Robust reliability or reliable robustness?

Integrated consideration of robustness- and reliability-aspects

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Kurzfassung

Als zuverlässig bzw. robust werden im Allgemeinen Produkte oder Prozesse beschrieben, die den bestehenden Qualitätsanforderungen entsprechen. Gleichzeitig haben Definitionen aus dem Bereich Zuverlässigkeitstechnik und Robust Design allerdings keine grundlegende Übereinstimmung. In Wissenschaft und Praxis ist weitgehend ungeklärt, inwieweit die Entwicklung robuster Produkte zwangsläufig die geforderte Zuverlässigkeit sicherstellt bzw. ob eine Zuverlässigkeitsanalyse notwendigerweise zur Robustheit führt.

Um den zwischen beiden Theorien bestehenden Zusammenhang zu verdeutlichen und gezielt auszunutzen, werden im vorliegen Beitrag Vorteile und potentielle Synergien diskutiert. Die Entwicklung eines grundlegenden Modells für eine integrierte Betrachtung von Produktzuverlässigkeit und -robustheit bietet darüber hinaus erste Leitlinien für die Auswahl geeigneter Entwicklungsmethoden und somit eine geeignete Grundlage für zukünftige Untersuchungen.

Abstract

Commonly, the terms reliability and robustness are used to describe products and processes, which are in accordance with the customer requirements and fulfil high quality expectations. However, significant differences between the underlying definitions raise the questions how reliable robust products are and vice versa.

For a comprehensive understanding and to use existing synergies between both domains, this paper discusses the basic principles of *Reliability-* and *Robust Design theory*. The development of a comprehensive model will enable an integrated consideration of both domains in the future, will offer guidance for a systematic choice of corresponding methods and is thus aiming to pave the way for future research.

1. Introduction

The terms robust and reliable are both used to describe products and processes, which are in accordance with the customer requirements and fulfil high quality expectations. In academia as well as in industrial practice, this common objective seems to have led to an ambiguous use of basic definitions and terms. Johannesson et al. [8] for example state that “failures caused by bad designs, rough usage, and poor quality could be denoted as lack of robustness”. In contrast, Gamweger et al. [6] use the widely used bath-tub curve for a distinction of a product’s robustness during normal operation and its reliability focusing on the degradation of product performance over time.

At the same time, previous investigations of the authors [4, 11] suggest that robustness and reliability are not necessarily achieved simultaneously. Robust products might, for example, fail during their expected life time. Similarly, reliable products are obviously not robust per se. Large safety factors, for example, help to prevent quality issues and product failures but lead at the same time to a reduced efficiency and an increased consumption of resources, i.e. reliability at excessive costs.

Concluding, there neither seem to be a generally recognized agreement on the range of *Reliability-* and *Robust Design philosophy*, nor a clear delimitation of corresponding *Reliability Engineering* and *Robust Design* approaches which are frequently subsumed under one single category in surveys on the use of design methods in industrial practice [4].[1] Therefore, the purpose of this paper is to offer support and guidance for a clear assessment of interdependencies and existing synergies between the two domains. The overall aim is to lay the foundation for an integrated consideration of product reliability and robustness enabling a systematic choice of corresponding methods and stimulating future research. Three guiding questions structure the paper:

1. What are the fundamental principles of *Reliability-* and *Robust Design theory*?
   (section 2: explanation of basic objectives, principles as well as an overview about used approaches)
2. How can the merits of product reliability and robustness be combined?
   (section 3: model foundation for an integrated consideration of product reliability and robustness)
3. What is the potential for an integrated consideration of *Reliability-* and *Robust Design theory* for academia and industrial practice?
   (section 4: discussion of potential benefits for the choice of methods as well as future research)

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[1] Please see Eifler et al. [4] for an overview of the corresponding basic references.

2. Basic principles of Reliability Engineering and Robust Design

For an in-depth discussion of fundamental differences, interdependencies and synergies between reliability and robustness, the basic principles of the two domains are presented.

2.1 Reliability Engineering

Due to various influences, product lifetime is a stochastic rather than a deterministic value. Therefore, it is commonly described by means of statistic measures, illustrated for example by the widely known model of the stress strength interference [1]. A convergence of loading capacity and occurring stresses over time, e. g. due to degradation effects, leads to an interference, and thus a product failure. The resulting probability of when a failure occurs, the expected time period without failures respectively, is described as reliability. A product's reliability is consequently defined as its "ability to perform as required, without failure, for a given time interval, under given conditions" [7].

A variety of qualitative and quantitative methods is available to assess the expected reliability of products and components [1] as well as for the acquisition of trustworthy data required for a meaningful stochastic description of the product lifetime [13, 14]. Complemented by the calculation of confidence intervals, which accommodates the uncertainty of how good the used samples reflect the true population parameters [15], these approaches are an essential part of *Reliability Engineering* in industrial practice.[2] However, in addition to the importance of a systematic reliability assessment, various authors also emphasize the relevance of design decisions for the assurance of the required product performance over time in case of wear, corrosion, etc. [1, 5, 17]. Elsayed [5] for example clarifies that reliability indicators "may be used as a measure of the system's success in providing its function properly during its design life" indicating that reliability largely depends on the quality of designs [17].

The overall objective of *Reliability Engineering* consequently is the comprehensive analysis, assurance and improvement of the expected product reliability by means of suitable qualitative and quantitative methods. Including a variety of tasks, such as the systematic description of failure causes, the identification of relevant components, the assessment of failure probabilities extended by a calculation of confidence intervals for the drawn conclusions, *Reliability Engineering* is a highly complex but, at the same time, extremely important challenge for quality assurance purposes in industrial development projects.

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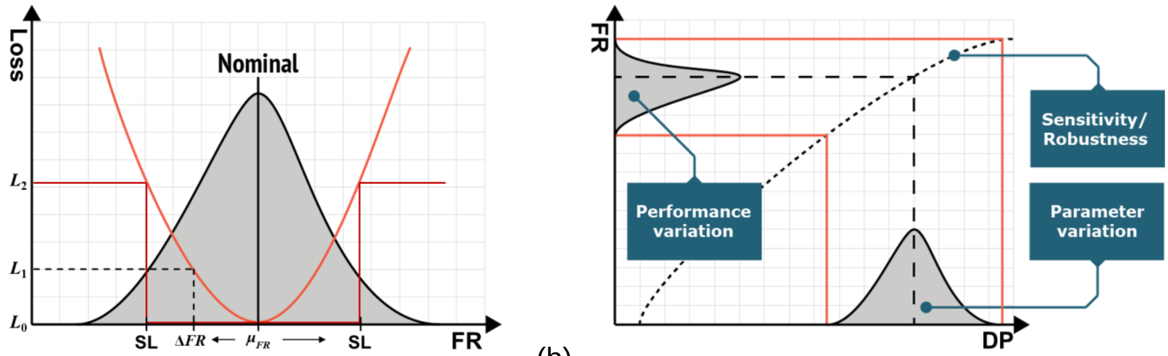
[2] Whereas Meeker [13] and Nelsen [14] offer an overview of suitable data acquisition approaches, further information on the calculation of confidence intervals can be found in O'Connor, Kleyner [15].

2.2 Robust Design

Robust Design has evolved into a variety of research fields over time, including *Robust Design Methodology*, robust parameter optimization, etc. [4, 9]. Nevertheless, the basic principles mostly originate from the work of the Japanese engineer and statistician Genichi Taguchi in the late 1950's [16]. To extract the essence of robustness and to clarify the overall objective of *Robust Design*, they are still the most relevant.

Fundamentally, robustness describes the insensitivity of products or processes against different sources of variation, such as production or assembly tolerances, not (fully) specified load scenarios or ambient use conditions [16, 9]. Whereas traditionally accommodated by quality control measures, safety factors, etc., i. e. additional costs or inefficiencies built into products, *Robust Design* consequently aims at the development of products or processes which function as intended in spite of this variation [2]. The underlying, essential assumption is best illustrated by means of the *Quality Loss Function*. Traditional quality control methods interpret all products within specification limits (SL) as equally good. In contrast, Robust Design is based on the awareness that every variation of the required product performance ΔFR can lead to a loss L_x of the customer's quality perception [16, 4], see Figure 1 (a).



(a) (b)

Figure 1: Relevance of variation described as (a) *Quality Loss* and the (b) *Transfer Function*

The aim of Robust Design is consequently to minimize the variation of the relevant product performance which is usually influenced by a large number of different factors. Figure 1 (b) illustrates this dependency simplified to one single design parameters (DP). The gradient of the shown so-called *Transfer Function* $FR = f(DP)$ represents the product's sensitivity towards the variation of the input parameter $\Delta\sigma_{DP}$, in other words its robustness [15, 9]. The steeper the gradient is, the higher the resulting variation of the performance $\Delta\sigma_{FR}$ will be. The design of robust products or processes relates consequently to an intended and systematic manipulation of the transfer function's gradient. Please see the summary of Eifler et al. [4] for an overview about the variety of corresponding methods available nowadays.

3. Integrated consideration of product robustness and reliability

The explanation of fundamental principles and aims in section 2 indicates the close correlation between a product's reliability and its robustness. At the same time, the existing similarities seem to have led to an ambiguous use of terms and corresponding methods in literature and industrial practice as pointed out in section 1.

To bridge this gap and to offer guidance for the choice of methods and thus the exploitation of synergies, a model linking the fundamental principles of *Reliability Engineering* and *Robust Design* is developed in three subsequent steps (see sections 3.1 to 3.3 below). Using the example system proposed in Eifler [3], the potential of the integrated consideration of the two domains will be illustrated based on two different embodiments of a friction plate clutch. The main purpose of these almost identical clutches, shown in Figure 2 (a) and (b), is the transmission of a constant torque between input shaft and output gear. Realized by means of a spiral spring in Figure 2 (a) and a disk spring in Figure 2 (b), which both set the maximum force between the friction plate and the gear wheel, the clutch furthermore acts as safety device as an overload will cause the components to slip.

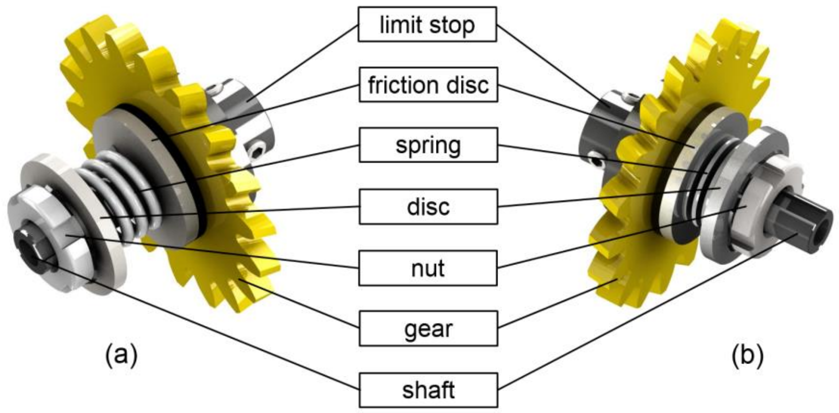


Figure 2: Embodiment of a friction plate clutch using (a) a spiral spring and (b) a disk spring

3.1 Variation-focused reliability assessment

One essential conclusion for an integrated consideration of reliability and robustness is the fact that the two theories are built upon different failure criteria. As pointed out in section 2.1., *Reliability Engineering* approaches commonly rely on the *Stress-Strength Interference*, i. e. an increasing probability of failure over time due to the interference of load capacity and occurring stresses. In *Robust Design theory*, on the other hand, every variation of design parameters, quality characteristics or product performance is understood as a quality loss as indicated by the *Quality Loss*, the *Transfer Function* in section 2.2.

To allow for an integrated consideration of both aspects, the importance of variation as well as of a stochastic indicator describing product quality, the stress-strength interference is combined with the description of the Transfer Function in a first step, see Figure 3. In accordance with the previously presented methodology SMART (*Systematic Method for Axiomatical Robustness-Testing*) proposed by Kemmler [10, 12], the assessment of reliability is thus generalised to a comprehensive consideration of varying design parameters $\Delta\sigma_{DP}$ leading to a variation of the overall product performance $\Delta\sigma_{FR}$. By the definition of specifications limits (SL), the model moreover enables the determination of the probability that intolerable variation occurs $F = P(|\mu_{FR} + \Delta FR| \notin SL)$ and accordingly the calculation of a stochastic reliability index $R = P(|\mu_{FR} + \Delta FR| \in SL)$.

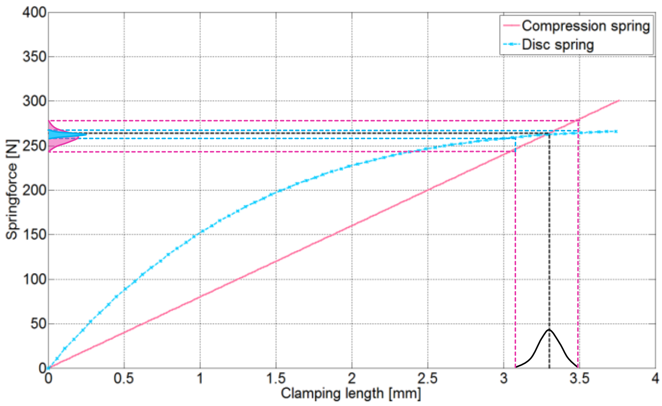


Figure 3: Linear/non-linear transfer function for two embodiments of the friction plate clutch

For clarification purposes, the variation-focused reliability assessment as well as the importance of robustness is illustrated using the example of the friction plate clutches shown in Figure 2. Neglecting potential variation of the planned clamping length ($s = 3{,}3\ \mathrm{mm}$), both springs generate the required nominal force ($F = 260\ \mathrm{N}$). However, whereas the spiral spring is characterised by a linear interdependency between the clamping length and the resulting spring force, the disk spring shows a degressive spring characteristic, see also Figure 3. In accordance with the explanations above, the disk spring is consequently less sensitive to variation resulting for example from a gradual wear of the friction disk or assembly tolerances, and is thus more robust.

Concluding, the safety function as well as the required torque transmission of the clutches is secured by a specified window for the tolerable contact force between friction disk and gear wheel ($SL_{F,min}$ and $SL_{F,max}$) applying to both embodiments. The reliability of the clutches consequently depends on the ***variation of DPs*** (the clamping length s) as well as on the system's ***robustness*** which both have a significant influence on the resulting variation of the contact force and a potential interference with the specifications limits.

3.2 Time-dependent change of quality characteristics

It has to be noted though, that the presented variation-focused view on reliability is limited to a non-time-dependent consideration. Whereas technical systems and components are inevitably exposed to wear, fatigue, creep, etc., the focus of *Reliability Engineering* methods on the assurance of the resulting long-term product performance is neglected so far.

To capture corresponding degradation effects occurring over time, the variation-focused analysis of product reliability presented in section 3.1 is extended by a time axis, see Figure 4 (a). Referring to the example of the friction plate clutch, the resulting generalized and comprehensive consideration of a time-dependent change of the target function for the system's robustness $FR(t) = f(DP(t))$ allows for the differentiation of two different key drivers for long-term product performance, i. e. the product's reliability indicated by the distribution interference at t_2:

(1) inevitable ***degradation of DPs*** over time leading to a mean shift $\Delta\mu_{DP}(t)$ and/or an increasing variation $\Delta\sigma_{DP}(t)$ (e. g. the wear-out of the friction disk usually described stochastically in *Reliability Engineering*)

(2) a ***reduced robustness*** due to the impact of noise factors during the product's lifetime as pointed out by Yang [16] (e. g. a changing transfer function induced by temperature effects affecting the spring constant over time)

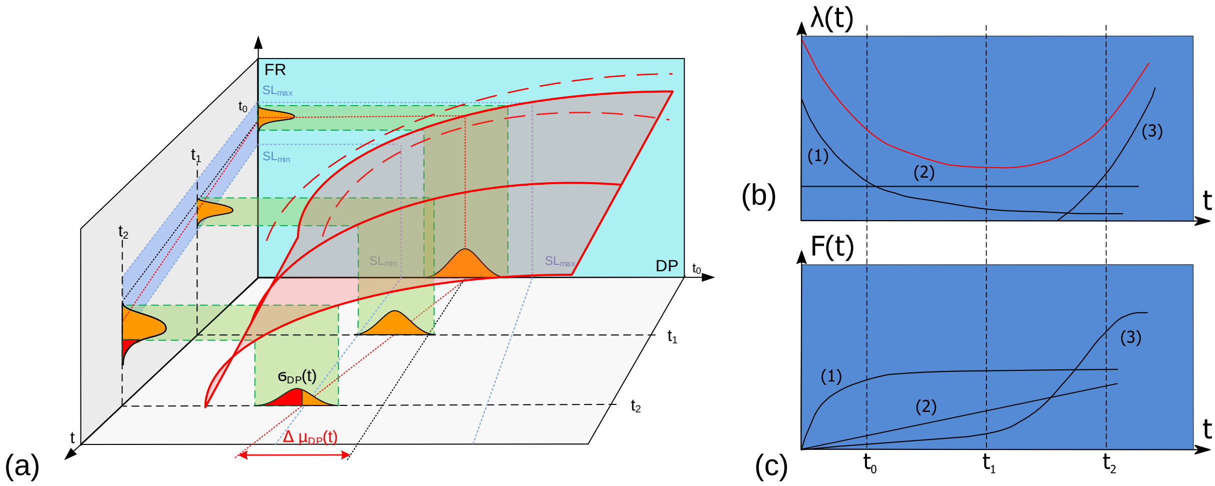


Figure 4: Time-dependency of (a) a variation-focused reliability assessment, (b) failures rates as well as (c) failure probability

However, as indicated by the description of the widely known bath-tub curve, an increasing failure rate $\lambda_3(t)$ due to degradation effects over time and the corresponding increasing failure probability $F(t)$ (curve 3 in Figure 4 (b) and (c)) is just one driver for reliability. The focus on a single failure cause consequently needs to be extended by a consideration of underestimated variation due to misjudgements in design $\Delta\sigma_{DP}(t_0)$ (curve 1) and a random variation $\Delta\sigma_{DP}(t_1)$ (curve 2) caused for example by an ambiguous/overconstraint design and the resulting uneven wear-rate [2]:

(3) ***unexpected variation of DPs*** $\Delta\sigma_{DP}(t_i)$ (e. g. an uneven wear rate of the friction disks due to overconstraints resulting in internal stresses)

4. Discussion

A model for a comprehensive variation-focused reliability assessment is presented in this paper. As visualised in Figure 5, it combines basic principles of *Robust Design* and *Reliability Engineering* allowing for a mathematical description of the time-dependent failure probability:

$$F(t) = \int_0^{t(\int f(t)=1)} (FR(t) \geq SL_{max} \vee FR(t) \leq SL_{min})\, dt$$

Given that $FR(t) = f(DP(t))$, i. e. that variation of performance $\sigma_{FR}(t)$ can either result from degradation or a changing transfer function, the model consequently supports the assumption from section 1 that product reliability and its robustness are interdependent.

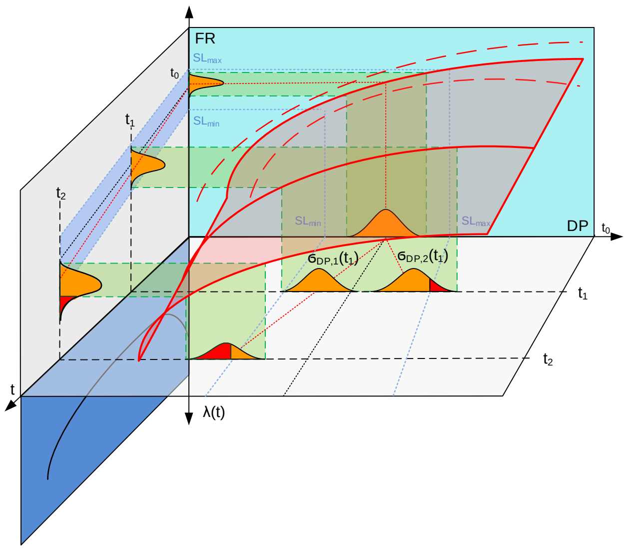


Figure 5: Integrated consideration of *Reliability*- and *Robust Design* theory

Whereas the paper consequently has yielded a deeper understanding from an academic perspective, its practical implications remain vague up to this point. However, a reference to section 3 clarifies the paper's purpose. Based on the distinct delimitation of key drivers for product reliability, i. e. (1) ***degradation of DPs***, (2) ***reduced robustness***, and (2) ***random variation of DPs***, a framework for the systematic choice of qualitative or quantitative methods can be derived. Table 1 illustrates an exemplary assignment of approaches.

Table 1: Framework for the choice of *Reliability Engineering* and *Robust Design* methods

		Early Failures	**Random Failures**	**Wearout Failures**
Early Failures	• design errors • misjudged variation • etc.	DFMA, Design Methodology, Tolerancing, etc.		
Random Failures	Random variation due to • overconstraints • ambiguous design		Design Clarity, Kinematic Design [2]	
Wearout Failures	• degradation			Reliability ass.
	• reduced robustness			

Based on the pairwise comparison of failure key drivers, the framework in Table 1 thereby also indicates distinct white spots where no methods are available. Next to a changing robustness which is frequently neglected in *Robust Design*, the integrated consideration of effects seems to be a particularly challenging task. A deviation of DPs in two different directions due to simultaneously occurring degradation and random noise effects is for example neither addressed by current *Reliability Engineering* nor *Robust Design* techniques.

Once again referring to the friction clutches in Figure 2, a corresponding effect could be caused by a wear-related reduction of the clamping length and a thermal expansion due to unforeseen temperature effects. Whereas in a reliability assessment of single components, a potential interference of the resulting distribution curves $\sigma_{DP,1}(t_i)$ and/or $\sigma_{DP,2}(t_i)$ with the specification limit would directly imply a failure, it might not necessarily lead an intolerable product performance due to the compensation of variation effects.

5. Conclusion

As a generally recognized agreement on the range of *Reliability*- and *Robust Design* philosophy neither seems to be available in academia nor in industry, this paper identifies existing interdependencies as well as potential synergies between the two domains. On this basis, the presented model for an integrated consideration of reliability and robustness enable a systematic choice of corresponding methods and stimulates future research.

In conclusion, the paper consequently allows for a clear determination of the underlying causality between reliability and robustness of products. On the one hand, reliable robustness, or in other words a system's robustness not affected by degradation effects, is one driver to achieve efficient reliability while avoiding over-dimensioning and excessive safety factors. Assuring robust reliability, i. e. a high quality level and a long, predictable life time of products and components is, on the other hand, the overall aim of both approaches.

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