The idea of Reliability Influencing Factors (RIFs) is based on the following definition:

"A RIF is a relatively stable condition, which by being changed will increase or reduce the failure rate of the item." [69]

A RIF can be an external condition, such as wind that induces vibration, or component-specific, like the surface roughness in a bearing. The RIFs are grouped into categories based on the component they belong to. Figure 5b shows an example of such grouping and the failure cause relation. For the component Gear, the RIFs are design properties like material quality, surface hardness and surface roughness. Changing the RIF brings a change in the associated failure cause. All the major RIF - failure cause interactions for gears are presented in Fig. 5b. The two independent reliability models were extended by coupling them with distinct RIF connections. In the extended FMEA model, we use the same RIFs as those stated in [24]. For the extended FTA approach, we use different RIFs, which are shown in Table 2. Oil bath lubrication is often used in wind turbine gearboxes, where the same lubricant is supplied to the gears and bearings. There are, however, solutions with separate lubrication systems. In our study, the lubricant impact on bearings and gears is analysed separately by using independent RIFs - Bearing Lubricant Quality and Gear Lubricant Quality. Further details on the influencing factors for wind turbine gearboxes can be found in [70, 71, 72].

Table 2
RIFs used in FTA approach

Component	Reliability Influencing Factor	Component	Reliability Influencing Factor
Bearing	Surface Hardness	Gear	Gear Design
	Surface Roughness		Material Quality
	Bearing Design		Surface Roughness
	Material Quality		Surface Hardness
Lubricant	Bearing Lube Quality	Other	External Vibration
	Bearing Lube Contamination		Temperature
	Gear Lube Quality		Environment
	Gear Lube Contamination		Filter Design

2.5. Including the cost of failure

A gearbox mainly consists of bearings, gears, shafts, and auxiliary components such as the lubrication system (pump, filters, etc.) and seals. While timely inspection and repairs can prevent failure, the failure definition used in our study specifies that at least one component has failed and requires manual repair or replacement. Replacement strategies can involve replacing only the failed components to save costs. This may not be the most cost-effective method, as pointed out in [73]. Their initial analysis indicates that replacing all the bearings, even if a single bearing failure is observed, would result in the overall lowest operation and maintenance costs [73]. However, according to [74], single-component replacement or repair is much more beneficial and applied in the industry when a fault is detected. Furthermore, the study [74] provides the following gearbox repair conditions, which are adopted in our work:

- Gear fault: replace all gears and bearings
- Bearing fault: replace all bearings
- Lubrication system failure: replace appropriate lubrication system components

The cost of failure comprises four major constituents: cost of replaced parts, cost of service, which includes all facilities and devices needed to make the repair/replacement, cost of labour, and opportunity cost [63]. The data for the cost of parts/components, cost of service(crane rental costs), and cost of labour are taken from [74] and adjusted for inflation. Opportunity costs are derived from Eq. 1:

$$C_{opp} = P \bullet C \bullet R \bullet t_{down}$$

1

Rated power of the wind turbine P is assumed to be 2.5MW. The Capacity factor C of the wind turbine is taken to be 0.41 [14]. R is the commercial cost of energy production. It is assumed to be 0.06 €/kWh. Downtime t_{down} is the total inactive time of the turbine due to a failure.

Downtime per failure may vary from 0.18 to 7.29 days across databases [28]. For a gearbox, this variation accounts for 0.3 to 25.08 days per failure and is probably due to the different nomenclatures across databases. The average failure downtime of 2 to 3 MW turbine subsystems was reported in [61], showing that downtime could vary significantly based on the component that required repair or replacement. This component-wise variation was estimated by using the Strathclyde data [13]. The Strathclyde data provide repair time information, which, unlike downtime, does not include travel time, lead time, and other time losses. The data split all repairs into minor repairs, major repairs, or major replacements. We assume that bearing and gear failures represent a major replacement while a lubrication system failure represents a major repair. Furthermore, we assume equal failure rates and repair ratios for onshore and offshore data. With these assumptions and using Eq. 2, 316 hours of downtime for major replacements (gears and bearings) and 30 hours for major repairs (lubrication system) are identified.

$$d_{replacement} = d_{avg} \frac{\lambda_{replacement} + \lambda_{repair}}{\lambda_{replacement} + r_{repair2replacement} \lambda_{repair}}$$

2

$d_{replacement} =$ is the downtime of a major failure and d_{avg} is the average downtime reported in [61]. $r_{repair2replacement}$ is the ratio of gearbox major repair to major replacement downtime and $\lambda_{replacement}$ is the failure rate for major gearbox replacement, taken from [13]. The final numerical data used for the failure cost calculations are summarised in Table 3.

Table 3
Data used in this study and cost of failure

Failure	Component[74]	Crane[74]	Labour[74]	Downtime	Opportunity	Total
Gear	431 135 €	290 653 €	17 439 €	316 hr	19 434 €	758 661 €
Bearing	139 513 €	290 653 €	7 750 €	316 hr	19 434 €	457 350 €
Lubrication system	3 875 €	0	484 €	30 hr	1 845 €	6 204 €

3. Results

The results of the bottom-up extended FTA simulation approach are discussed in detail in this section.

The focus is on the quantification of the impact of tribology on the failure costs of the wind turbine gearbox. A sensitivity study is performed to validate the results. The simulation results for the failure rates are applied to the 2.5 MW turbines to demonstrate the economic impact.

3.1. Sensitivity study The sensitivity study shows how different values of an independent variable affect a particular variable. In our study, we analyse the sensitivity of certain improvements on Gearbox Failure Cost by simulating a fixed percentage change of one factor (Failure cause or RIF) at a time while keeping the others constant. Figure 6 shows the changes in gearbox failure costs due to a decrease in failure rates by 5%. The Corrosion of Pins and abrasive wear in the bearing has the most impact. Both failure causes can be improved by optimised tribology-based design.

The impact of investments in the RIF improvements has an essential role in economics. Figure 7 shows changes in gearbox failure costs due to an improvement of RIFs by 5%. The RIFs are grouped into the following categories: Bearing, Lubricant, Gear, and others. Bearing Lubrication Quality emerges as the most influential RIF in terms of reducing failure cost and is followed by Bearing Lubricant Contamination and Bearing Surface Hardness and Roughness. These factors highlight the need to investigate bearing tribology in wind turbine gearboxes in more detail.

3.2. Extended FTA Simulation

The FTA-based simulation model was used to make quantitative estimations of the impact of tribology on wind turbine reliability. The analysis is performed with a particular improvement on each tribological

RIF simultaneously, implying that all connected failure causes are influenced simultaneously. The estimated economic impact is presented as a function of the percentage improvement in the tribological RIFs in Fig. 8. An improvement of 5% in the gearbox tribology results in an overall annual cost savings of 13470 €/turbine, which is an 8.78% saving in the total annual gearbox failure cost. If this improvement is implemented in a wind farm of one hundred 2.5 MW turbines, the farm owner will save 29.6 million Euros in a period of 20 years. Figure 8 shows how further RIF improvements increase the gearbox failure cost savings. A 25% RIF improvement leads to 32.05% higher savings. If all tribological problems are eliminated, i.e. a 100%RIF improvement RIF, an ideal final result would give 72.76% savings. In general, it is difficult to provide an exact estimate of how much improvement is possible [75]. For example, a 5% target can be achieved relatively easily, while advanced measures such as new materials and lubricants are required for 25%. The most interesting finding is that the graph shows the highest slope at the beginning, which implies that even small tribological improvements may give significant savings.

3.3. Sample Case - Bearing Lubricant Improvement

Bearing failures are connected to non-tribological reliability influencing parameters of Bearing Design and Bearing Material Quality and also to several tribological parameters like Bearing Lubricant Quality and Surface Properties. We focus on Lubricant Quality since it can be improved relatively easily by changing the lubricant. The research reported in [76, 77, 78, 79] deals with gearbox power losses due to lubrication. The results focus on the friction and power losses, whereby an influence on the RIF can be deduced. Since the deviations in friction and losses are up to 30% between various oils, we conservatively assume an improvement of Bearing Lubricant Quality by 10%. In-depth adjustments to this RIF, as described in [75] can lead to even greater long-term improvements. This conservative estimate of 10% better Bearing Lubricant Quality will lead to annual savings of 9940 Euros per turbine.

Modern experimental methods allow the tailoring of lubricants for a particular application targeting specific causes of failure. Table 4 presents examples of three such lubricating oils with different performance impacts on the Corrosion of Pins, Abrasive Wear, and Surface Fatigue. A positive value represents an increase in the failure rate.

The values in Table 4 indicate Lubricant A as the most promising candidate, while Lubricant B only saves 200 €/turbine/year. Lubricants A and C are very similar, with one having more influence on abrasive wear while the other one on Surface Fatigue. This slight difference leads to 600 €/turbine/year savings or losses. Lubricant A provides potential savings of 2545 €/turbine/year. For one hundred 2.5MW wind turbines, designed to have an operational life of 20 years, the total savings will be more than 5 million Euros due to the reduced gearbox failure rate.

3.4. Influence of RIF Connections and Input Data

Reliability studies are influenced by the available data and the connection between failure and effect. We used both the FTA-based model and the FMEA based model, as described in Section 2.3. The approaches use different databases and RIF connections.

In comparison to our FTA approach, the FMEA approach, adapted from [24], does not focus on tribology. As a consequence, the failure cause connections are somewhat obscure. For example, the failure cause Improper Lubrication of the bearing is not connected to Smearing, Fretting Corrosion or Contact Fatigue, although these connections are shown in failure atlases and scientific literature i.e [80, 81, 82, 83, 84]. The differences between cost-saving estimations derived by the used extended FTA and FMEA approach are shown in Fig. 9 which depicts how the models react to improvements of all RIFs related to tribology. Due to the differences in failure-cause connections, the models predict significantly different saving potentials.A50%improvement in tribology related RIFs gives the annual failure cost savings of 50.70% for the FTA and 24.94% for the FMEA. This highlights the importance of developing and incorporating the RIF connections in the modelling. The failure causes must also be linked to one another to further improve the simulations, as, for example, spalling can be influenced by false brinelling [81]. By actively involving tribology experts in the model development, prediction analysis and maintenance planning, reliability and economic estimations will be significantly improved.

The absolute values of the estimated failure cost of the models show differences due to the input data used. The FTA input uses a gearbox failure rate of 0.34/year [68], while the FMEA input uses a 0.13/year failure rate [24]. The models are indeed sensitive to the input data, but this does not influence the comparison shown in Fig. 9, due to the dimensionless scales.

4. Discussion

Overall, gearbox failure costs are shown to have the highest sensitivity to the variations in the lubricant properties. Furthermore, among the observed failures, bearing failures make up more than two-thirds of all gearbox failures, as highlighted previously [85]. This trend also translates into the gearbox failure costs, shown in Fig. 6.

A higher failure rate for bearings can be partially attributed to their high number in the gearbox. Arguably formulation of a lubricant that is optimum for the gears and bearings at the same time is still an outstanding engineering challenge. Anti-wear additives in gear lubricants are essential to forming sacrificial wear reducing films in gear contacts, but such additives may be damaging for the rolling element - raceway contacts in bearings. Corrosion of Pins is a failure mode that occurs due to moisture or friction, sometimes loosely referred to as fretting. This failure mode is closely followed by Abrasive Wear as the leading failure cause of the bearings in the wind turbine gearboxes.

Bearing Lubricant Quality shows the highest impact, according to Fig. 8, which reflects on the sensitivity of different RIFs to gearbox failure costs. Bearing failure modes are primarily contact wear SHENG ET AL. [86, 85]. Improving lubrication hence has a direct influence on the failure rate of all these failure modes.

Complete elimination of tribological failures would save 72.76% of gearbox failure costs, as shown in Fig. 9. The graph has the highest slope for small improvements. Therefore, even marginal tribological improvements provide a significant impact on the saving potential. For example, just a 10% improvement in tribological RIFs will lead to 14.96% annual failure cost savings.

5. Conclusions

The results of this study highlight the importance of considering tribology in the reliability analysis of wind turbines. The study points out the challenges with existing failure databases and the lack of detailed failure data for tribological studies. While the importance of tribology was previously noted, this study succeeds in incorporating tribology into the reliability analysis and quantifies the impact of tribology in terms of potential economic benefits to wind turbine owners. Our case study shows that the annual gearbox failure costs can be reduced by 14.96% by improving tribology-related reliability influencing factors by 10%. This relates to savings of 13470 €/turbine/year and shows the importance of integrating expertise in tribology and cooperation between park owners, manufacturers, suppliers and academia. In a case study, we showed the impact of improving bearing lubricant quality by 10%. Such an improvement is easy to implement by changing the lubricant. Furthermore, the costs of improving lubricant quality are lower compared to the redesign of mechanical components. The lubrication improvements could lead to a saving of 9940 €/turbine/year in our case study. An important finding is that even marginal improvements in tribology significantly enhance the saving potential.

Declarations

Conflicts of Interest: *No potential conflict of interest was reported by the authors.*

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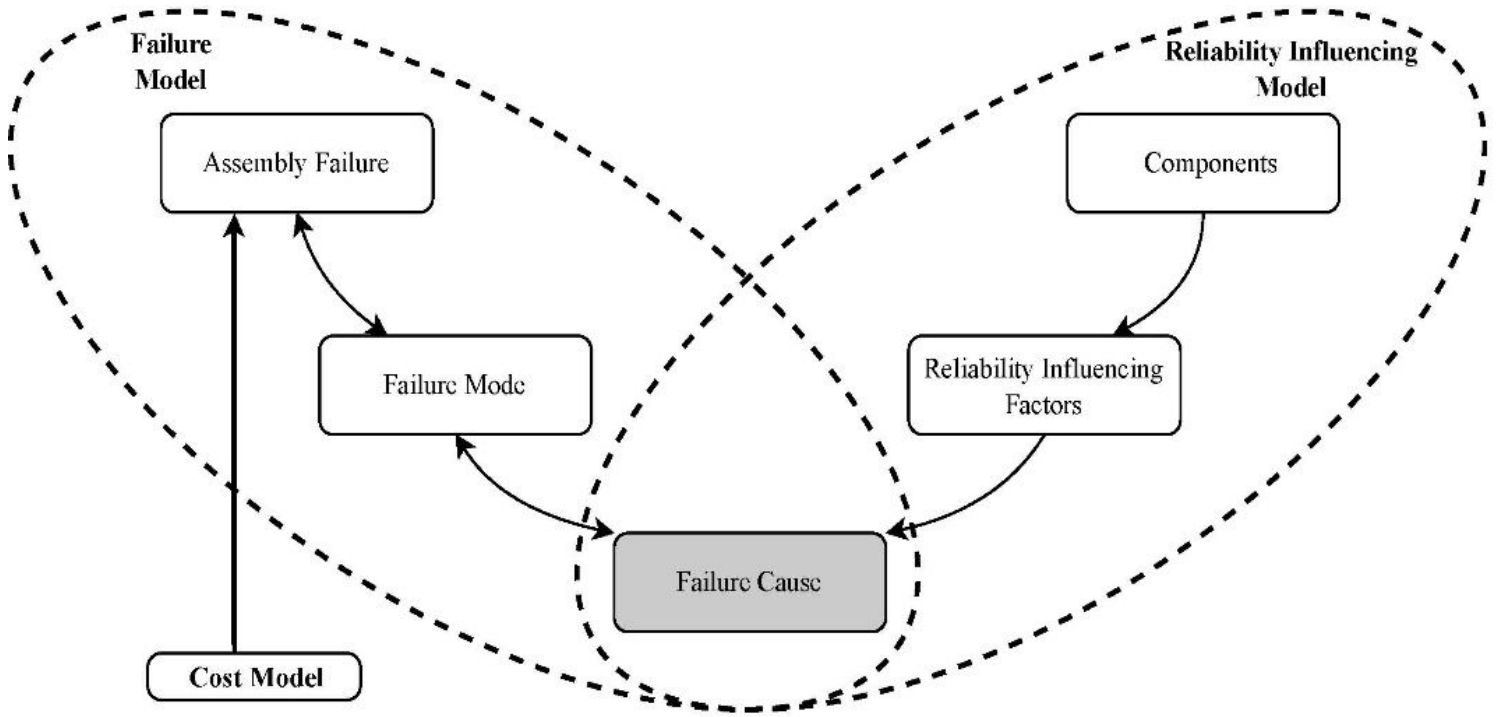
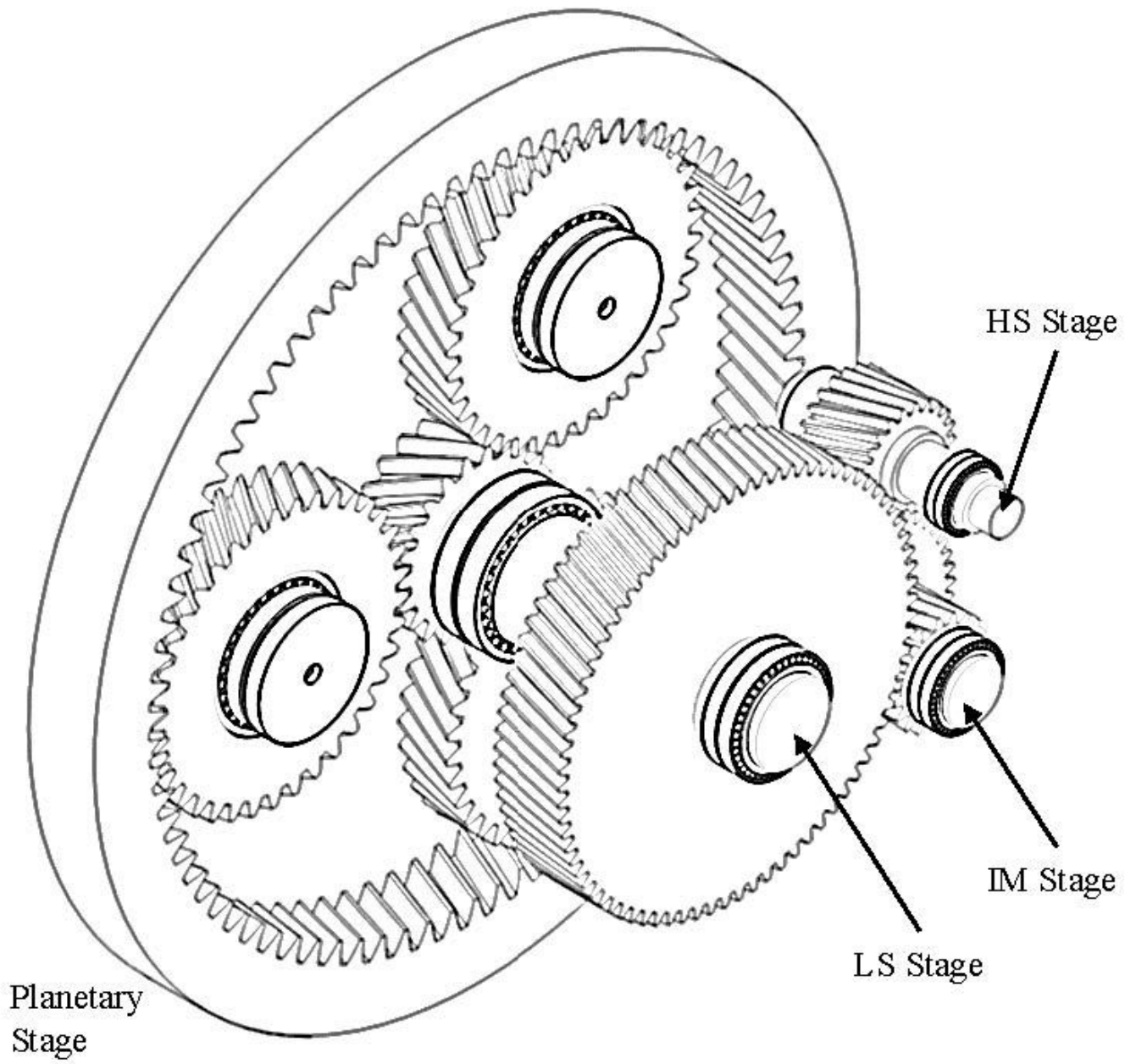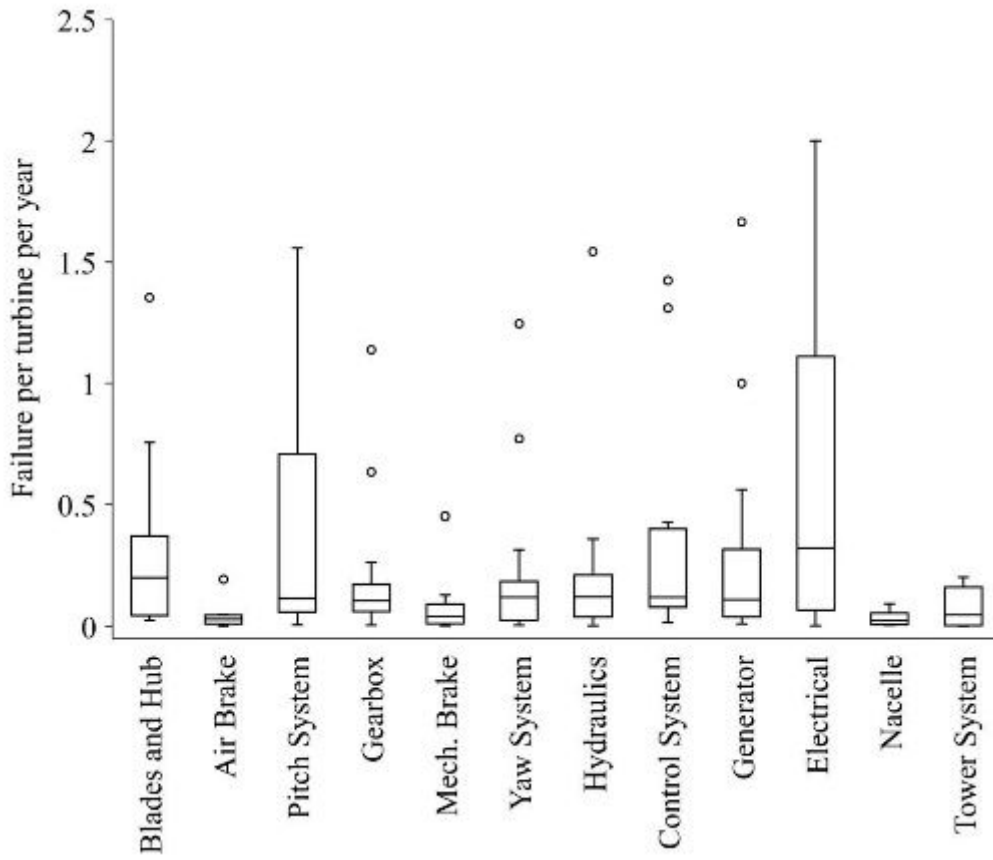# Figures

Figure 1

Model Methodology

HS Stage

IM Stage

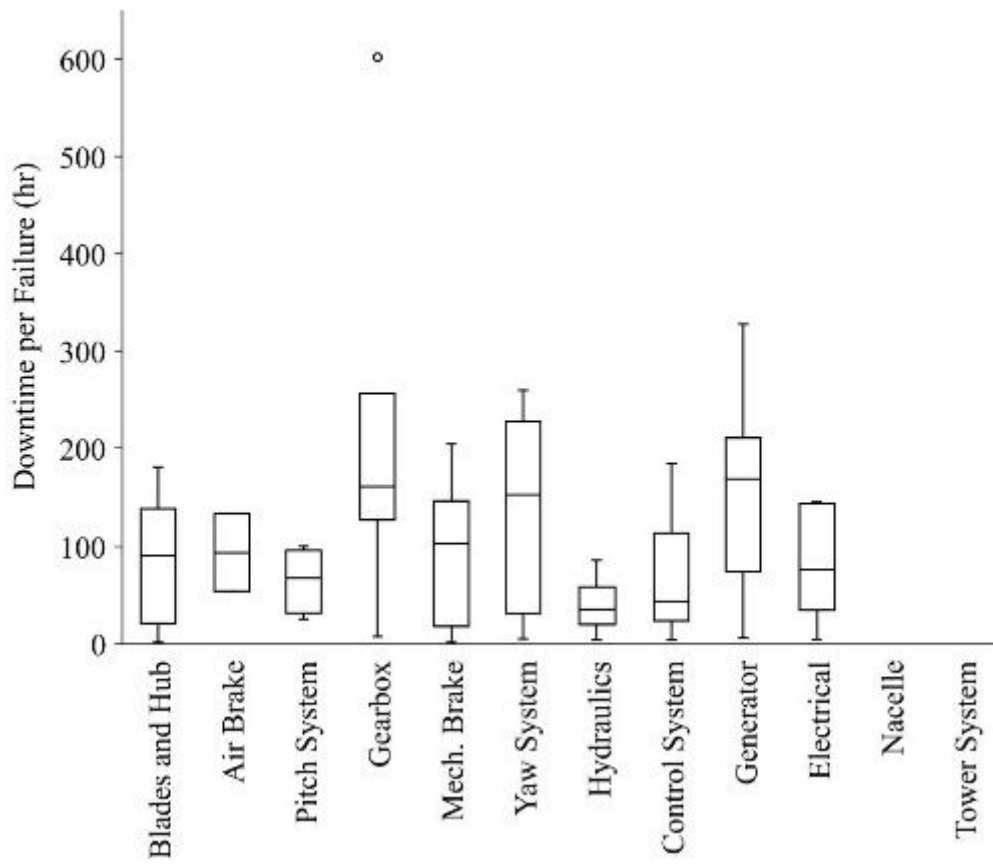LS Stage

Planetary Stage

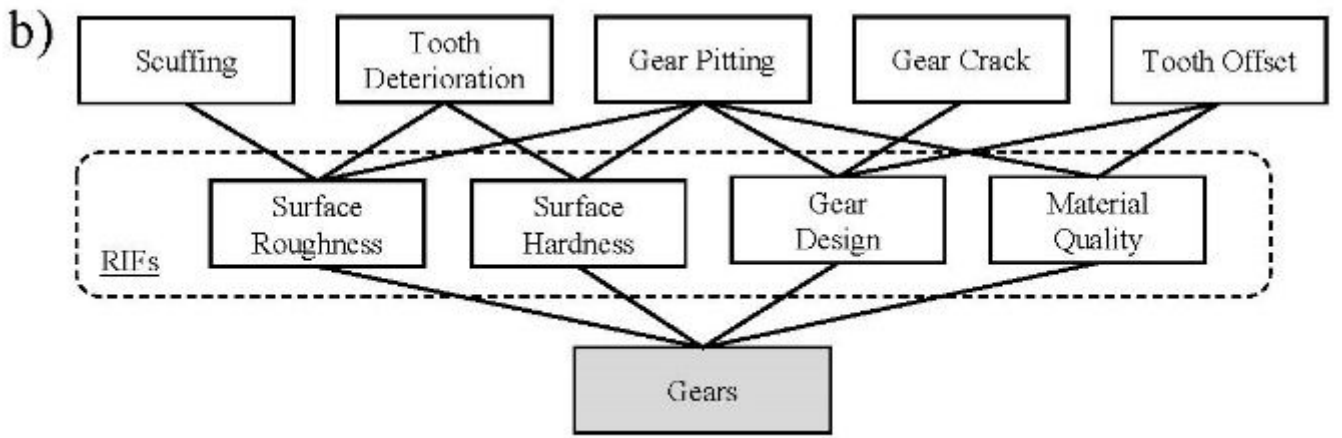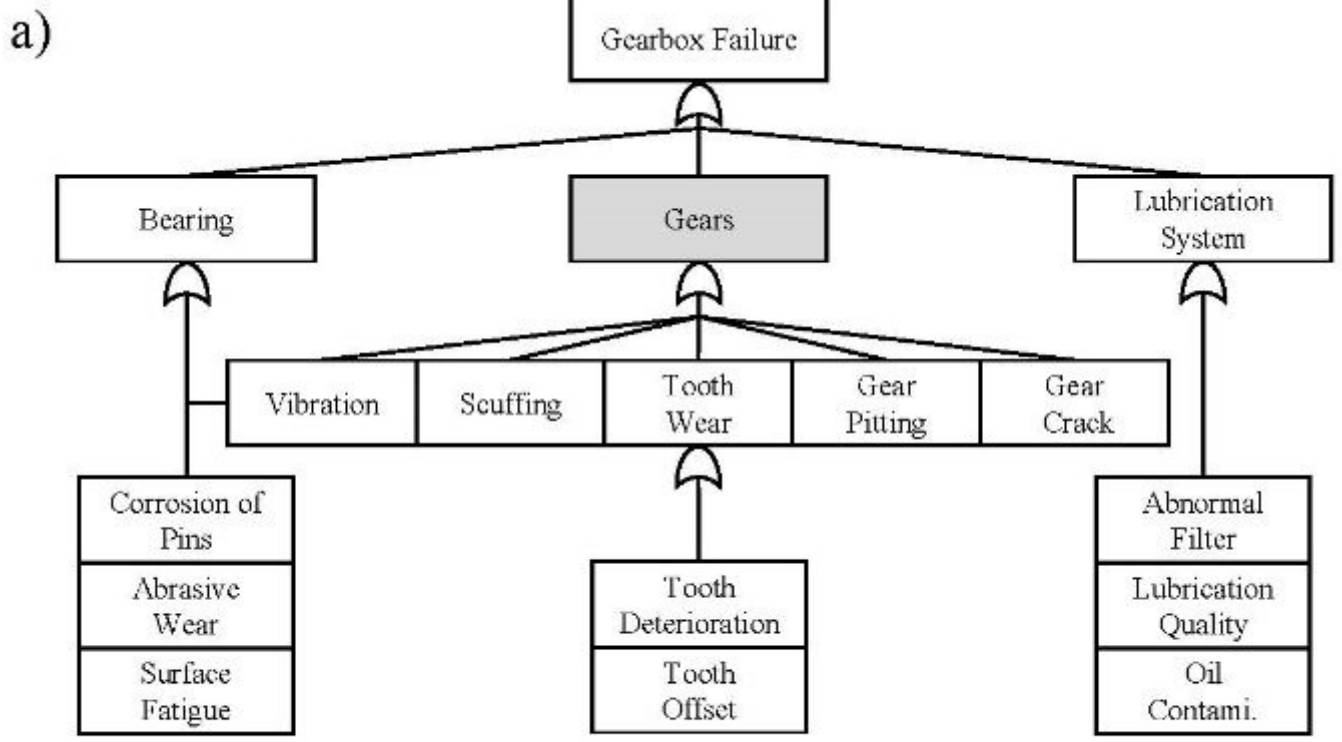**Figure 2**

Gearbox Schematic

Figure 3

Average assembly failure rates in failures per turbine per year across databases.
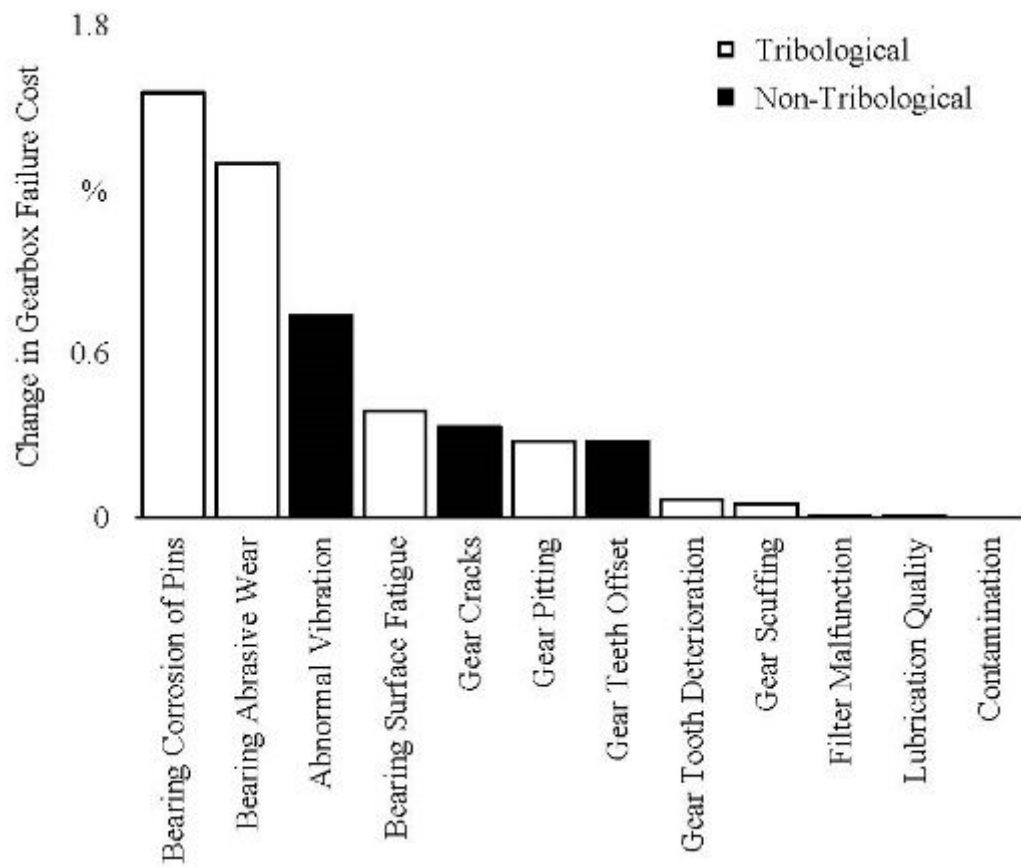
Figure 4

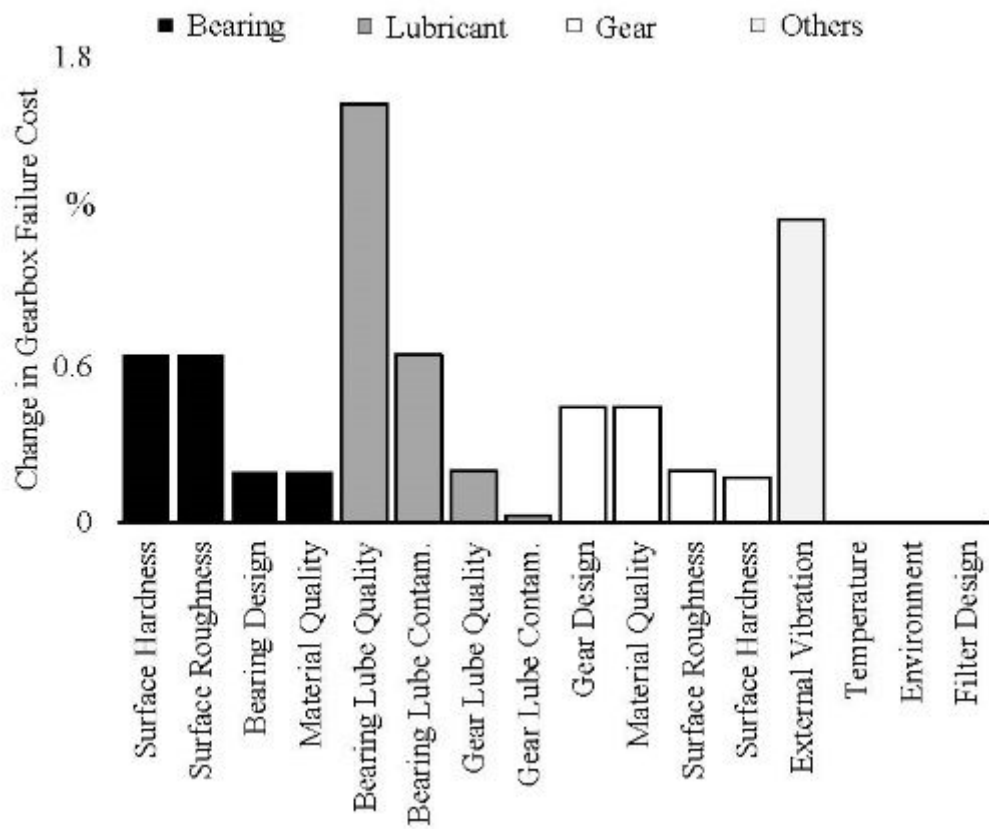Average assembly downtime per failure across databases

Figure 5

a) Gearbox Fault Tree Analysis according to [68] b) Component Reliability Influencing Factors and Failure Cause Relations
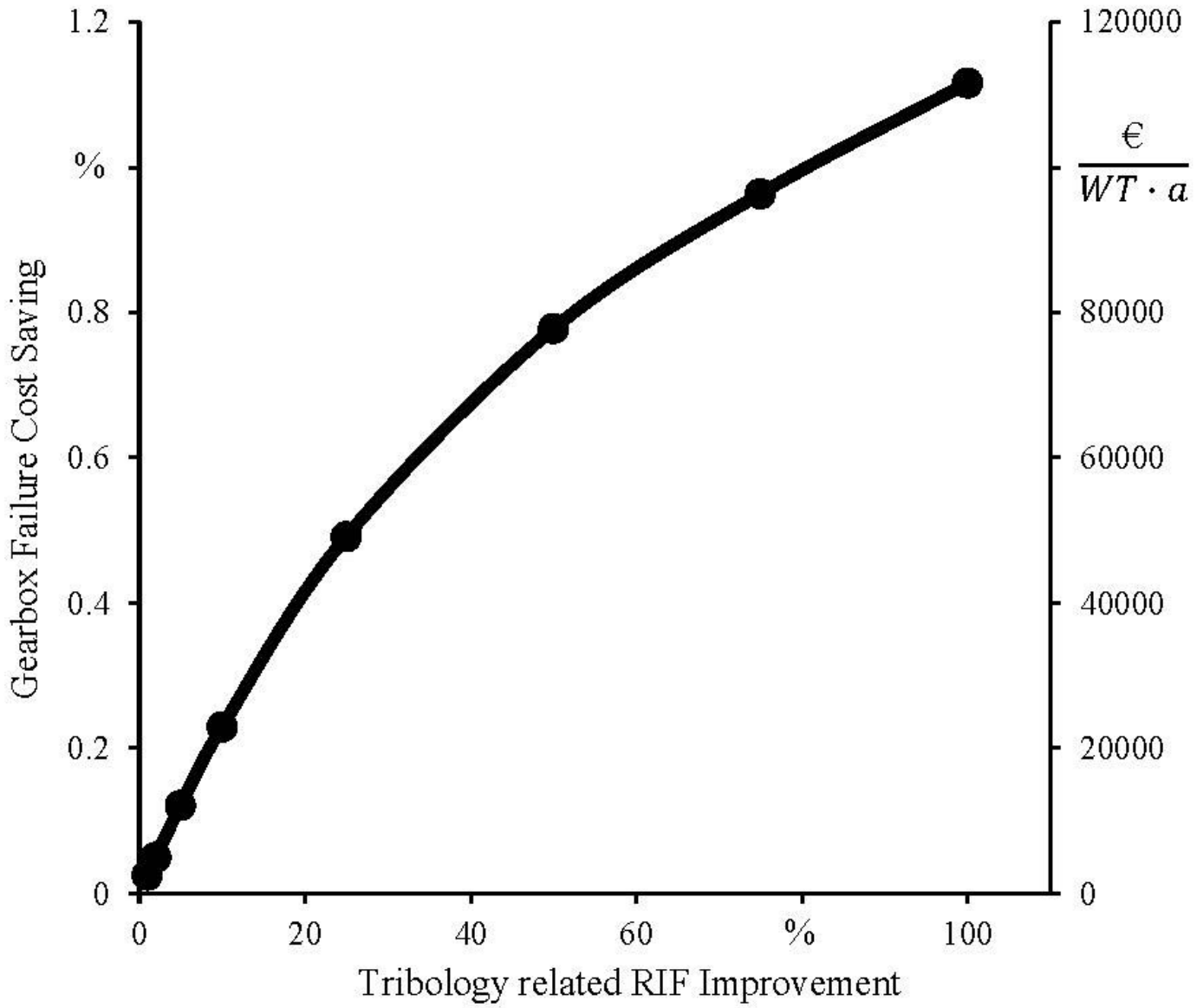
Figure 6

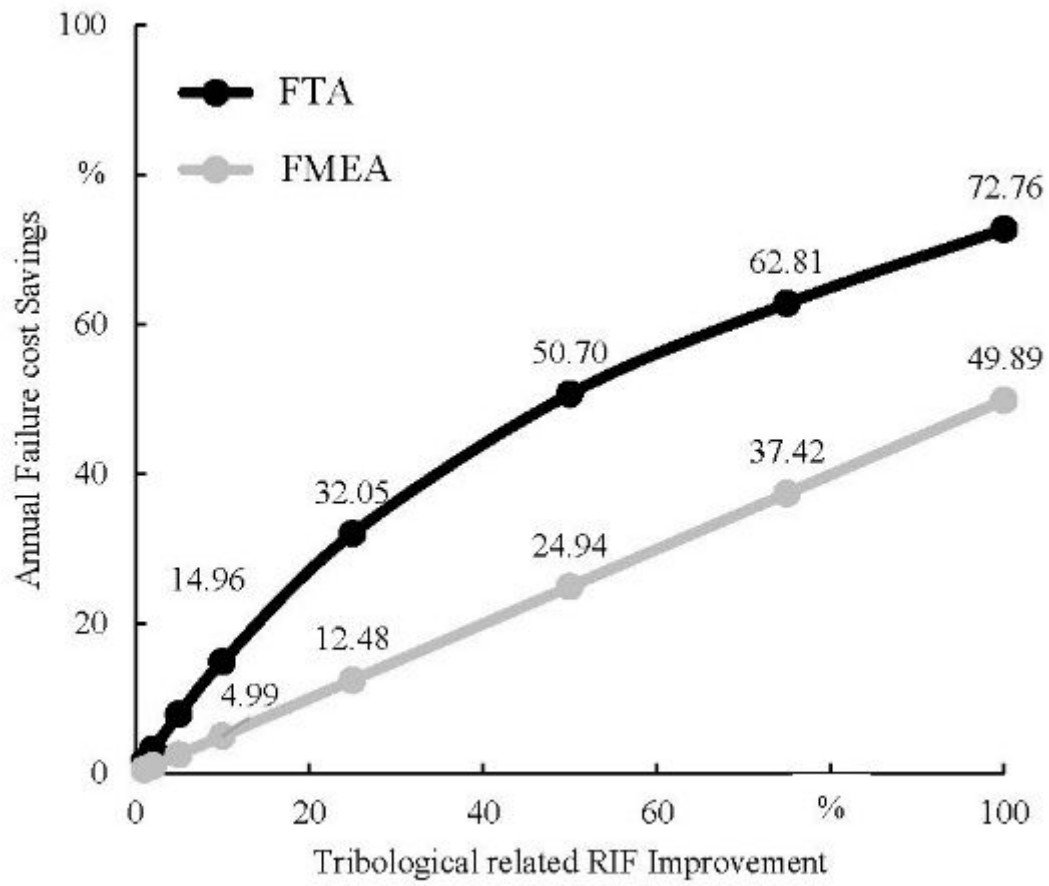Gearbox failure cost sensitivity to failure rate improvements

Figure 7

Gearbox failure cost sensitivity to 5% RIF improvement

Figure 8

Annual Savings in Gearbox Failure Costs vs Improvement in tribological RIFs for FTA simulation

Figure 9

Annual Savings in Gearbox Failure Costs vs Improvement in tribological RIFs.