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Ensuring Reliability in Practice: An Exploratory Interview Study on Challenges, Trends, and Optimization Potentials

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Abstract

Ensuring the reliability of technical products is an essential part of modern product development processes. In the face of increasing complexity and variant diversity, companies are faced with numerous challenges. This paper presents the results of an explorative interview study conducted in various industries and company sizes. The aim was to analyze current practices, challenges, and potential for optimization in reliability assurance, especially for variant management. The results show amongst others that digital technologies, such as AI and digital twins, as well as a stronger integration of reliability into the product development process are key starting points for the future.

Keywords
Reliability Assurance, Variant Management, Quality Engineering, Digital Twins, Exploratory Interview Study

1. Introduction

Reliability assurance is a crucial factor for the safety, quality, and competitiveness of technical products. In many industries, short development cycles, growing product complexity, and increasing variant diversity pose enormous challenges. While safety-critical fields, such as automotive or aerospace, are guided by stringent standards (e.g., IATF 16949, ISO 26262), companies in less regulated sectors also experience a need to ensure reliable products. Traditional methods (e.g., FMEA, durability testing) remain vital. However, the pressure to reduce cost and time triggers a search for new, more efficient approaches, including digital twins, data analytics, and AI-based solutions. In particular, the increasing demand for individualized products significantly amplifies the challenge of variant diversity, posing additional complexity for reliability assurance. Ideally, each product variant would require individual reliability testing and validation, a process that becomes infeasible in practice due to resource and cost constraints. Consequently, systematic approaches that analyze and evaluate similarities between variants are necessary, enabling the efficient transfer of reliability information to new product variants.

This paper investigates a threefold perspective - past, present, and future - to assess the state of reliability assurance in different organizations (varying by size and sector):

- A literature review was conducted to understand established standards and approaches (the past).
- An exploratory interview study was conducted to uncover practical, real-world methods currently employed by organizations (the present).
- In the same interview study, experts gave their opinion on future trends and emerging technologies, aiming to identify how reliability assurance may evolve (the future).

This paper is structured as follows: Section 2 describes our methods and outlines the primary research questions. Section 3 presents results from both the literature review and the interview study, highlighting the gap between established standards and real-world applications. Section 4 offers a discussion of these findings, and Section 5 summarizes the core insights. Finally, Section 6 proposes an outlook on how reliability assurance could adapt to future demands.

2. Methods and Research Questions

To gain a comprehensive understanding of reliability assurance in industrial practice, we combine a literature-based analysis of established approaches with an exploratory interview study. This mixed-methods approach enables both a theoretical and empirical view on current procedures, challenges, and future potentials. The following section outlines the research questions guiding the study and describes the methodological steps taken in the literature review and the interview study.

2.1 Research Questions

The paper addresses three research questions:

1. How do organizations in different industrial contexts currently ensure product reliability during their development?
2. What are specific barriers, especially related to variant diversity and resource constraints?
3. Which optimization potentials and future trends do practitioners foresee, including digital solutions and organizational changes?

2.2 Literature Review

First, we conducted a structured literature review aimed at identifying established methods, tools, and standards in the field of reliability assurance. The search included both English and German terms such as “reliability engineering,” “reliability engineering testing,” “lifetime testing,” and “reliability engineering management.” Searches were carried out using Google Scholar, IEEE Xplore, and Scopus.

Relevant publications were selected based on topical relevance, citation frequency, and practical applicability. The review focuses on sources that describe qualitative and quantitative approaches, standardized procedures, and emerging technologies related to reliability assurance. Section 3 summarizes the key findings from this literature review, including common practices and methodological foundations.

2.3 Exploratory Interview Study

To complement the literature review’s historical and theoretical perspectives, we performed an exploratory interview study. Our aim was to ascertain what organizations currently do and to explore experts’ views on future developments. We interviewed ten participants from eight companies located in Europe, however primarily in Germany. These companies represented different sizes (from medium enterprises to large multinational companies) and operated in diverse industries, such as automotive components, mechanical engineering, renewable energy systems, and consumer goods. The experts hold positions such as Reliability Engineer, Development Operations Manager, or Head of Quality. Thus, they play a central role in reliability-related decision-making.

We developed a semi-structured interview guide, covering five key topics:

1. **Company and the participant Background including their role**
2. **Current reliability assurance practices in the company**
3. **Approaches to assuring the reliability of product variants**
4. **Challenges and pain points in current reliability assurance in the company**
5. **Prediction of a possible future in reliability assurance**

Each interview lasted between 60 and 90 minutes and was held via an online meeting platform. After obtaining consent, we audio-recorded the sessions and then transcribed them. We performed a qualitative content analysis, focusing on recurring themes, similarities, and differences across participants.

For the analysis, we applied a qualitative content analysis approach, which is well-suited for systematically evaluating large amounts of textual data while maintaining flexibility in interpreting meaning (Mayring, 2014; Schreier, 2012). The process involved several steps. First, we familiarized ourselves with the transcripts and developed a preliminary coding frame, derived deductively from the interview guide and inductively from the data. The coding frame was applied to the full dataset, allowing us to identify recurring themes, patterns, and contrasts across participants and companies. Afterall, we summarized and interpreted the results in both the empirical material and the theoretical background. This methodological approach ensured transparency, traceability, and analytical stringency in the interpretation of the data (Kuckartz, 2014).

3. Results

This chapter presents the results of the literature review and the exploratory interview study. First, we summarize the state of the art in reliability assurance based on relevant publications and standards. Subsequently, we present key findings from the expert interviews, including practical procedures, current challenges, strategies for managing product variants, and perspectives on future developments.

3.1 State of the Art in Reliability Assurance

The term *reliability* is defined in various ways throughout literature. A common textbook definition describes it as the ability of a product to perform its intended function under specified conditions for a defined period (Meeker und Escobar 2004). Condra offers a more user-centered definition:

"*A reliable product is one that does what the user wants it to do, when the user wants it to do so*"
(Condra 2001)

The terms reliability and functionality are not interchangeable. Therefore, it is important to distinguish clearly between *functionality*, which indicates whether a product performs as designed, and *reliability*, which refers to the probability that it will consistently maintain its intended performance under given conditions over time.

Bertsche and Dazer (2022) divide the assurance of system reliability into design driven and analytical methods. Design driven methods rely on optimized design processes leveraging precise stress calculations in components and the application of proven design guidelines. Analytical methods aim to estimate a product's reliability and optimize it where needed. The objectives are to project reliability and identify vulnerabilities in both the product and its manufacturing process. Both quantitative and qualitative methods can be used in this context.

Failure Mode and Effect Analysis (FMEA) is a commonly applied qualitative method developed by NASA (National Aeronautics and Space Administration) during the Apollo Project in the 1960s. The American military standard MIL-STD-1629A outlines the fundamentals of the method . Updates to the method can be found in more recent literature (;). In summary, the aims of an FMEA are to identify possible failure modes, their consequences, and causes, and to assess the resulting risk.

Fault Tree Analysis (FTA**)** is another qualitative, top-down method developed in the early 1960s at Bell Laboratories for the U.S. Air Force (Ericson 1999). FTA identifies potential causes of system failures by modeling the logical relationships between components and subsystems using Boolean logic gates. This approach helps to pinpoint critical failure paths and understand how basic events can lead to system-level failure. For standardized application, guidelines are provided in standards such as IEC 61025:2006 .

A significant part of quantitative reliability assessment involves testing products or systems under load and measuring the time or cycle count until failure. This can be approached in different ways. One method is to conduct failure-free lifetime tests until a specified time is reached, resulting in a so-called success run test. These tests are suitable for reliability demonstrations but do not offer information on the failure behavior, as no failures are expected to occur. Alternatively, failure-based lifetime tests are conducted until the product fails. Combining both failure and survival information results in censored data. Failure-based testing provides insights into actual failure behavior and, when sufficiently replicated, yields a distribution of failure times.

To reduce test time, Accelerated Lifetime Tests (ALTs) can be employed by increasing the load on components, provided that the resulting failure mechanisms remain representative. Additionally, Highly Accelerated Life Testing (HALT) exposes products to stress levels well beyond operational conditions to rapidly identify weaknesses and failure points. Comprehensive overviews of test planning, execution, and evaluation of lifetime data can be found in the literature. Notable references include Meeker and Escobar (1998), Nelson (2005), Bertsche and Dazer (2022), and Yang (2007).

3.2 Interview Results

The interview participants in this study hold various positions within their organizations. Three participants are Reliability Experts. Additionally, roles such as Head of Development Operations, Reliability Engineer, Lean Development Manager, Head of Development, Development Engineer, R&D Manager, and Central Quality Management are represented by one participant, each. The sample comprised eight companies: automotive supplier, renewable energy systems, precision positioning systems, steel tubes and components, special vehicles, machine tools, cleaning systems, and household appliances.

We provide an overview of the companies interviewed. In this overview, the sector of the company is given, number of employees and the dedicated staff in regards of reliability. Dedicated employees for reliability mean that employees have to deal with reliability in their everyday work due to their job title or area of responsibility. Moreover, in what context each company uses reliability and what their main obstacles in regard of reliability are (see Table 1).

Table 1. Overview of participating companies and reliability resources

ID	Sector	Employees	Dedicated reliability staff	Context highlights	Main obstacles
A	Automotive supplier	≈35 k	≈12	Operates under strict automotive standards (IATF 16949); uses FMEA, lifetime tests and risk analyses; combines data from warranty databases to design test plans	High variant diversity; identifying worst-case loads; need for improved AI based data analysis and collaboration with research institutions
B	Renewable Energy Systems	≈5 k	4 full time	Focus on long-term reliability (e.g., 20 years); emphasizes component level tests, uses a question catalogue and risk priority numbers; obtains data from suppliers	Ensuring reliability of 24/7operating devices; limited test equipment and high costs; need for more resources and better data from suppliers
C	Precision positioning	≈2 k	≈200	Recently introduced a new product development process (PEP); phases include strategy, concept, prototype, testing and iteration; uses Wöhler tests and probability calculations	Lack of mature requirements (incomplete required specifications); insufficient field data; need for efficient test strategies for many product variants
D	Steel tubes	≈2 k	n/a	Relies on compliance with industry standards and experience-based test plans; uses FMEA and risk analyses mainly for new product fields (e.g., battery housings)	Relatively low variant complexity; limited automation; dependence on operator experience; desire for automated quality control
E	Special vehicles	≈1 k	Mixed (not specified)	Product variants defined by application (snow vs. industrial); uses	High variety of customer-specific variants; limited

				audits, validation, and stress tests on steel components; calculates failure probability using Wöhler curves	dedicated reliability resources; need for staff training and a company-wide reliability database
F	Machine tools	≈20 k	Integrated (not specified)	Emphasizes data-driven development; uses FMEA, simulation and condition monitoring; extremely high number of product variants (estimated 10^{30}–10^{40}); invests in connectivity and AI features	Managing variant complexity; lack of standardized software architectures; integrating data from multiple sources; need for simulation models and digital twins
G	Cleaning systems	≈16 k	≈1 k	Comprehensive reliability process covering concept, design, testing and field trials; uses FMEA, PPAP, accelerated tests, simulation, and field tests; monitors products for up to 12 months after launch	Growing variant diversity and shorter development cycles; need for early integration of reliability; requires greater transparency and digitalization across departments
H	Household appliances	≈40 k	≈100 (25 core)	Uses a global reliability program ("Reliability Excellence") and V-model; analyses requirements and loads, performs component and system tests; uses "golden samples" and reference loads for variants	Lack of clear load definitions for variants; cultural resistance to reliability as a design criterion; need for simple training materials and improved digital tools

Participants emphasize that the sophistication of reliability assurance varied markedly between companies. Large organizations in regulated sectors have dedicated reliability programs, specialized departments and formal training. Medium-sized firms often integrate reliability into general quality assurance and rely more on experience and pragmatic testing.

Aside from the company contexts and reliability resources, we identified four topics from the ten expert interviews: (3.2.1) current reliability procedures, (3.2.2) challenges in practice, (3.2.3) strategies for variant management, and (3.2.4) perceived future directions. Those are described in the following sections.

3.2.1 Current Reliability Procedures

Across the sample, companies employ a combination of qualitative and quantitative methods. All participants use FMEA to identify failure modes and prioritize risks. FTA is less widely used, but some companies rely on it for complex failure scenarios. Lifetime testing, including success-run tests and accelerated tests, is common in safety critical sectors. Several organizations collect field data from warranty databases or sensors to inform load profiles and test plans. Digital tools, such as data management platforms and simulation software, support analysis.

Nevertheless, the extent and sophistication of reliability assurance varies. Large companies in regulated sectors (e.g., vehicle suppliers, machine tools, household appliances) have dedicated reliability processes, specialized departments, and formal training programs. The company in the field of renewable energy systems and other medium enterprises often integrate reliability into general quality assurance and rely more on experience and pragmatic testing. Key methods and tools for each company and highlights similarities and differences are summarized in Table 2.

Table 2. Reliability assurance methods, processes, and tools by companies

Category	Example Elements	Companies (ID from Table 1)
Qualitative methods	FMEA, Risk Priority Numbers, Question Catalogues	A, B, C, D, E, F, G, H
Quantitative testing	Weibull analysis, Success-run, Wöhler tests	A, B, C, E, H
Digital tools	Simulation, nCode, DOE, IoT platforms	A, B, C, F, G, H
Variant management methods	Golden Samples, Worst-case, Component aggregation	A, B, C, E, H
Formal process models	PEP, V-Model, APQP/PPAP	C, F, G, H
Field data integration	Warranty data, Field monitoring	A, G, H
Supplier collaboration	Supplier data exchange, External test labs	B, E

3.2.2 Challenges in Practice

Interviewees highlighted several recurring challenges:

1. **Resource constraints:** Many companies struggle with limited budgets, time, and personnel. Longterm life testing, especially with large sample sizes, is costly. Obtaining sufficient test specimens is problematic for expensive products. Smaller firms often lack dedicated reliability engineers and rely on generalists.
2. **Variant diversity:** The proliferation of product variants makes exhaustive testing impractical. Participants emphasized the difficulty of extrapolating test results from one variant to another as small design changes or new use cases can alter failure behavior. Identifying critical differences and designing efficient test plans is challenging.
3. **Insufficient data:** Reliable load profiles and field data are often missing, particularly for new products or novel applications. Without realistic stress profiles, companies cannot design representative tests or calibrate models. Even when data exist, they may be siloed across departments or suppliers.
4. **Awareness and company culture:** In several companies, reliability is not yet viewed as a strategic priority. Decision makers sometimes regard reliability tests as a cost rather than an investment. This leads to late integration of reliability tasks and insufficient training for developers.
5. **Complexity and digitalization:** The integration of electronics and software increases system complexity and introduces failure modes not covered by traditional mechanical tests. Data integration across platforms and the lack of standardized software architectures hinder the use of analytics and digital twins. Ensuring the reliability of AI enabled products is itself an emerging challenge.

3.2.3 Strategies for Variant Management

A central challenge across companies is managing variant diversity without testing every variant. Strategies identified include:

- **Worst-case testing:** The automotive supplier identifies the worst-case load conditions and tests only those scenarios. Variants within the "load envelope" are assumed to be covered. Renewable energy system developers and precision positioning systems similarly identify critical components or paths and apply tests under the harshest conditions.
- **Critical path or module analysis:** The company in precision positioning systems considers defining a "critical path" through the modular product architecture and testing it thoroughly. The company in the sector of household appliances uses "golden samples" and reference loads; by comparing how loads and stress differ across variants, they infer reliability without testing every variant.
- **Simulation and digital twins:** The machine tools manufacturer relies on simulation to handle its enormous variant space. By virtually testing configurations, it reduces physical prototypes. Digital twins could enhance this approach by providing synchronized virtual models that predict performance and identify critical configurations.
- **Component focus:** The renewable energy system manufacturer tests components individually and then aggregate reliability at system level. The assumption is that a variant's reliability is largely driven by its

most sensitive components. The special vehicles manufacturer uses a similar approach by grouping variants with comparable loads and using results from the more severe variant.

- **Experience and standards:** The steel tube producing company emphasizes compliance with standards and relies on experience; as its products differ mainly in dimensions, the company assumes the same reliability behavior. The manufacturer of cleaning systems often does not retest country variants when changes are minor, instead relying on knowledge of components.

These strategies reveal a tradeoff between efficiency and risk. While worst-case and component focused approaches reduce test effort, they depend on accurate identification of critical conditions. Simulation and digital twins can help by exploring a larger design space and quantifying uncertainty but require high-quality data and validated models. Despite these efforts, several participants emphasized the risk of "false confidence" when untested design elements deviate more than anticipated.

3.2.4 Future Directions and Optimization Potentials

In the interviews, the interviewees spoke about several promising trends and improvement areas. We summarized them to the following five topics:

1. **Digital twins and predictive analytics:** Many practitioners foresee digital twins becoming integral to reliability assurance. Digital twins provide synchronized virtual models that allow monitoring, simulation, and prediction without interacting with the physical asset. Establishing reliability in a digital twin depends on reliable data acquisition, accurate models, and platform stability. By enabling scenario simulation and predictive maintenance, digital twins can reduce physical testing and accelerate design iterations.
2. **AI and machine learning:** AI can process large data sets to detect patterns, estimate remaining useful life and predict failures. Participants hope that AI will help identify critical loads, automate data analysis and recommend test scenarios. However, they emphasize the need for explainable models and caution against overreliance on black box algorithms.
3. **Data-driven processes:** Improved data capture (e.g., via sensors, IoT) and integration across the product life cycle enable better load modelling, risk assessment and variant management. Automated data checks, model validation and uncertainty quantification – as suggested in digital twin reliability literature – can enhance trust in simulation outputs.
4. **Early integration and culture change:** Embedding reliability considerations early in the product development process can prevent late redesigns and reduce costs. Participants advocate for training programs to raise awareness of reliability engineering and to integrate FMEA, FTA and lifetime testing into design reviews. Upper management support is crucial to prioritize reliability.
5. **Standardization and collaboration:** Participants desire more standardized methods for variant management and reliability assurance across industries. Collaboration with research institutions, adoption of common data formats and participation in industry consortia could accelerate development of best practices. International comparison studies could broaden perspectives and reveal regional differences.

4. Discussion

The following chapter discusses the key findings of this exploratory study in relation to existing standards, current industrial practices, and anticipated developments in the field of reliability assurance. By comparing the insights from expert interviews with the existing body of literature, the discussion highlights gaps, trends, and practical implications for both practitioners and researchers. The chapter concludes with a reflection on the study's limitations and avenues for future research.

4.1 Established Standards

The literature review reveals a clear discrepancy between the availability of standards and methods for reliability assurance and their practical applicability. General frameworks such as IEC 60300 (IEC 60300) aim to support dependability assurance but often lack clarity, actionable guidance, and explanatory use cases, especially in complex, variant-rich environments. More specific handbooks, such as MIL-HDBK-217F (Department of Defense, Washington DC 1991) for electronic components, offer detailed prediction methods but are too narrowly focused to support holistic reliability assurance across diverse product types.

This observed gap underscores the importance of investigating current industrial practices to understand how companies adapt and implement reliability measures. It also highlights the need for more flexible, scalable, and practical tools, especially in the context of high product variety and digital transformation.

4.2 Current Practices

The interviews confirm that FMEA and FTA remain the backbone of systematic failure analysis in industrial practice. FMEA is used to identify potential failure modes and their effects, while FTA provides a top-down analysis of system-level failures. These qualitative methods are complemented by lifetime testing, component qualification, and increasingly by simulation and data-driven approaches.
Companies strive to embed reliability assurance throughout the product development process, from concept and design, to testing and launch. Larger organizations, particularly in regulated industries, often have dedicated reliability departments and structured processes. Smaller companies typically integrate reliability tasks into quality assurance functions and rely more heavily on experience-based knowledge. Despite these efforts, several challenges persist:

- Limited resources, especially in smaller firms.
- High product and variant complexity, which complicates testing and validation.
- Lack of representative field data, making extrapolation across variants difficult.
- Fast-paced development cycles, which leave little room for comprehensive reliability testing.
- Cultural resistance to early investment in reliability, as it is still often perceived as a cost factor rather than a strategic enabler.

These challenges lead to heterogeneous approaches and highlight the need for stronger integration of reliability thinking, clearer responsibilities, and improved awareness across organizational boundaries.

4.3 Future Trends and Digital Technologies

Digital technologies such as digital twins, AI-driven analytics, and predictive maintenance are widely discussed in the literature as enablers of next-generation reliability assurance. In practice, however, adoption remains limited. Many companies are only beginning to collect relevant field data or experiment with simulation-based methods.

Developing validated digital twin models, establishing data governance structures, and investing in sensor technologies are crucial steps toward building trustworthy digital solutions. The combination of simulation, statistical design of experiments (DoE), and sensitivity analysis is seen as a promising approach to identify critical parameters and reduce physical testing effort, especially in variant-rich development environments.

Variant management emerged as one of the most pressing yet underdeveloped areas. Current strategies such as worst-case testing and component-level risk assessment offer partial solutions but lack systemic integration. Standardized frameworks and the sharing of best practices across industries could improve the handling of variant diversity. Looking ahead, practitioners anticipate significant potential through:

- Earlier integration of reliability in the development process.
- Cross-functional collaboration and improved training.
- The use of technologies such as 6G and quantum computing to enhance data transmission and simulation capabilities.

Nonetheless, the foundation of any digital approach remains high-quality, validated data. Without it, digital tools will not be able to replace the insight gained from physical testing. The integration of traditional engineering rigor with modern digital techniques is thus seen as essential for achieving reliable products in increasingly complex environments.

4.4 Limitations

As an exploratory study, this work has limitations that affect the generalizability of its findings. The interview component is based on qualitative insights from ten experts in eight companies. While the data is rich in context, it cannot be extrapolated to all organizations. The sample was limited to firms based in Europe, and practices may vary across different regulatory environments or business cultures.

A larger, more diverse sample, regarding both geography and lines of business would be needed to draw firmer conclusions about sector-specific patterns and international differences. Furthermore, self-reporting by interviewees may introduce bias. Future research should aim to complement interview data with quantitative surveys or direct observations to strengthen validity and triangulate findings.

These limitations should be considered when interpreting the results and formulating recommendations for practice and policy.

5. Conclusion and outlook

This exploratory interview study demonstrates that reliability assurance in practice is multifaceted. Companies employ a blend of traditional methods and emerging technologies, adapting them to their sector, size, and product complexity. Resource constraints, variant diversity and data limitations remain significant obstacles. Nevertheless, practitioners foresee substantial optimization potential through digital twins, AI based analytics, and early integration of reliability into development processes.

For the future, the following recommendations emerge:

- **Adopt data-driven digital twins:** Develop and validate digital twins by focusing on accurate data acquisition, model fidelity and platform stability. Use digital twins to explore variant space and predict failures, thereby reducing physical tests.
- **Invest in AI and predictive maintenance:** Leverage AI to process field data, identify patterns and estimate remaining useful life. Ensure explain ability and integrate AI results into reliability planning.
- **Enhance variant management:** Combine simulation, design of experiments, and sensitivity analyses to identify critical parameters and reduce the number of required tests. Develop standardized frameworks for variant assurance across industries.
- **Strengthen culture and training:** Promote reliability awareness among engineers and management. Integrate reliability engineering into curriculum and professional development programs. Use simple, practical training materials to demystify statistical methods.
- **Encourage collaboration:** Collaborate with academia, industry consortia, and standards bodies to share best practices and develop harmonized methods. International comparison studies will broaden perspectives and foster innovation.

As products become more complex and digital technologies evolve, reliability assurance must evolve as well. By combining the rigor of classical methods with the agility of data driven tools, organizations can ensure that future products remain dependable despite the challenges of variant diversity and rapid innovation.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used trint, ChatGPT, DeepL, Grammarly, and LanguageTool in order to improve readability, grammar and to support translation into well written English. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. The authors were responsible for the study design, data collection, data analysis, and interpretations. The tools mentioned were used exclusively for transcribing the recorded interviews and for language and translation services.

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