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Towards Perpetual Innovative Products Through Circular Factories: Integration of Functional Behavior into System Reliability

Felix Leitenberger[a,*], Victor Mas[a], Nehal Afifi[a], Lukas Kleinhans[a], Jonas Hemmerich[a], Sven Matthiesen[a]

[a]*Institute of Product Engineering (IPEK), Karlsruhe Institute of Technology (KIT), Kaiserstr. 10, 76131 Karlsruhe, Germany*

**Corresponding author. Tel.: +49-721-608-41871. E-mail address: felix.leitenberger@kit.edu*

Abstract

Circular Factories (CFs) embody a sustainable manufacturing paradigm that emphasizes resource efficiency, waste minimization, and perpetual innovative products. A critical challenge within CFs is accurately predicting the functional behavior, which is essential for making informed reprocessing decisions. The integration of functional behavior into system reliability as compatible models in CF is currently still unclear. This paper describes a framework that integrates the functional behavior into system reliability, that aims to close this research gap. The framework is demonstrated through a theoretical case study on an angle grinder and a cordless drill. The metrics of Multi-State System (MSS) Reliability is going to be used to describe the continuous degradation of the system. To achieve this, a Performance Rate is employed, which uses the measured values of the functional behavior as input variables. By representing the functional behavior through the Performance Rate, the functional model can perform a state estimation. The reliability model then utilizes this metric for state prediction. While the study highlights significant potential benefits, it also uncovers several limitations that need to be addressed through further research. The theoretical case studies implies that empirical data is lacking. To validate the proposed framework and models, it is essential to collect and analyze real-world data. However, the described framework is able to integrate functional behavior into system reliability and therefore contributes to perpetual innovative products in the CF.

Keywords: reliability, sustainability, design, remanufacturing, circular economy

1. Introduction

The aim of the Circular Factory (CF) is to reprocess used products from the market into products of the current product generation, bringing the vision of a perpetual innovative product closer to reality [1].

When deciding how a product should be reprocessed in a CF, it is essential to predict the product function. The functional and reliability model of the product are essential for predicting functional fulfillment. The prediction for pairing and reprocessing of the embodiment is one of the key challenges in the CF. [3]

The concept of a CF involves the reuse, remanufacturing and repair of parts from used products in combination with newly manufactured parts to create as-new products. This approach aims to address the challenges posed by the unpredictable conditions of used parts. Pfrommer et al propose an ontology-based knowledge backbone to manage these challenges [4]. The ontology facilitates the representation of knowledge, particularly under conditions of uncertainty, and supports the design of queries and the detection of similarities and analogies. This framework is crucial for the efficient operation of a CF, ensuring that the production system, which includes disassembly, testing, and assembly steps, can handle the complexity of reprocessed parts effectively. This aligns with the End-of-Use strategies known as R-strategies which are a set of approaches aimed at extending the lifecycle of products and materials, thereby reducing waste and promoting sustainability. Ortegon et al outline several strategies seen in Fig. 1, including reuse, repair, remanufacture, and recycle,

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which are integral to the circular economy. These strategies help in minimizing the consumption of natural resources and support the recycling of materials, thus reducing the generation of waste [2].

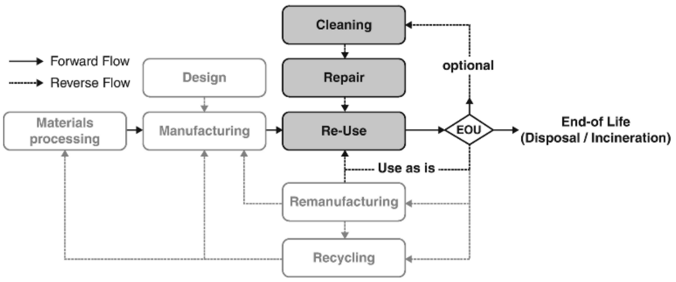

Fig. 1 An Example of End-of-Use Strategies proposed by [2]

Function Models and Behavior Models

Functional fulfillment can be determined by evaluating functional behavior [5]. In order to assess the functional behavior of a product, function models and behavior models can be utilized. Functional modeling helps to specify system requirements and depict their interactions. Nevertheless, function models are developed in an abstract manner and do not provide direct access to the product's embodiment and behavior [6]. They must therefore be integrated with behavior models, which often include information on the embodiment in addition to behavior [7].

The Function-Behavior-State Modeler by Umeda is a design methodology that links function with its behavior and state. Function describes the intended purpose, the behavior captures how to achieve it, and the state represents its physical condition. It provides a methodology for understanding and modeling those relationships, but primarily qualitative rather than quantitative. [8]

Both qualitative and quantitative behavior models are required in relation to functional fulfillment. Qualitative approaches are able to identify relevant relations between embodiment and functional behavior at subsystem and component level. The aim of quantitative approaches, such as simulation models, is to capture individual attributes of the functional behavior and thus quantify the identified relations. Furthermore, the individual attributes of functional behavior must be combined into a single variable in order to assess the overall functional fulfillment of the product. As of now, there is no common technique to create this variable in behavioral models. Some concepts like the objective function in Multidomain-Design-Optimization [9] or Value-Driven Design [10] combine individual attributes, for example, by using a weighted sum. But these concepts focus on the overall design optimization rather than the specifics of the product's embodiment.

Reliability Models

In this paper the definition of IEEE which defines reliability as the ability of a system or component to perform its required functions under stated conditions for a specified period of time is used [11]. For complex systems, ensuring reliability is especially challenging because of the strong interdependencies between the subsystems and their environment [12]. Failures of individual components do not always lead to system failure, and system failures are not always caused by the failure of specific components [13].

Reliability analysis of systems can be approached from multiple perspectives, each designed to address specific questions and achieve distinct goals. The two major sub-areas in reliability analysis are Multi-State Systems (MSS) reliability and Prognostics and Health Management (PHM). Both approaches address similar problems but differ significantly in their objectives and the nature of questions they address.

MSS reliability focuses on evaluating the performance of a system across different states. It is primarily used during system design and reliability planning. In contrast, PHM focuses on predicting system maintenance needs by monitoring its condition and forecasting its health status while the system is in use. These two closely related approaches investigate from different angles the overarching question of system reliability. The combined use of well-established methods from both MSS and PHM to derive answers to complex reliability questions.

To perform MSS reliability analysis, various methods are employed that are either graph-based or analytical/approximate approaches [14]:

- Bayesian Networks (BNs): Probabilistic graphical models to understand dependencies among components and their impact on reliability [15].
- Universal Generating Function (UGF): Computes overall reliability and performance of multi-state systems [16,17].
- Stochastic Processes: Techniques like Markov or semi-Markov models to predict system behavior over time.
- Monte Carlo Simulation (MCS): Simulates different system states to estimate reliability in complex scenarios [18].

For PHM, the methodologies can broadly be categorized as either data-driven, model-driven, or fusion approaches [20,19]. Data-Driven Approaches rely on system data to predict failures. Examples include statistical approaches, which use probabilistic models like the Bernstein and Weibull distributions to predict failures [21], and machine learning approaches, which use degradation data to learn patterns and predict the time to failure [19]. Model-driven approaches are Physics of Failure (PoF), which involves understanding the physical processes of component wear to predict failure [19], and Multi-State Models, which include semi-Markov models and Piecewise Deterministic Markov Processes (PDMP) to understand system dynamics in a more granular manner [21]. Fusion approaches combine data-driven and model-driven methods to improve prediction accuracy.

Metrics

Depending on the specific goals of an analysis, different metrics can be used to assess system reliability and performance. It is possible to group these metrics into two categories: time-based metrics and output-based metrics. Time-based metrics describe system reliability in terms of time, such as Remaining Useful Life (RUL) [23,22], Mean Time to Failure (MTTF) [24], and Mean Time to State (MTTS) [16]. Output-based metrics evaluate the output performance of a system, such as the Health Index [23], which represents system health and performance based on selected parameters, depending on the specific use case.

Many of these metrics can be interpreted in a specific way to suit the unique needs of an analysis. For example, the Health Index depends on the chosen indicators of system health [23], and the interpretation of such metrics is often subjective, making it crucial to align them with the intended use case.

PHM has been explored in remanufacturing scenarios [26,25] but not directly in the context of improving a used product beyond its original state, as intended within a CF.

Research Gap

The prediction of functional behavior is one of the key challenges in the CF and is essential for decision-making on how to reprocess. The functional model and system reliability are part of this process. However, there is a lack of a structured, quantitative metric to integrate functional behavior into system reliability within the context of CF.

2. Materials and Methods

This paper introduces a novel framework, shown in Fig. 2, that integrates the functional behavior into system reliability using a quantitative metric, specifically designed to support the principles of the CF.
An application is described through theoretical case studies on an angle grinder and a cordless drill. The angle grinder FEIN CG 15-125 BL is used. It performs three essential functions: Cutting, grinding and polishing. The FESTOOL TDC 18/4 serves as example system of the cordless drill. It is used for screwdriving and drilling. In this theoretical case study the focus is on drilling. The aim of the theoretical case studies is to highlight the need of a combined metric and showing the need for transferability.

3. Results

3.1. General Framework

To be able to integrate functional behavior into system reliability, it is important that the reliability model is not only using binary states. MMS reliability is required to define the degree of degradation in the system. Each state represents a different level of functional fulfillment, from fully functional to completely failed, with intermediate degraded states. For this purpose, it must be possible to describe and measure the functional behavior based on the function of the product. The functional behavior is influenced by the embodiment material and tolerences [27].

The Performance Rate is introduced that quantifies the level of functionality of a system in a given state. The Performance Rate as metric has to use input parameters that are able to describe the functional behavior of the system. Methods like Universal Generation Function (UGF) can use the parameters that describe the functional behavior to describe the Performance Rate.

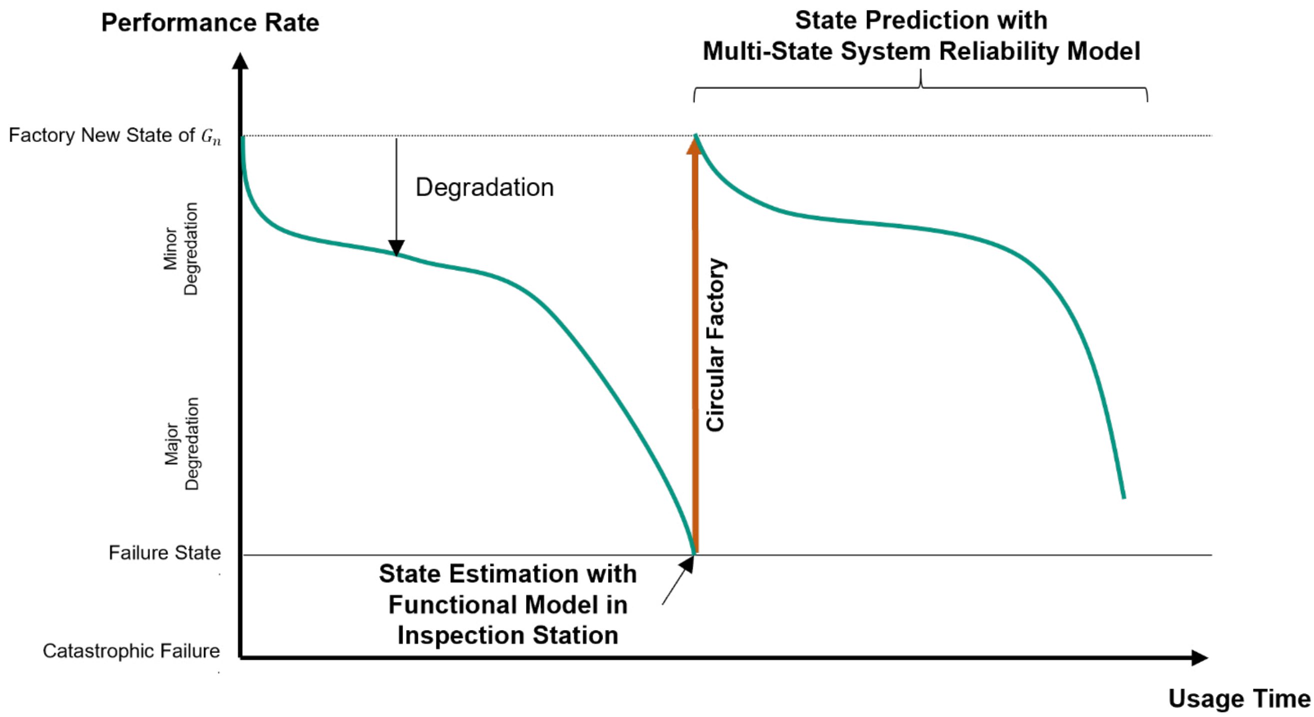

Fig 2: Framework that integrates functional behavior into system reliability

Within the concept of the CF there are the following different relevant states that have to be described:

- Factory-new state of the current product generation G_n: The system performs its intended function with factory-new functional requirements of G_n.
- Failure state: The system no longer perform its required function, but it may still operate at a reduced or impaired level. Critical functional requirements are no longer fulfilled.
- Catastrophic failure state: The system fails completely, it is non-operational.
- Factory-new state of next product generation G_{n+1}: System performs its intended function with factory-new functional requirements of G_{n+1}

In between factory-new state and failure state there can be defined phases like minor or major degradation for a finite number of defined states.

When the product comes back into the CF there will be an inspection. The functional model will be able to make the state estimation based on the data generated in this inspection. In the CF, a decision concerning the R-strategies has to be made. A digital twin of the CF will use the functional model, reliability model and additional data for decision-making [3]. In this context the reliability model will be used to make a state prediction as basis for decision-making. Time-based metrics from state-of-research such as MTTS, MTTF and RUL can be used for that. Those metrics will be one criteria of how to reprocess the product in the CF.

3.2. Theoretical Case Study: Angle Grinder

The framework is applied to a theoretical case study using an angle grinder (see Fig. 3). The angle grinder performs the functions cutting, grinding and polishing. Each function requires the tool to operate at specific performance levels to ensure quality.

The functional behavior of the angle grinder without considering the discs can be described by power output, efficiency, speed, and emission levels such as vibration and noise. Vibration is based on vibration emission level ah and noise on sound pressure level. Both are measured in accordance with DIN EN 62841.

The factory-new functional requirements of G_n, here CG 15-125 BL, can be found in the datasheet [28]. The critical functional requirements and the factory-new functional requriements of G_{n+1} are theoretical assumptions (see Table 1).

Use-Time refers to the actual time the angle grinder is actively being operated for its intended function, such as cutting, grinding, or polishing. It's the cumulative duration when the tool is powered on and engaged in work. Aging effects resulting from non-use and storage are not taken into account.

Table 1: Functional requirements of the angle grinder

Functional behavior	Factory-new functional requirements of G_n	Critical functional requirements	Factory-new functional requirements of G_{n+1}
Power Output	> 1050 W	> 950 W	> 1100 W
Efficiency	> 70%	> 65%	> 75%
Speed	> 9000 rpm	> 8900 rpm	> 9000 rpm
Vibration	< 4.5 m/s²	< 6.0 m/s²	< 4.0 m/s²
Noise	< 91.3 dB(A)	< 95 dB(A)	< 90 dB(A)

Degradation is changing material and tolerances, and therefore functional behavior. In the context of the angle grinder this means for example that the tolerances in the gear can change due to wear. This leads to increasing vibrations. The failure state is mainly influenced by the vibration. Critical

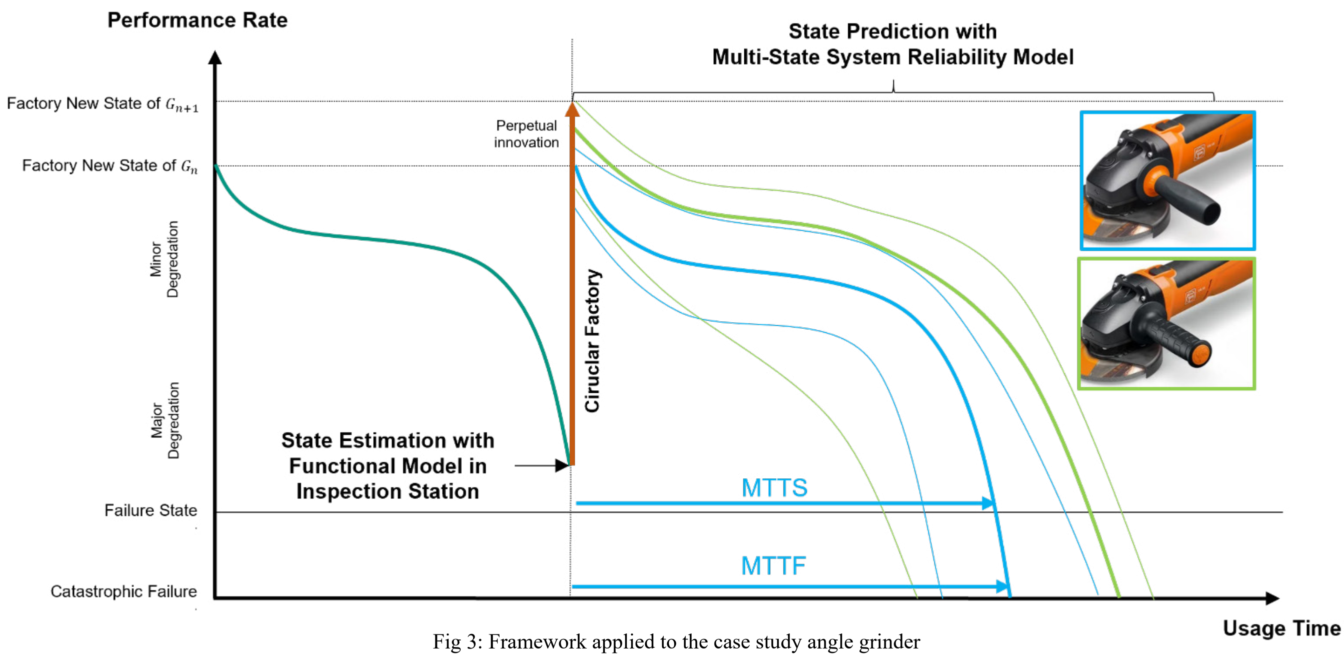

Fig 3: Framework applied to the case study angle grinder

functional requirements can be early achieved by vibrations in the system. The angle grinder can still be used, but does not fulfill safety requirements. The catastrophic failure state will probably take place, when there is a total breakdown of the gear and therefore no power will be transferred.

For the next product generation the aim is to reduce the vibration in the system. In this case study, a new anti-vibration handle has been introduced. Therefore, the next time the angle grinder is remanufactured in the CF, not only the used components will be remanufactured, but the handle will also be upgraded to enhance performance and therfore Performance Rate. This ongoing enhancement is why it is referred to as a perpetual innovative product, as it is possible to increase the functional requirements.

3.3. Theoretical Case Study: Cordless Drill

In this study the focus of the function is on drilling. The function behavior of the cordless drill can be described by torque output, efficiency, speed, vibration, noise and run-out (see Table 2). Vibration and noise are measured in accordance with DIN EN 62841 as the angle grinder. Run-out is definded by the Total Indicator Reading (TIR).

The factory-new functional requirements of G_n, here TDC 18/4, can be found in the datasheet [29]. The critical functional requirements and the factory-new functional requriements of G_{n+1} are theoretical assumptions.

The failure state is mainly influenced by the run-out. Critical functional requirements can be reached by wear in the bearing, that leads to a run-out, which is the inaccuracy of the drill chuck. Qualitative investigations in the context with tolerances already described this effect [30]. If there is a lack of required roundness and concentricity, the quality of the boreholes are not fulfilled anymore, even though the cordless drill is still running.

Table 2: Functional requirements of the cordless drill

Functional behavior	Factory-new functional requirements of G_n	Critical functional requirements	Factory-new functional requirements of G_{n+1}
Torque Output	> 75 Nm	> 70 Nm	> 80 Nm
Efficiency	> 70%	> 65%	> 75%
Speed	> 3600 rpm	> 3500 rpm	> 3600 rpm
Vibration	< 3.0 m/s²	< 6.0 m/s²	< 3.0 m/s²
Noise	< 73 dB(A)	< 95 dB(A)	< 73 dB(A)
Run-Out	100 µm	300 µm	100 µm

The catastrophic failure state will probably take place, when there is a total breakdown of the gear and therefore no power will be transferred.

The tolerances of the bearing and other components have a huge influence on the run-out and therefore on the functional behavior. The CF can use the information of the tolerances in combination with the reliability model to make a instance-specific state prediction.

4. Discussion

The theoretical case studies presented in this paper demonstrate the potential benefits of integrating functional behavior into multi-state system reliability models. The metric of the Performance Rate can be used to describe the functional behavior and the system reliability which is applied to the angle grinder and cordless drill case study. Depending on the function a different functional behavior occurs and therefore needs different parameters to describe it. Depending on the failure that will happen, different parameters that describe the functional behavior are in focus. This is for the angle grinder vibration and for the cordless drill the run-out. The framework is therefore transferable to different systems.

However, several limitations and opportunities have emerged from this study, which warrant further exploration. A limitation of defining the performance rate is to identify the parameters which comprehensively and accurately describe the functional behavior.

The theoretical nature of the case studies implies that empirical data is lacking. To validate the proposed framework and models, it is essential to collect and analyze real-world data. To do so we will use an instance-specific reliability modeling approach that is suitable for the context of the CF [31].

It remains uncertain whether the states defined in the current multi-state system reliability model are sufficient to capture all relevant aspects of the systems' functional behavior. Additional states may need to be incorporated based on the parameters that describe functional behavior more comprehensively. This expansion could improve the model's granularity and predictive capabilities but also adds complexity that must be managed.

To address the identified limitations, application studies have to be conducted to determine the parameters that describe functional behavior comprehensively.

5. Conclusion

The paper presents a framework in reliability engineering by integrating functional behavior into system reliability with a quantitative metric. Functional model and system reliability model are compatible with the same, introduced metric: Performance Rate. Both models use this metric to either make a state estimation in the functional model or a state prediction in the reliability model. To validate the proposed framework and models, it is essential to collect and analyze real-world data in future. The proposed framework aligns with the principles of the CF.

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