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Robust design as a team sport – mastering upcoming challenges in modern product development

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ABSTRACT: Robust Design is essential for developing high-quality products by minimizing their sensitivity to variation and uncertainties from diverse sources. Despite the wide range of approaches from industry and research, it faces challenges due to their siloed usage. Motivated to gain a better understanding of these challenges and to derive implications for how to overcome them, this paper discusses different viewpoints on Robust Design, taking into account different life cycle phases, domains, and system levels. This highlights the challenges of enhanced product complexity and shifting focuses, for instance, when it comes to cyber-physical systems or sustainable design, and the need for collaboration. Accordingly, the vision of a collaborative approach to Robust Design in a team is presented, in which the actors' strengths are combined to further increase efficiency and significance.

KEYWORDS: robust design, collaborative design, design engineering, design practice, design challenges

1. Introduction

Motivated by the demand to meet increasingly challenging requirements while keeping life cycle costs low, Robust Design (RD) approaches have been proposed and adopted in industry over the past few decades. While diverse in nature, all approaches have the goal of making the product behaviour insensitive to disturbances or uncertainties, both internal and external, across the product life cycle. However, as shown by an earlier study (Eifler & Schleich, 2021), the various RD activities are heterogeneous because they address different aspects of the product, have to be applied in different product development phases and at different levels of abstraction. This hampers the harmonization of the various approaches, exacerbated by the different industry perspectives (Eifler et al., 2023).

However, as the RD process according to Taguchi (Taguchi et al., 2004) already indicates, the collaboration of different actors is inherent in RD. This is also evident from the fact that RD has to be directly or indirectly considered from multiple viewpoints, typically spread across multiple departments (Hasenkamp et al., 2009). This necessity to address RD as a team is further exacerbated by increasingly complex products, such as cyber-physical systems (CPS), which require a systemic approach instead of an isolated consideration. Furthermore, additional requirements, e.g., concerning sustainability, lead to further conflicting goals in RD, which require collaboration in a team in an interdisciplinary environment (Eifler et al., 2023).

Recognising that RD thinking and approaches are still suffering from the “silo” effect, this position paper authored by the core members of the Special Interest Group (SIG) on RD sets out to establish future research directions by highlighting the necessity of interdisciplinary collaboration in RD as a team sport. This aims to meet the future challenges in product development, exemplified by the position paper of Isaksson & Eckert (2020), and industry examples such as the development of autonomous vehicles,

which underlines the link between robustness and other aspects such as reliability or safety. Thus, this paper assembles viewpoints of RD from experts in several key areas of product development and complex systems lifecycles, highlighting inherent and evolving dependencies on interdisciplinary collaborations. This supports the establishment of an up-to-date comprehensive understanding of RD, highlighting challenges, opportunities and directions for future evolution of RD.

The paper is structured as follows: First, the evolution of RD with increasing interdisciplinary aspects is presented, followed by the description of different RD viewpoints. This forms the basis for identifying challenges in RD and how they can be tackled as a team. Finally, a conclusion and outlook are given.

2. Historical evolution of Robust Design

The concept of robustness is widely used in various areas, from robustness in terms of strength to robust decision-making and robustness of applications based on artificial intelligence (AI). Robustness is often associated with other concepts such as resilience, reliability and safety aspects, or design margins (Ferguson et al. 2024) and is also defined differently. For example, in contrast to the engineering design view, a robust AI algorithm ought to be unaffected by malicious input or extreme cases (Hamon et al., 2020), whereas a robust production system aims to ensure high performance when faced with disturbances (Stricker & Lanza, 2014). However, regardless of the differences, robustness considerations always imply the analysis of internal and external uncertainties and their impact on the output parameters or performance.

This article focuses on Robust Design in the sense of the development of robust products and thereby incorporates different perspectives and terms. In the early days, aspects of RD were considered the same as fault-tolerant design, for example, and were primarily taken into account via corresponding product development methods (Höhne et al., 2024). Then, motivated by the quality control efforts of Deming, statistical RD was introduced by Taguchi (Taguchi et al., 2004). With a background in the telecommunications industry, he has established practical approaches such as the Quality Loss Function concept, enabling the linkage between the system performance and the perceived quality, or the Signal-to-Noise Ratio, which can be used as a robustness indicator. These are based on the experimental quantitative determination (real and, with advancing computer technology, increasingly virtual) of the influence of varying factors (noise) on the performance (signal) using specific Design of Experiments. This enables targeted quality optimisation by combining parameter design (defining an optimal nominal value that leads to a low system sensitivity) and tolerance design (defining optimal tolerances delimiting the permissible variations of the factors, respectively, parameters). Taguchi's work was popularised by implementation in the US in the 1980s and since then has formed the basis for further research and application in industry (Hasenkamp et al., 2007).

Thus, manifold RD approaches have been developed by adopting theories from other areas, like statistics and optimisation, enabling, for example, the simultaneous parameter and tolerance design in a Robust Design Optimisation (Park et al., 2006). These approaches partly overcome the limitations of Taguchi's experimental approach (Box, 1988; Davis, 2004), especially with complex systems. In particular, model-based approaches (e.g. presented by Nair et al., (2002)) supported by the response-surface methodology (e.g. in Allen et al., 2006), often combined with multi-physics simulations, are widely used today. In addition to these approaches, some methods have been developed that aim to integrate aspects of RD into the early product development stages, e.g., by providing a method for the early assessment of product robustness (Goetz et al., 2020), network-topological metrics to describe the robustness of engineering systems (Haley et al., 2015) or an assessment method of visual robustness (Forslund et al., 2013). These approaches benefit from the expertise in other research areas like precision engineering (Hansen, 1970; Harfensteller et al., 2022), and widely adopted theories, e.g., from Suh's Axiomatic Design (Suh, 1998). Thus, numerous approaches are available along the phases of product development. However, the wide range of approaches at different levels of detail poses challenges regarding selection and consistent application (Eifler & Schleich, 2021). For this reason, related approaches for structuring the procedure, such as the Six Sigma methodology, were introduced in the extended RD environment. It provides principles and methods for the systematic identification and quantification of potential variations as well as for controlling them to ensure product quality (Breyfogle, 2003). The Failure Mode Avoidance (FMA) paradigm is another related approach aiming to enhance robustness in the sense of reliability by assessing the likelihood of product failures (Clausing, 1998). Applying the FMA framework in the automotive industry (Saxena et al., 2015) has demonstrated the effectiveness of integrating RD-specific methods,

such as the P-Diagram for noise identification, which supports the development of RD verification plans (Henshall & Campean, 2010).

The increasing mechatronisation and the emergence of CPS opened new areas for RD, particularly in software engineering, embedded systems, and AI components (Shahrokni & Feldt, 2013; Kim et al., 2021). CPS robustness is often defined by its ability to handle “unforeseen or erroneous inputs” or stressful environmental conditions through stable dynamic input-output control systems (Rungger & Tabuada, 2016, p. 1). Due to the change of domains, the wording also changes so that robustness in the context of CPS is often equated to system vulnerabilities affecting safety, security, reliability, and dependability (Hu et al., 2016; Shafique et al., 2020). However, the corresponding approaches often overlook system behaviour, focusing instead on input uncertainties. CPS robustness is also discussed alongside systems resilience, associating it with adaptability and flexibility to enhance system performance (Bagchi et al., 2020; McDermott, 2019).

In conclusion, RD research and practice have evolved considerably in the last century and now encompass many different interdisciplinary aspects for which numerous specifically tailored approaches are available. However, an overarching, generally applicable RD approach that combines all the different aspects is neither available nor reasonable, given the diversity of the products to be developed. (Eifler et al., 2023) Nevertheless, an organised interaction between the roles involved in RD is needed to overcome current and future challenges in product development. Thus, this paper addresses the exploration and unification of various viewpoints in RD.

3. Methodical approach

The methodical approach in this paper is driven by the discussions and findings from the SIG workshop at the ICED 2023, augmented with insights from subsequent SIG virtual workshops. These discussions have pointed to the need to consider RD viewpoints alongside three axes: (i) product lifecycle phases; (ii) domain specific viewpoints; and (iii) system levels of integration or decomposition. Figure 1a illustrates the cartesian structure of the approach, including the rough positioning of the six viewpoints within this paper.

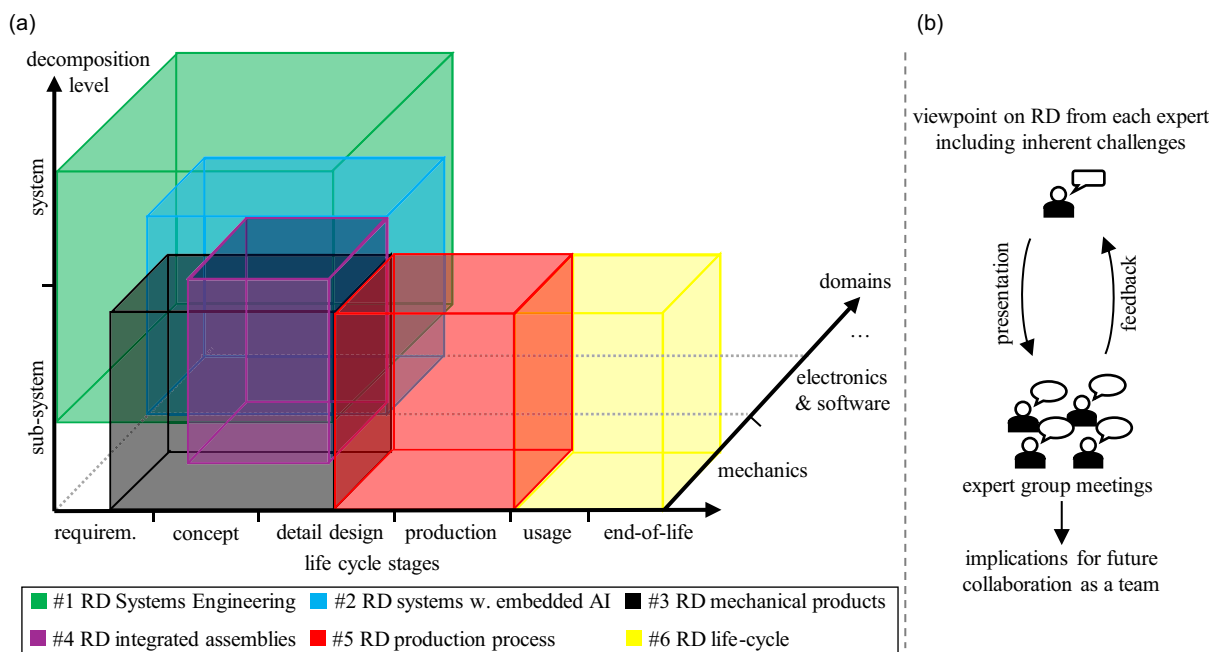


Figure 1. Cartesian structure of the approach with viewpoints (a) and procedure (b)

The process of collecting and validating viewpoints in each of the identified viewpoint blocks is summarised in Figure 1b. In the first phase, Design Society experts, identified from the SIG core group based on their track record of expertise including relevant funded research projects involving industry stakeholders, were assigned the task to articulate key viewpoint dimensions and challenges. In a second phase, each expert presented their input to the expert group, in a workshop style setting, leading to a cycle

of discussion, refinement and validation. In the next phase, the Design Society expert group works together to identify interactions, dependencies and trade-offs requiring a collaborative approach, and define challenges and opportunities for further research.

4. Introduction of different viewpoints on Robust Design

In the following, six viewpoints on RD are presented according to the respective expert areas represented in Figure 1a. Thereby, the level of detail of the viewpoint description varies in line with the different widths of the expert fields.

Viewpoint 1: RD in Systems Engineering

To apply RD, the technical product can be described from a systemic point of view with the help of a black box representation with input and output variables, including their variations or noises (Brix et al., 2024). Considering complex systems, the system theory suggests breaking this product down into several sub-systems (Ariyo et al., 2008), such as the mechanical braking system and its autonomous control system needed, e.g., in autonomous vehicles. This allows distributed and federated product development of the sub-systems. Their subsequent integration finally leads to the overall product behaviour resulting from the interaction of sub-systems.

Mechatronic products usually have mechatronic sub-systems at the upper system levels, while domain-specific sub-systems (e.g., mechanics, electrics/electronics, software) can be found at the lower sub-system levels (Böhm et al., 2021; Husung et al., 2022). Depending on the sub-system and the domain, the causes for variations relevant to RD can widely range from, e.g., changing operating conditions or wear effects of mechanical systems to, e.g., lacking determinacy of the behaviour of software, particularly when it is based on AI solutions. Accordingly, to identify possible variations in the sub-systems and to define the measures necessary to limit these variations, different approaches are used at the various system levels and in the domains, depending on the maturity level of the development (from early conception to detailed design), also see viewpoints in Figure 1a across the domains.

While the systemic decomposition proposed in Systems Engineering is beneficial for the RD optimisation of the single sub-systems, the consideration of emergence effects is challenging. Thus, decomposing the product and planning the integration of the sub-systems is important for overall robustness. Correspondingly, the interaction of the different actors (in a team) with domain-specific models is required and already partially supported by model-based approaches like MBSE. This shows that the robustness of a system is already largely dependent on the methodical procedure in Systems Engineering and must be considered from the very beginning to avoid extensive iterations between system levels.

Viewpoint 2: RD of systems with embedded AI modules

These challenges are further intensified when it comes to systems with embedded AI modules, such as those widely used in autonomous vehicles today. These systems consist of multiple modules from different domains, which are affected by the respective uncertainties, which are passed on differently, and finally interact with each other. The control of autonomous vehicles is an illustrative example of how data from physical sensors or cameras is converted into information for vehicle control by embedded AI.

In this context, the primary research focus has been on improving the robustness of the AI module. This means that the machine learning algorithm is aimed to be insensitive to unforeseen input variables from the sensor or even cyber threats both in learning and inference (Kim et al., 2021; Vargas et al., 2021). Beyond that, the robustness of the sensor performance itself (Juul-Nyholm et al., 2020) to external noise factors or degradation plays an important role. However, a comprehensive and systematic consideration of both internal and external uncertainty factors on the robustness of the whole system across the intended life cycle is missing. This is particularly challenging since the physical module usually operates on continuous variables. In contrast, the AI operates on discrete variables, complicating the determination of the entire system's behaviour under uncertainty in extreme or rare situations.

Consequently, a comprehensive verification and validation strategy for the whole system is needed, especially when dealing with safety-related systems (International Organization for Standardization, 2022). This includes the identification of all potentially eligible corner cases, both as discrete sets and

continuous variables, to appropriately reflect both external and internal factors by unifying the actors from different domains. In summary, the heterogeneous nature of the system represents a central challenge in RD and highlights the close link between robustness, safety and reliability.

Viewpoint 3: RD of mechanical products using quali- and quantitative approaches

As already indicated in [Section 2](#), numerous RD approaches exist that aim to improve the insensitivity of mechanical products or their behaviour to variations or uncertainties. They can be divided into qualitative and quantitative approaches.

Qualitative approaches are primarily used in early design stages, such as in concept design, where only a small amount of information about the system and potential variations is available. Thus, these RD approaches aim to reduce the large inherent uncertainty and subjectivity by partly formalising product development and RD knowledge in the form of design principles or guidelines, like Axiomatic Design principles, the principles of fault-tolerant systems ([Brix et al., 2024](#)) or short load paths ([Eburo & Howard, 2016](#)). To structure these partly redundant and contradicting principles, robustness evaluation methods, e.g., adopted from the Failure Mode and Effect Analysis ([Goetz et al., 2019](#)), or approaches for automated concept design adaptations ([Goetz et al., 2021](#)) are developed, combining the various robustness aspects. This enhances the objectivity and reliability of design decisions, whereby the quality of the results is usually linked to a high manual effort ([Goetz, 2024](#)), and a residual subjectivity remains due to the lack of quantification.

In contrast, quantitative approaches commonly use a mathematical description (e.g. transfer function) of the product behaviour under variation. Thus, it is usually applicable in the embodiment design stages and prevalent in the parameter and tolerance design stages. Utilising the approaches described in [Section 2](#), these approaches enable the quantification of Key Performance Indicators, like variance and quality loss, and the targeted optimisation of parameter values and their tolerances ([Fowlkes & Creveling, 1995](#)). Nevertheless, a comprehensive representation of the system behaviour is necessary for high-quality behaviour and requires a lot of effort for information procurement and model setup, as well as statistical knowledge.

Both types of approaches are interdependent and can significantly enhance design robustness when integrated. Considering the change in uncertainty elements along the product development process ([Morse et al., 2018](#)) and the inherent uncertainties, it makes sense to use both qualitative and quantitative approaches to strike a balance between effort, traceability and quality of results. This especially applies to the design of complex sub-systems, such as a sensor adjustment system, where system, parameter, and tolerance design strongly interact. By using qualitative and quantitative RD approaches in a complementary way, the achievement of product quality requirements can be assured.

Viewpoint 4: RD of deeply integrated assemblies

The aforementioned challenges gain in complexity when deeply integrated assemblies are involved. Understood as systems with heavily coupled system elements, these interdependencies are, for example, driven by a small design envelope and a high production volume, hence a constant pressure to realise product functionality with as few components as possible. A consequence is that requirements, for instance in the field of medical devices, wearables or autonomous systems (including AI-embedded systems), cannot just be cascaded down from the overall system to its individual elements. Instead, every designed element will not only affect several product functions but also establish a variety of additional physical constraints that have a drastic influence on the available design freedom for the rest of the assembly.

In this context, robustness is increasingly related to trade-off decisions between sub-domains, disciplines, technologies, or also physical elements. Resulting from contradicting requirements and the complex, physical interdependencies between system elements, these trade-offs limit the available design space and often result in a reduced window for allowable variation. This is neither addressed by qualitative RD principles, given limited consideration of detailed technical constraints ([Sigurdarsson 2022a](#)), nor by formal optimization techniques that largely disregard the design freedom beyond the used optimization model ([Papalambros & Shea, 2001](#)). Instead, the resulting effect is often mitigated by excessive design iterations and additional, narrow tolerance windows ([Göhler et al., 2016](#)).

Hence, the challenge of RD of deeply integrated assemblies is the systematic consideration of trade-off variables and relevant technical constraints beyond the detailed calculation of the (Pareto) optimal solution for one single design proposal. This includes equipping design engineers with the knowledge and tools needed to systematically include early embodiment information in concept decisions (Juul-Nyholm & Eifler, 2024), the systematic consideration of knowledge on constraint activity and design trade-offs when embodying initial product layouts and geometries (Sigurdarson et al., 2022b) as well as systematic Re-Design efforts to systematically identify critical constraints in a complex and discontinuous objective space for potential design improvements once an initial embodiment solution is available (Sigurdarson, et al., 2022a).

Viewpoint 5: RD linked with production process design

The manufacturing process of mechanical products is inevitably associated with unavoidable production-related geometry variations that affect product behaviour and, thus, their quality (Morse et al., 2018). Hence, a set of geometry assurance activities is needed to verify, reduce, and monitor the geometrical part variations within the product development process (Söderberg et al., 2006; Thornton, 1999). However, reducing geometrical variations in the production process by tightening tolerances is strongly connected with costs (Hallmann et al., 2020). In contrast, robust product design, including, e.g., decoupling of functions or robust datum systems, helps counteract this problem early before the beginning of process planning (Söderberg et al., 2016) by making it less sensitive to geometric variations. This puts less strict constraints on all subsequent product planning and realisation activities. In addition, robust process design, for instance, through robust fixture layouts and joining sequences, makes the final product less affected by part variations and additional manufacturing uncertainties (Söderberg et al., 2006). Consequently, a harmonised, robust product design, including tolerancing and robust process design, is desirable.

However, their interactions pose a significant challenge, further exacerbated by the current developments and trends on both product and process levels. For example, megacasted parts replace numerous assembled sheet metal parts and thus reduce the number of sources of geometrical variations (Wärmefjord et al., 2023). However, the need to realize multiple functions in one production step of the megacasted part complicates RD. Similarly, the increasing level of integration in mechatronic products (Isaksson & Eckert, 2020) introduces additional sources of variation beyond geometry variations. While these additionally affect product behaviour, CPS bear the potential to counteract the effects of geometric variations in product use, for example, by adjusting sensors or software routines. Analogously, digital twins contribute to a robust production process, e.g., by providing individually adapted fixture layouts, part matching, or remanufacturing to balance out geometrical variations (Söderberg et al., 2017). However, this requires that all necessary data and information are consistently available (Schleich et al., 2018) and reliably processed. Hence, besides robustness to geometrical variation, the effect of further uncertainties will play an increasing role in the future.

Viewpoint 6: RD linked with life cycle and sustainability

In times of progressing climate change and resource scarcity, it becomes inevitable to consider not only functional and economical aspects during product design but also their ecological impacts from a life cycle perspective. In this regard, RD with associated safety or reliability aspects can contribute to the sustainability of products including their repairability. This is because product robustness has substantial repercussions on the ecological impact of products as robustly designed products may lead to less scrap in production, longer product lifetime, and potentially easier to disassemble products, e.g., by the prior decoupling of sub-systems in the sense of RD.

However, RD of products may also lead to less sustainable products with higher weight, higher energy consumption during use or poor recyclability, e.g., due to the use of compliant materials to compensate for geometric variations. This ambiguity is particularly evident in designing complex technical products with a high level of function integration, such as autonomous cars, where inherent trade-offs between product sustainability and other customer or technical requirements are common. In this regard, some works have focused on numerical optimisation to balance some of these requirements, such as (Hoffenson et al., 2013). Nevertheless, companies often struggle to identify suitable sustainability requirements. As a response to this, some approaches have been proposed to derive sustainability requirements from reporting frameworks, such as (Quernheim & Schleich, 2024).

Hence, incorporating the diverse requirements and dealing with the inherent trade-offs is an ongoing challenge. To overcome this challenge, a structured procedure linking the (robust) design decision process with the sustainability strategy and assessment, including the corresponding experts, is necessary.

5. Consolidation and discussion

The presentation of the viewpoints in Section 4 highlights that RD faces new research and methodological challenges, driven by the recent technological trends and developments and the increasing product complexity, e.g., through functional integration (Isaksson & Eckert, 2020). The key challenges highlighted by the analysis in this paper include:

- New sources of variation, e.g., non-determinism of AI and system vulnerability to data and parameters uncertainty, including impact of malicious cyber interference;
- Multidisciplinary trade-offs, particularly e.g. in the context of sustainability;
- Interdisciplinary collaboration, requiring effective interaction between experts from different domains and sub-disciplines; and
- Harmonisation of methods and tools, ensuring compatibility between diverse approaches.

Since RD inherently involves multiple actors working toward reaching the high product quality requirements, see Figure 2, addressing these challenges requires a collaborative approach. This is already evident within the presented viewpoints, e.g. in the combination of robust product and process design. While individual experts make significant contributions to robustness, a holistic collaboration can enhance overall product robustness by leveraging complementary strengths and mitigating weaknesses. For instance, a robust electronic control system can compensate for a less robust conceptual design.

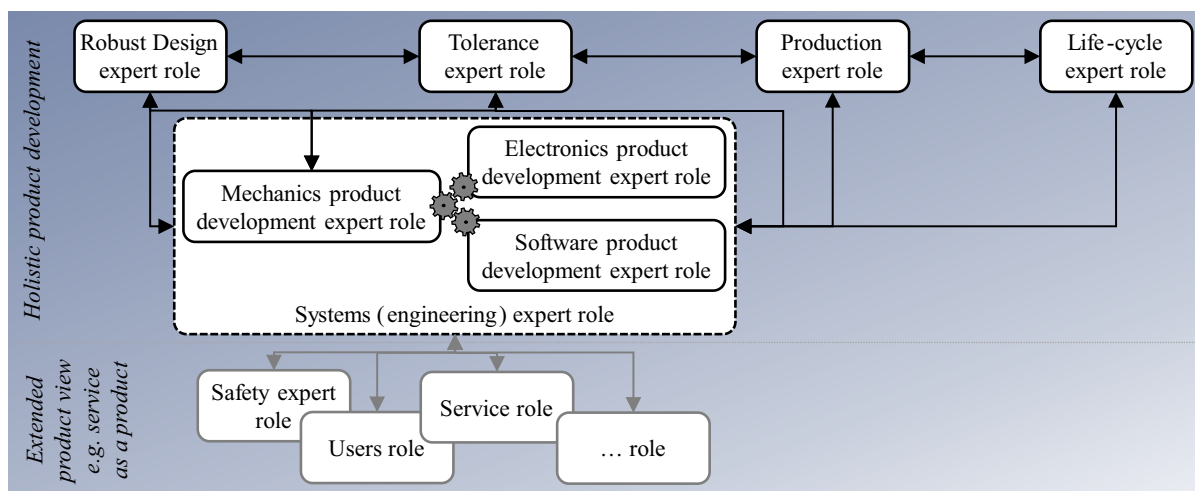


Figure 2. Interactions of the RD expert role with other actors in the product development environment. The blue shading indicates the extension of the traditional Robust Design (dark blue) to other areas by incorporating additional aspects of robustness

To ensure high product robustness throughout its lifecycle, a coordinated strategy is needed – one that aligns the contributions of various actors toward a shared objective. This strategy must be tailored to each product and explicitly incorporate the diverse definitions of robustness (see Section 2) to streamline the development process. However, achieving this requires overcoming the challenges related to working on RD in a team:

1. Organizational challenges arising from the need to orchestrate multiple actors and establish clear responsibilities should be addressed by providing a structured collaboration framework. A key step is defining a shared understanding of robustness, e.g., by discussing and coordinating the used Key Performance Indicators such as robustness indices, Signal-to-Noise-Ratios, process capabilities or adversarial loss values.

2. Technological challenges resulting from the lack of interoperability of tools, models and methodologies should be handled by a common unifying platform. Emerging digital thread technologies provide a promising foundation for integrating multiple information formats, ensuring that data and results can be shared efficiently across disciplines.
3. Human-driven challenges including different mindsets, expertise levels, and terminologies across the actors, which can lead to inefficient processes, require intuitive and accessible RD solutions. This ensures that all actors can utilize them effectively and aligns with the concept of model and simulation democratisation (Isaksson & Eckert, 2020).

Future RD research should, therefore, prioritise collaboration over isolated refinements of specific methodologies. Given the increasing complexity of RD, fostering cross-domain (e.g., mechanics, electronics) and cross-disciplinary (e.g., design, testing) interactions represents the logical next step in its evolution. To achieve this, additional perspectives beyond those discussed in Section 4 should be incorporated – particularly from computer science and diverse industrial sectors, where robustness is a key factor in ensuring reliability and long-term performance.

6. Conclusion and outlook

This position paper highlights the interdisciplinary nature of Robust Design (RD) and its critical role in modern product development. The viewpoints presented highlighted both heterogeneity in approaches and common ground, and hence the need for collaboration to address increasing product complexity, cross-disciplinary trade-offs and digitalization-driven uncertainties. However, approaching RD as a cross-disciplinary team still presents significant organizational, technological, and human-driven challenges that must be overcome. Therefore, future research should prioritise frameworks that enhance collaboration among all actors to dismantle silos that hinder progress. This also enables synergies with other areas that have so far addressed robustness in other contexts or use related approaches.

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