Incorporating Tolerances into Qualitative Reliability Models

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Abstract

Reliability of products is important to remain ahead in today's highly competitive markets. Especially in products such as power tools, that are used in highly individual tasks in partially extreme environments, it becomes a main selling criterion. Qualitative reliability models are used to assess function-related reliability. The research problem is that state-of-the-art qualitative models do not take the complete influence of tolerances into account. The aim of this paper is to incorporate tolerances into qualitative reliability models. For this purpose, the methods of the Embodiment Function Relation and Tolerance model (EFRT model) and the sequence model are linked to derive the qualitative reliability model. This approach is illustrated using the example of a cordless drill and supports early reliability assessment.

Keywords

qualitative reliability model, tolerances, power tool, EFRT model

| DOI: 10.35199/dfx2024.19

1. Introduction and Motivation

Reliability, defined as the probability of the system to fulfil a specific function over a defined period of time under given circumstances [1], is an important aspect of product development to be ahead in a highly challenging and competitive market. Especially for power tools it is important due to individual and partly unknown use cases in various environments.

To achieve a reliable product, it is important to ensure the functional fulfilment at an early stage of product development (see also frontloading [2]). One of the main aspects at this stage is the specification of tolerances in product design. This is challenging because of the conflict in the different goals of functional fulfilment, product lifetime and production costs [3].

To meet this challenge, a better understanding of the influence of functionally relevant design parameters on wear and thus on product lifetime and reliability is required. Due to scatter in the material as well as manufacturing, a higher number of lifetime tests is necessary. To reduce this effort, the reliability of a product should first be assessed using qualitative or quantitative models. In early development stages, qualitative models are used due to the insufficient information [4]. Currently there is a lack of a qualitative reliability model that takes tolerances and their effects on product lifetime into account. This paper aims to incorporate the effects of tolerances on product lifetime in a qualitative reliability model. By modelling the relationship between tolerances and functional fulfilment, this model is intended to support the challenging specification of tolerances.

2. Related work

In this paper, we understand the quality of functional fulfilment as an essential part of reliability. There is a state of the product in which the product is still working but the quality isn`t sufficient for the customer. Matthiesen uses the example of an angle grinder that may still work mechanically, but is no longer suitable for use in steel processing due to the vibrations that occur during operation.[5]

State-of-the-art methods and models already exist to help the engineer assess the reliability of the product at an early stage in the development of mechatronic systems [4], [6]. This section gives an overview and is divided into three different sub-sections. First relevant qualitative reliability analyses are shown, followed by tolerances and wear analysis with a more detailed look at the EFRT model.

2.1. Qualitative reliability analyses

One method that analyses the reliability of mechatronic systems is the method according to Bertsche [4]. This method is intended for the early development stages and is designed to support the developer in evaluating the reliability of cross-domain systems. After a detailed analysis of the system, existing methods such as Failure Mode and Effects Analysis (FMEA) are used to assess reliability[4]. A detailed consideration of the wear and the effect on the functional fulfilment and reliability of the products is not taken into account.

Another method is the SMAR^{2}T method according to Kemmler [6]. It aims to present a holistic method for industrial purposes that can establish the connection between robustness and reliability. The method is divided into four main steps: System Design, Parameter Design, Tolerance Design and Robust Reliability Testing. In Addition to failure mode analysis using methods such as Fault Tree Analysis (FTA) and FMEA , the tolerance assessment takes place after the simulative reliability assessment and therefore tolerances are considered at a late stage of the product development.[6] In addition, the method has never been applied to power tools and it is unclear if it is suitable due to different boundary conditions such as manufacturing processes.

In summary, qualitative reliability analysis still does not adequately address the relationship between component tolerances and reliability. Common qualitative reliability models such as

FTA [7], FMEA [8] and Reliability Block Diagrams (RBD) [9] do not focus on possible changes in system parameters over the product's lifetime and do not consider the influence of tolerances on functional fulfilment.

2.2. Tolerance and wear analyses

Wartzack et al. [10] propose a holistic tolerance management process that takes different stages of product development into account. The methods used are mostly computer-aided and based on simulations and statistical models. The combination of methods and adapting the models to the specific problem is identified as a key challenge.[10]

Götz also describes a method for early tolerance management during design. However, the approach focuses on computer-aided robustness assessment and does not take a reliability assessment into account.[11]

Atalay et al. present a method for designing bearings taking deviations into account. After defining the tolerances, simulations are used to generate samples for statistical evaluation. The product lifetime is determined in the simulation by exceeding a limit value. A comparison with data from real tests is not dealt with.[12]

Heling et al. describe a procedure for the validation of virtual tolerance analysis methods for mechanisms. The model is to be used for the prediction of wear in product development and primarily helps to compare experimental data with a virtual data set. The method is applied using the example of an X-ray diaphragm.[13]

In his article, Bode et al. deal with the prediction of product lifetime functionalities. In addition to time-dependent wear, he also examines the process-related geometric deviations and makes it possible to estimate the failure. He uses an algorithm based on the Archard model that iteratively calculates the geometric deviations and the associated wear. The procedure is demonstrated using the example of a one-way clutch and simulated using Monte Carlo samplings. Some simplifications were made for the simulation, so that only certain components are affected by wear and in order to save computing time, the calculations were only carried out every 100 rotations. In addition, the wear rate is required, which must be determined by prior testing.[14]

The study by Bajpai et al. deals with a method for predicting wear on gear pairings. It is assumed that the wear is proportional to the contact force and the slip distance. Both wear patterns are applied iteratively in the simulation model to predict the wear.[15]

A qualitative model that takes into account the relationship between function and component tolerances is the Embodiment Function Relation and Tolerance model (EFRT model [16]. This model is a combined model from the tolerance graph [17] and the Contact and Channel Approach (C&C^2-A)[5]. The EFRT model integrates the various information available in the early stages of product development and enables conclusions to be drawn about the embodiment function relation in relation to the component tolerance chain using the EFRT sketch and the EFRT graph [19]. The EFRT model is mainly used to examine the robustness of various product concepts and to support decision-making in design. Therefore, it is suitable for performing qualitative reliability analyses. Although individual states are included in the model, considered over the lifetime of the product, which means that no lifetime analysis can be carried out and the model is only of limited use for reliability assessment.

In summary, a number of methods and models for tolerance and wear analysis already exist. Most of them are based on simulative models which can only be used in the later stages of product development. In addition, application to more complex systems is still challenging. Existing model such as EFRT model take the influence of tolerances into account but do not consider their impact on reliability. Another aspect is that reliability tests are commonly defined with the complete failure of the system and therefore only the state of complete failure is investigated.

3. Research question

Summarising the state of the art, there are already a number of methods for assessing the reliability of mechatronic systems. However, reliability assessment from the state of the art based on specific industrial context, which means that transferability of the models and methods are limited [1], [12], [13], [14], [15] In addition, tolerances and their influence on wear and thus the product's lifetime are often not sufficiently considered in the early stages of product development. To address this problem, a qualitative reliability model that incorporates the influence of tolerances is needed. Motivated by this, the research question of this paper can be derived as follows:

How can the influence of tolerances be incorporated into qualitative reliability models?

4. Materials and methods

To answer the research question, this paper attempts to apply the EFRT model to the reliability assessment and is demonstrated using the example of the drivetrain of a cordless screwdriver.

4.1. Cordless screwdriver

The influence of deviations over the product lifetime is shown in this paper using the example of the drivetrain of a cordless screwdriver. Due to the variety of use cases and the different and often harsh application environments, the reliability of this system is crucial and has to be taken into account during the product development process.

This power tool is mainly used for drilling holes and fastening screws. The reliability of the product can therefore be determined by the quality of the drilling. The more precisely the cordless screwdriver drills holes over lifetime, the more reliably it fulfils this function. The concentricity of the output shaft can be used as a measure of this, as it directly affects the drill. The deviation of concentricity can be described as the deviation of the shaft from the axis of rotation. If the concentricity is too high, the function of "producing a drill hole that deviates minimally from the ideal shape" can no longer be fulfilled with sufficient quality and the system can be considered a failure. The Festool T18+3 cordless drill serves as an example system. The schematic diagram of the drivetrain is shown in Figure 1 and describes the functional structure of the drivetrain.

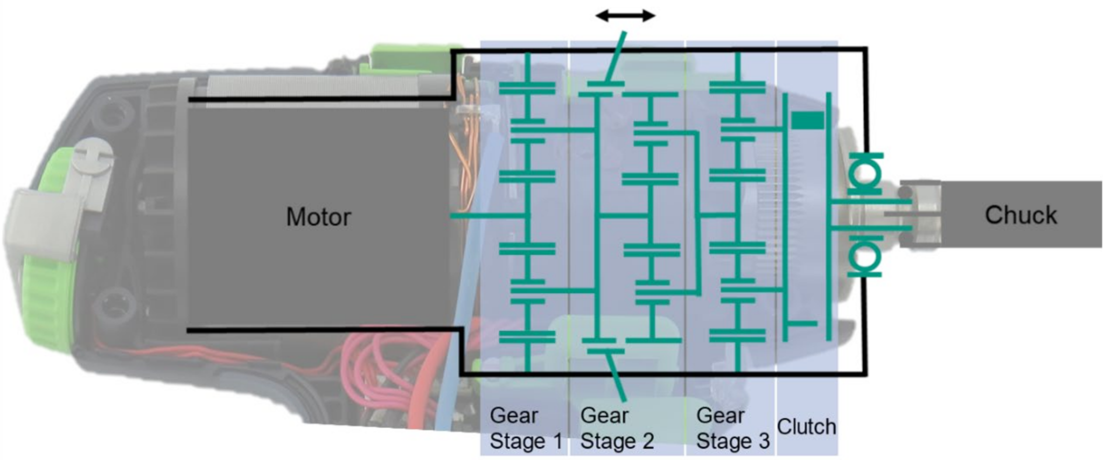


Figure 1: Structure of the drivetrain of the cordless drill (Festool T18+3) using a schematic diagram

The system is driven by a battery-powered brushless motor. This transfers the torque from the motor to a two-speed gearbox. The gearbox consists of three successive planetary gear stages. Depending on the gear selected, either the sun gear or the planetary gears are fixed by the ring gear of the second planetary gear. The ring gear can be shifted via a mechanical actuator on the top of the device. The torque is further transmitted to the output shaft via the third planetary gear stage with three planets. The shaft is supported by a ball bearing which is pressed into the housing and the connection to a clutch. The torque is transmitted from the output shaft to the chuck via a quick-release fastener and a hexagonal connection. The maximum torque is set electrically.

4.2. Methodical approach

The procedure in Figure 2 is used to determine the reliability of the cordless screwdriver taking wear into account. In this paper, the EFRT model is used to identify the critical tolerances for the function, in this case concentricity of the output shaft. In order to make a statement about the reliability for a longer operating time, a modified form of the sequence model is also used. Here, the larger deviations caused by wear can be considered and, in combination with the tolerance chain from the EFRT model, a conclusion can be drawn about the effects of tolerances on the lifetime of the product.

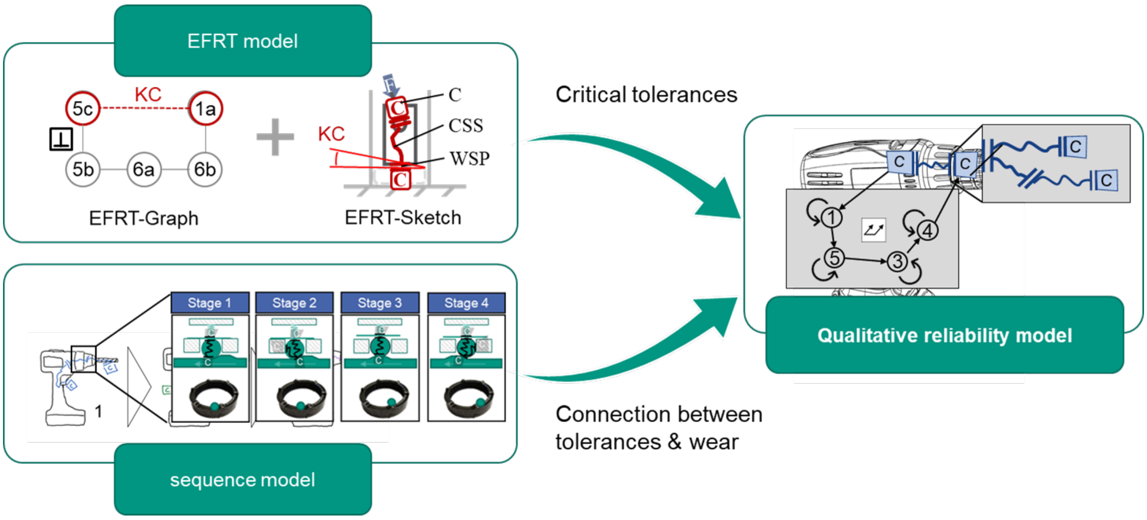


Figure 2: Methodology to get a qualitative reliability model that take the influence of tolerances into account. KC (Key characteristic), C (Connector), CSS (Channel and Support Structure), WSP (Working surface pairs).

The EFRT model consists of the EFRT graph and the EFRT sketch (Figure 3) [19]. To build the EFRT graph, the assembly of the product concept is first divided into several parts. The next step is to divide a part into Geometry Elements (GEs), i.e., interacting surfaces (see Figure 3 system structure modeling). In the EFRT graph, the GEs are represented as nodes. Their relations are labeled on the edges, e.g., required tolerance information such as parallelism between two GEs. The tolerance requirement for a GE itself, e.g., flatness, is labeled on the backward arrow (see Figure 3 EFRT graph) [19]. In this paper, the EFRT graph is built at the component level. To do this, the system is represented in a schematic sketch. The drivetrain is then analysed and all deviations and their relationships to each other are shown in a graph. This allows relevant tolerances for concentricity to be identified.

In a further step, the EFRT sketch is created. In the EFRT sketch, a certain area in the product concept, which is considered to be important for function fulfillment, is visualized in a principle sketch with the elements from C&C²-A. Three key elements are needed to describe a function: the Working Surface Pair (WSP), the Channel and Support Structure (CSS), and the Connector (C). For better understanding, the definition of the key elements of the C&C²-A from [5] is given below. WSPs are formed when two arbitrarily shaped surfaces of solid bodies or generalized interfaces of liquids, gases, or fields come into contact and are involved in energy, substance, and/or information exchange. A WSP consists of two working surfaces (WS). CSSs describe volumes of solid bodies, liquids, gases, or field-permeable spaces that connect exactly two pairs of WSPs and enable the conduction of material, energy, and/or information between them. The information on the system boundary is stored in the Connector [5].

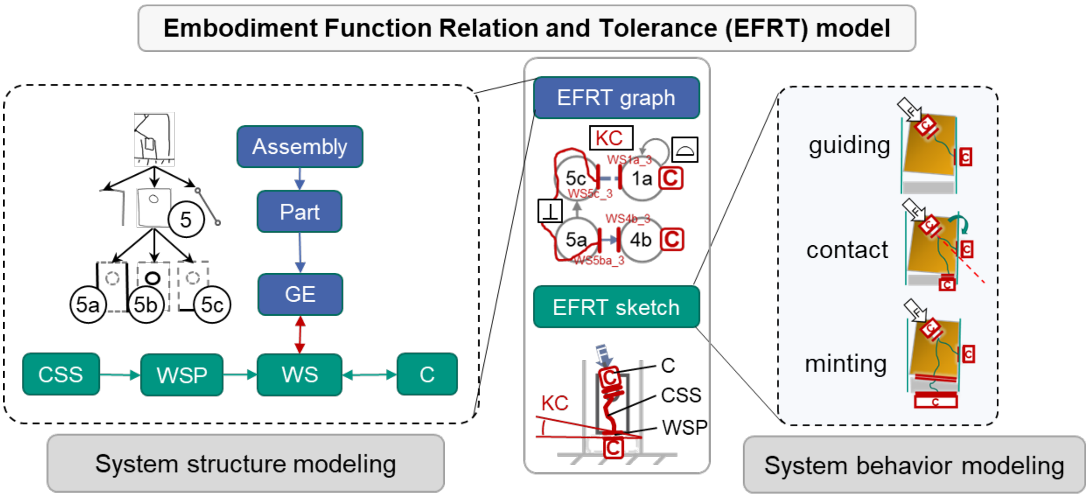


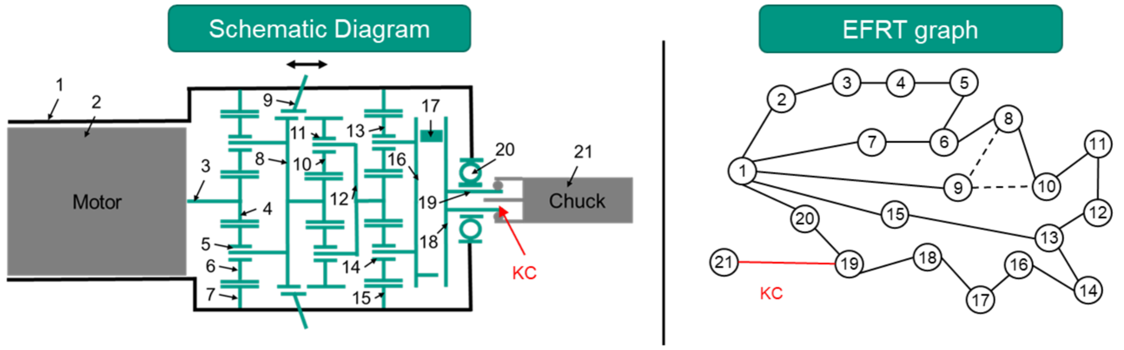
Figure 3: structure of the EFRT model containing the EFRT graph and the EFRT sketch according to [18]

For analyzing the functional fulfilment, Key Characteristics (KCs) are used. KCs are parameters that describes the influence of part deviation on the quality of an assembly [19]. In an EFRT model, KCs can be integrated into the EFRT graph between two GEs, or it can be drawn directly in the EFRT sketch (see Figure 3). Meanwhile, different deviations in the design parameters can be modeled in the EFRT graph and visualized in the EFRT sketch. The analysis of the functional fulfillment is made on the one hand by analyzing the GEs contributing to KCs in the EFRT graph and on the other hand by visualizing the effect of the deviations on KCs in the EFRT Sketch [19]. This is required to identify the critical points for wear and system states. The force flows are modelled with WSP, CSS and C at the critical points. The system behaviour with manufacturing deviation, but without temporal changes such as wear, will be analysed and visualized first.

The next step is to investigate the system behaviour caused by critical deviations over time using the sequence model. This involves analysing how the increase in deviation due to wear affects the tolerance chain and the force flow and how this influences the concentricity of the output shaft The procedure is based on the C&C² sequence model according to Matthiesen et al [20]. Heavy wear can cause existing WSP to break up and new WSP to form. This changes the force transmission path and therefore also the CSS of the individual components. This in turn causes other areas to be subjected to greater loads and the wear at these points increases, resulting in greater deviations in the geometry. These correlations can be traced back to the EFRT graph and thus conclusions can be drawn about the product lifetime.

5. Results

Figure 4 shows the schematic diagram with the individual components on the left side of the figure and the EFRT graph on the right side.



1. Housing
2. Motor
3. Input Shaft
4. Sun Gear gs 1
5. Plain Bearing Planet Gears gs 1
6. Planet Gear gs1
7. Ring Gear gs 1
8. Carrier Frame / Sun Gear gs 2
9. Actuator / Ring Gear gs 2
10. Planet Gear gs2
11. Plain Bearing Planet Gears gs 2
12. Carrier Frame / Sun Gear gs 3
13. Planet Gear gs 2
14. Plain Bearing Planet Gears gs 3
15. Ring Gear gs 3
16. Carrier Frame gs 3
17. Cylinder Clutch
18. Carrier Clutch
19. Output Shaft
20. Bearing
21. Chuck

gs= Gear Stage
KC = Key Characteristics

Figure 4: Schematic diagram and the EFRT graph for the cordless screwdriver Festool T18+3

The EFRT model was used to identify the critical tolerances that have the greatest influence on the fulfilment of the function and therefore on the concentricity of the output shaft. The EFRT graph in Figure 4 shows the connection between the single parts and therefore their dependencies. The KC is shown in red, which symbolises the connection between the output shaft and the chuck. This is where the deviation from concentricity, can be measured. Figure 4 shows that the KC is directly depended on the bearing (20) and the wear of it have a direct effect on the concentricity. In addition, the connection between the output shaft (19) and the clutch (18) that transfers the torque is involved in the quality of the functional fulfilment. Therefore, the critical parts in this study are the bearing and the connection to the clutch, even though clutch (17, 18) and some parts of the planetary gear (14-16) have an influence as well. Furthermore, the dependencies of the critical parts to the rest of the system are shown. To illustrate the steps of the approach, this paper focuses on the bearing as an example of a critical part.

The critical parts need to be analysed in more detail to understand the influence of wear over time, as the EFRT graph in Figure 4 only shows single system state. Therefore, the bearing connection is further investigated and the sequence model is applied into the EFRT sketch. The results including the effect of wear for bearing (20) are shown in Figure 5.

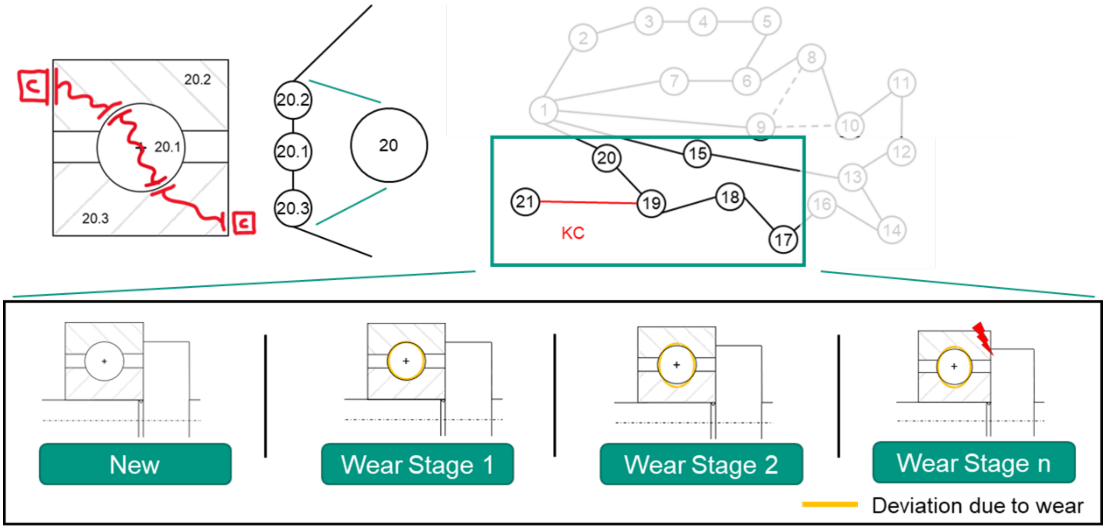


Figure 5: The bearing as exemplary representation of the qualitative reliability model for the concentricity

For a new, unused product, the concentricity of the output shaft depends solely on the manufacturing and component tolerances. During the use of the power tool the running surfaces and the balls get a higher deviation due to wear. This leads to a greater deviation developing over time. As a result, this deviation has an influence on the output shaft and the concentricity deteriorates due to the increased clearance. Deterioration in the concentricity of the drive shaft in turn means that more lateral forces are transmitted between the gearbox and the output shaft via the connection to the clutch. This means that the gears of the planetary gearbox must also withstand more loads and wear increases there too.

Due to wear, the deviation increases and the force guided through the CSS of the bearing is redirected. This leads to a change in the optimum support structure, which should be taken into account by the specification of tolerances in the critical parts. This affects other parts in the identified tolerance chain in EFRT graph, as these parts are now also subject to wear progression.

6. Discussion

The results of this paper show that the EFRT model can be used in the first steps for reliability assessment. The EFRT graph can be used to show the connection and dependencies between the single parts of the system. Furthermore, the connections between the single parts and their tolerances can be analysed. Thus, the critical components can be identified with the EFRT sketch. However, there are a number of challenges with the procedure that have not been fully resolved in terms of the qualitative assessment of reliability and require further research.

The effects of the bearing tolerances on the wear, and thus on the concentricity and on the system, could be demonstrated only qualitatively using the drivetrain of a cordless screwdriver as an example. The research question “How can the influence of tolerances be mapped in qualitative reliability models?” could thus be answered as follows: combining the EFRT model and the sequence model into a qualitative reliability model, statements on reliability-relevant tolerances could already be made with limited available data. The new insights derived from the model offer high potential to avoid extensive testing to gather the necessary information for tolerance specification.

A challenge that occurs is the representation of interactions between the wear of the individual KCs. With the model, it is possible to show the direct effects of a deviation on relevant target values. However, due to the linear structure of the approach, the interactions of the individual KCs over time cannot be represented.

Furthermore, expertise about the system is required to set up the EFRT model. For example, precise knowledge of the structural and functional design is required in order to create a complete principle sketch that serves as the basis for the EFRT graph. Knowledge of the system is also required for the EFRT sketch in order to draw the force curves needed to determine the KC.

Another challenge in the sequences model is the discrete representation of wear and the transition between the individual states. The sequential analysis of wear makes it difficult to define the transition between one state to another.

The EFRT graph shows the dependencies in the system and the influence of tolerances on the KC. This helps to understand which parts are relevant for functional fulfilment and therefore which can be optimised for better reliability. This could be an advantage over the simulated approaches in the state of the art to provide faster information in the early stages of product development. However, simulations can be used to construct a failure curve. This is not possible with a qualitative reliability model.

The paper shows a few challenges to get a holistic qualitative reliability model of a complex system that takes the influence of wear into account. Due to the complexity of the example system, it is difficult to visualise all connections and dependencies. Although the fractal character of the model makes it possible to analyse the system at different levels, it is not clear what depth or number of sequences is useful to make a resilient statement about reliability. This remains a challenge by utilization of the proposed approach, which needs to be further developed for a better applicability.

These challenges should be part of future research. Furthermore, the qualitative reliability model should be substantiated with quantitative data to prove the approach.

7. Conclusion

Reliability is an important aspect of product development, especially in the competitive power tools market. It is therefore important to gather sufficient information about the product in the early development phase. In the state of research, methods and models already exist to support developers in evaluating reliability. However, the relationship between component tolerances, wear and product lifetime is not or not sufficiently considered. Often, simulative procedures are used that are based on models that are only close to reality to a limited extent. In this paper, an initial procedure is applied by adapting the EFRT model for the whole product lifetime to obtain qualitative conclusions about the relationship between component tolerances, wear and reliability. The drivetrain of a cordless screwdriver is used as an example system. The model was previously used to evaluate the robustness of various design alternatives. It is used to display the dependencies between the single components of the system and to identify the critical parts having an influence on the concentricity. To take the influence of wear into account a modified version of the C&C^2 sequences model is applied to one critical part the bearing of the output shaft.

The approach identified the bearing and the connection to the clutch as relevant parts that influences the concentricity of output shaft. Nevertheless, the application of the method revealed some challenges that cannot be solved by the approach and the EFRT model. For example, it is difficult to fully visualise the interactions of such a complex system over lifetime and the different states of the components.

In the next step, the challenges that arose here are to be solved using a complete, qualitative reliability model of the cordless screwdriver. In a further step, this model is to be quantitatively substantiated by data-based test series.

8. Acknowledgment

The authors thank the Industrielle Gemeinschaftsforschung (IGF) for supporting the project “Einfluss von Bauteiltoleranzen auf die Zuverlässigkeitsbewertung von Elektrowerkzeugen und die Qualität der damit ausgeführten Arbeiten“ (BTEW) under grant number N12077/22.

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