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Determine Input Parameters for Instance-Specific Reliability Models in the Circular Factory

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The vision of the Circular Factory (CF) is to extend product lifecycles by transforming used products into new generations through sustainable practices such as reuse, reconditioning, and remanufacturing. It aims to create perpetual innovative products. Achieving this vision requires developing instance-specific reliability models capable of predicting functional behavior at both subsystem and system levels supporting decision making for control of the CF. One challenge in building this reliability model is to identify input parameters that not only allow accurate predictions of functional behavior, but also account for time-dependent changes and interactions at both the subsystem and system levels within the CF. This study introduces a framework to determine the input parameters for instance-specific reliability models in the CF.
An angle grinder is used as an exemplary application of the proposed framework. The framework consists of five steps: (1) system decomposition, where the angle grinder is broken down into subsystems and components; (2) component prioritization, which identifies the elements most relevant to the functional behavior; (3) use case analysis, which examines how different operational scenarios affect component performance and failure modes; (4) failure mode identification, which links failure modes to the components; and (5) input parameter extraction, where the necessary input variables for the reliability model are extracted based on the results.
This study focuses on tooth breakage as it serves to illustrate the application of the framework through a single example. Identifying the correct input parameters lays the foundation for developing instance-specific reliability models that integrate various failure modes and subsystems within the CF. However, the framework is limited by its focus on a single failure mode, which restricts its generalizability. Future work should address multiple failure modes and validate the framework across diverse use cases.

Keywords: reliability model, circular factory, remanufacturing, functional model, angle grinder

1. Introduction & Motivation

The vision of the Circular Factory (CF) is to create perpetual innovative products. This approach focuses on transforming used products into new generations, maintaining their value while minimizing resource consumption and waste. Lanza et al. describe the CF as a production system capable of adapting to dynamic uncertainties and ensuring product reliability and functionality across generations, aligning with sustainability goals such as climate neutrality and resource efficiency. (Lanza et al., 2023)

A critical aspect of realizing this vision is the development of a reliability model that predicts the functional behavior of products at both subsystem and system levels. Together with a functional model of the product, these models are essential for decision-making processes in reuse, reconditioning, and remanufacturing within the CF framework. (Afifi et al., 2025; Grauberger et al., 2024)

Generally, reliability models often use approaches such as:

- Failure Mode and Effects Analysis (FMEA): This systematic approach identifies potential failure modes, their causes, and effects on system performance (Tinga, 2013).
- Historical data analysis: Examining past failure data and maintenance records to identify critical components and factors affecting reliability (Gorjian et al., 2010; Usher et al., 1990).
- Accelerated life testing: Conducting tests under stressed conditions to identify factors that impact product lifespan (Meeker et al., 2009).
- Fault tree analysis: Creating logical diagrams to identify potential causes of system failures and their relationships. (Tinga, 2013; Yazdi et al., 2023)

Leitenberger et al. (2024) outlined a structured and methodical approach to develop instance-specific reliability models within the context of the CF, addressing the unique challenges of reprocessing and perpetual innovation.

A key aspect of this process involves determining input parameters, which is particularly challenging due to the interplay between the functional behavior model and the system reliability model (Afifi et al., 2025). The functional behavior model evaluates the functional performance of components, while the system reliability model predicts their reliability under various conditions. In the CF, these models must operate in close integration to handle the variable nature of reprocessed components (Afifi et al., 2025). This integration presents two primary challenges: (1) ensuring the functional behavior model and system reliability model work in tandem by utilizing a shared performance metric to describe functional behavior, and (2) identifying suitable input parameters that effectively capture the time-dependent functional behavior of systems and subsystems. These challenges add a layer of complexity to parameter identification, making it uniquely demanding. This paper proposes a systematic framework to address these challenges by determining input parameters to instance-specific reliability models within the CF. The term "instance-specific" refers to the necessity of adapting the reliability model to each individual product - in this case, an angle grinder -considering its unique combination of components. Current models lack the ability to provide tailored reliability predictions for unique products in circular factories, as they fail to integrate data on wear, different failure mechanisms, dependencies, and uncertainties. By bridging the gap between functional behavior models and system reliability models, this framework enables the development of more accurate and adaptable reliability predictions, uniquely suited to the dynamic and sustainable goals of the CF.

2. Materials and Methods

This study uses a systematic framework to identify input parameters for an instance-specific reliability model, demonstrated through the exemplary application of the angle grinder FEIN CG 15-125 BL (Fig. 1) within the context of a CF.

Fig. 1.FEIN CG 15-125 BL angle grinder which is used for the case study (*CG 15-125 BL | C. & E. Fein GmbH*, 2025)

The framework consists of several interconnected steps, each contributing to the comprehensive understanding of the system's reliability (Fig. 2).

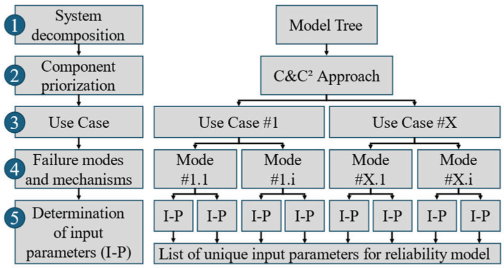

Fig. 2.Flowchart of the framework for determining the input parameters of the reliability model

The first step involves decomposing the overall system (angle grinder) into subsystems and components. This system decomposition is facilitated by analyzing the angle grinders explosion view diagrams and conducting a detailed analysis of the systems' structure. Following the decomposition, the components and subsystems are prioritized based on their relevance to the functional behavior of the overall system (step two). This prioritization is achieved through the application of the Contact and Channel (C&C²) Approach (Matthiesen et al., 2019). The C&C² method provides a structured way to analyze the functional and physical relationships within the system, allowing a more focused examination of critical components. Step three involves identifying different use cases of the power tool. Different use cases significantly influence the forces acting on the tool and thus determine which components and interactions to prioritize. Understanding the various scenarios in which the angle grinder is used allows for more precise identification of potential failure modes. Step four involves identifying specific failure modes and methods for each component and subsystem across different use cases. *Failure mode* refers to the specific way in which a system's function is no longer fulfilled, while failure mechanism describes the underlying process that leads to such a failure (Tinga, 2013). It is also important to note, that failure is not necessarily a catastrophic failure (complete and sudden breakdown of a system, no functionality left); it can also manifest as a significant change that prevent sufficient functional behavior (Cubillo et al., 2016; Leitenberger et al., 2024; Tinga, 2013). Identifying and understanding both failure modes and mechanisms is essential for determining the potential factors influencing the reliability model.

The final step in the framework involves translating these insights into measurement variables, which will act as the critical input parameters for the comprehensive reliability model. These parameters are selected based on their ability to represent and quantify the identified failure modes and their interactions.

This paper focuses on a selected group of failure modes and components, serving to illustrate the application of the framework through a single example.

3. Exemplary Application of the Proposed Framework

3.1. Step 1: System Decomposition

To effectively identify failure modes and determine the corresponding input parameters for a reliability model, it is essential to first develop a thorough understanding of the system and its structure. This process begins with a systematic decomposition of the system into its individual components. Exploded-view images of the angle grinder (Fig. 3) serve as a visual guide, providing a clear overview of the system's structure. Additionally, physically deconstructing the angle grinder offers valuable insights into the relationships and interfaces between its components.

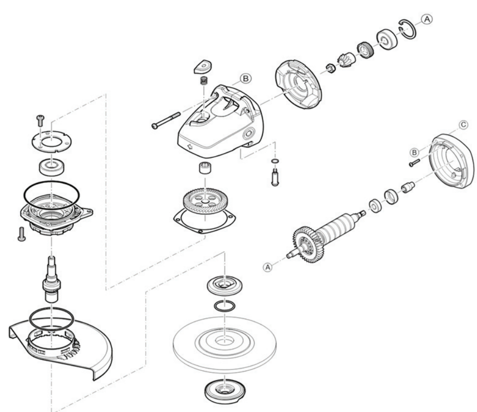

Fig. 3.Explosion view of the FEIN CG 15-125 BL angle grinder (adapted from FEIN 2025)

Further clarity is achieved by analyzing a computed tomography (CT) scan of the angle grinder (Fig. 4), which reveals internal interactions and connections that are not visible externally.

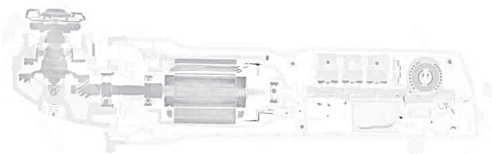

Fig. 4.CT scan of the FEIN CG 15-125 BL angle grinder (adapted from Blum, 2025)

The decomposition process successfully breaks the system into four hierarchical levels (Fig. 5):

1. System Level: Represents the angle grinder as a complete, functional unit.
2. Subsystem Level 1: Includes major functional subsystems, such as the housing and powertrain.
3. Subsystem Level 2: Comprises the components within each subsystem, which contribute to the overall functionality.
4. Component Level: Individual components, such as bearings, gears, shafts, and polymer parts, which can be assigned to the respective subsystems of the housing and powertrain.

This structured breakdown provides a comprehensive understanding of the system architecture, enabling the identification of critical components and their roles in the system's reliability.

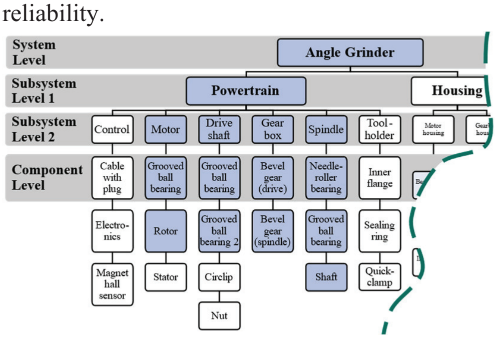

Fig. 5.Excerpt of the system structure of the FEIN CG 15-125 BL angle grinder, focusing on the powertrain

3.2. Step 2: Component Prioritization

Angle grinders are versatile power tools that operate by transferring rotational motion from an electric motor to a tool via a series of interconnected components. The components in the flow of force, and thus contributing to the functional behavior, can be identified using the C&C² approach (Fig. 6).

This case study focuses on the dynamic aspects of the mechanical behavior of the angle grinder, including characteristics such as torque transmission, vibration emission, and shaft deflection. On the powertrain side, motor control can be ruled out due to its electrical domain. All other subsystems including the motor, drive shaft, gear box and spindle are actively involved in the flow of mechanical energy. Regarding the housing, mainly the motor and gearbox housing are involved in the functional behavior, as power button, spindle lock button and wheel guard only contribute to auxiliary functions. From the remaining subsystems, certain components are picked to enable a detailed analysis of their failure modes and failure mechanisms (Table 1).

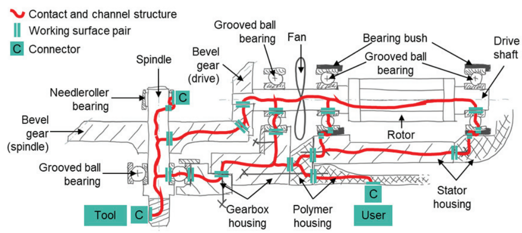

Fig. 6.C&C² Approach on the Angle Grinder

The grooved ball bearing and needleroller bearing are key to supporting the drive shaft and spindle. These bearings allow for the transmission of high-speed rotation of up to 40.000 rpm from the motor to the tool with minimal friction. Additionally, they absorb radial and axial forces that result from the operation of the angle grinder. To reduce the bearing seat stiffness and therefore influence the dynamic behavior, the grooved ball bearings of the drive shaft are mounted inside bearing bushes. Rotor and shaft are responsible for the actual transmission of the mechanical energy, directly impacting the torque and rotational speed delivered to the tool. The bevel gear stage is another vital component, as it changes the axis of rotation and provides the necessary torque for the specific use cases.

Together, these components are integral to the operational efficiency of the angle grinder. Their proper function and interaction ensure that the system performs reliably over its lifespan, which is essential for the context within a CF, where reusability and reprocessing depend on accurate state assessments of the components.

Table 1.Summary of components most critical for the functional behavior.

Subsystem Level 2	Component Level
Motor housing	Bearing bush 1 & 2
Drive Shaft	Grooved ball bearing 1 & 2
Gear box	Bevel gear (drive) Bevel gear (spindle)
Motor	Grooved ball bearing Rotor
Spindle	Needleroller bearing Grooved ball bearing Shaft

3.3. Step 3: Use Cases

Angle grinders are used in a variety of applications, each of which imposes different external forces and moments on the system. The external loads experienced by an angle grinder are primarily defined by its application, as these forces are transmitted through the grinding wheel into the drive train (Gwosch, 2019). Given the wide range of potential applications, numerous use cases can be identified, each with unique force and moment characteristics.

A study conducted by Gwosch (2019) systematically analyzed different use cases, ultimately deriving a representative load profile (Fig. 7) for three primary operations: cutting, roughing, and grinding.

The differences in moments and forces between different applications are clearly visible. Cutting generates the highest moments, while grinding generates the highest forces. As a result, the choice of application directly influences the expected failure modes.

For bevel gears, cutting operations appear to be the most demanding use case, as the high moments are fully transferred to the gears. In contrast, the axial and radial forces acting on the drive train are primarily supported by the bearings.

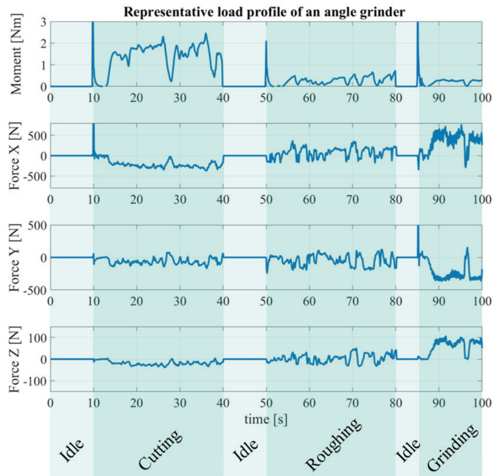

Fig. 7. Representative load profile of an angle grinder (adapted from Gwosch (2019))

3.4. Step 4: Component and Use Case Specific Failure Modes and Failure Mechanisms

As outlined in Section 3.2, bevel gears and bearings are critical components for achieving the functional requirements of angle grinders. This case study investigates bevel gears in angle grinders during cutting operations, identified as the most demanding and harmful use case for this application.

In the context of bevel gears in angle grinders, the literature identifies several failure modes, including but not limited to tribological damage, plastic deformation, fatigue phenomena, cracks, and tooth breakage (Fig. 8).

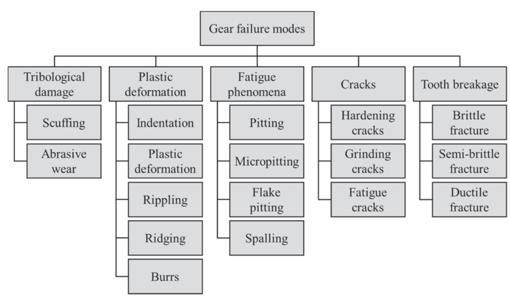

Fig. 8.Gear failure modes of an angle grinder (adapted from (Cubillo et al., 2016; ISO, 2022))

These failure modes are predominantly attributed to lubrication-related issues or strength-related causes (Ku, 1976). This case study focuses on strength-related causes, which are particularly relevant to high-speed bevel gears. Although lubrication-related issues are also significant and present unique challenges, addressing both simultaneously would dilute the study's focus. Common failure mechanisms in such gears include surface fatigue (pitting), abrasive wear, and tooth breakage (Joshi & Kothari, 2014; Wang & Wang, 2011).

Among these, tooth breakage is the focal point of this study due to its catastrophic implications for the application (Virtanen et al., 2024). The degradation mechanism underlying tooth breakage is typically excessive loading, which induces stresses beyond the material's fatigue limits (Cubillo et al., 2016).

3.5. Step 5: Input Parameters to Reliability Model

The final step in identifying the input parameters for the reliability model is to consider how the degradation of the system can be measured to its failure mode. In the case of tooth breakage, this involves to measure and analyze the identified failure mode, tooth breakage, and its associated degradation mechanism, excessive load. Excessive load can be quantified by monitoring torque, speed, axial forces and energy input during operation and comparing these measurements to baseline conditions representing 'non-excessive' loads.

For other degradation mechanisms, such as abrasive wear caused by metal-to-metal contact or surface fatigue in the form of pitting, parameters like noise, vibration, surface roughness and temperature are relevant for measurement. These indicators provide valuable insights into the progression of wear and can be used to assess the system's condition. Together, these measurement parameters describe the most common failure modes and mechanisms in high-speed bevel gears and are the input variables to the reliability model.

These measurement parameters (summarized in Table 2) provide a comprehensive assessment of the factors contributing to gear degradation and failure and should therefore be considered as input parameters to the instance-specific reliability model.

Table 2.Summary of possible measurement variables for the most common failure modes and mechanisms in angle grinders for high-speed bevel gears.

Failure mode	Measurement parameter	Measured quantity
Tooth breakage	Output-shaft torque	Nm
	Output-shaft rotational Speed	Rotation per seconds
	Axial forces	N
	Power input	A, V
Abrasive wear	Noise	dB
Surface fatigue (pitting)	Vibration	m/s²
	Surface Roughness	R_a, R_z
	Temperature	°C

4. Discussion

The presented framework for determining input parameters for reliability models offers a structured approach, providing a foundation for predicting the reliability in the context of the CF vision. However, its application in this study was restricted to a limited amount of components and use cases, making it largely exemplatory. For a complete analysis of the system, it is necessary to address all known failure modes across various components and use cases, extracting corresponding measurement variables for the reliability model.

This paper proposes the use of failure modes as a basis for determining the input parameters for the instance-specific reliability model. Failure modes are a good indicator of these input parameters because reliability models attempt to describe the degradation of the system over time until it fails. However, in the context of the circular factory, the instance specific reliability model needs to consider the full range of functional behavior. A degradation in functional behavior may not lead to a failure in the common understanding of failure.

The presented framework is uniquely suited to the CF because it focuses on instance-specific reliability models rather than general failure analysis. Unlike methods such as FMEA, which prioritize qualitative risk mitigation to prevent failures, this framework identifies quantitative input parameters essential for data-driven decision making in CF. Another key distinction is its integration with the functional behavior model, enabling a shared understanding and metric of system performance and degradation.

Challenges remain in determining the appropriate methods for measuring certain degradation mechanisms, like surface wear, as these mechanisms often need to be monitored in real-time during operation. Additional validation through diverse case studies and the extension of the framework to other product families and use cases would further strengthen its utility and generalizability.

One of the primary advantages of the framework is its systematic, step-by-step approach, which ensures that parameters are selected based on their relevance to specific failure modes. This step-by-step approach ensures that the model remains focused and avoids becoming too large and unmanageable. The framework's implications extend beyond this case study, offering a blueprint for creating reliability models tailored to complex systems.
The described framework not only depicts the system's architecture but also links it to specific use cases and component-based failure types. The framework highlights components and subsystems with significant interactions, providing a solid foundation for the determination of input parameters for instance specific reliability models capable of predicting the functional behavior of the angle grinder in a CF context.

The framework contributes directly to the CF vision by enabling the creation of reliability models that allow decisions to be made about the reprocessing within the CF based on data-driven reliability assessments.

5. Conclusion

In conclusion, this study presents a structured framework for identifying input parameters for reliability models within the CF context. The case study demonstrates the applicability of the framework through an analysis of tooth breakage in bevel gears of an angle grinder during cutting operations. By systematically decomposing the system and prioritizing components based on their contribution to functionality, the study identifies excessive load as a critical degradation mechanism. This enables the derivation of specific measurement parameters such as torque, speed, and axial forces, which serve as inputs for the reliability model.

While the framework is exemplary, its systematic nature offers significant potential for broader application. Future work will involve expanding the scope of the framework to other components completing the input parameter list for the reliability model. A potential advancement of the framework could involve mapping the interactions between components and the identified failure modes. This approach would establish a network of interconnected factors influencing system reliability, paving the way for the development of more sophisticated reliability models.

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While preparing this work, the authors used AI tools such as deepl.com and ChatGPT 4o to improve readability and language. After utilizing these tools, the authors reviewed and edited the content as necessary. The authors take full responsibility for the publication's content.

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