DTU Library

Perspectives on Robust Design – An Overview of Challenges and Research Areas Across Industry Fields

Eifler, Tobias; Campean, Felician ; Husung, Stephan; Schleich, Benjamin

Published in:
Proceedings of the International Conference on Engineering Design (ICED23)

Link to article, DOI:
10.1017/pds.2023.289

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

PERSPECTIVES ON ROBUST DESIGN – AN OVERVIEW OF CHALLENGES AND RESEARCH AREAS ACROSS INDUSTRY FIELDS

Eifler, Tobias (1);
Campean, Felician (2);
Husung, Stephan (3);
Schleich, Benjamin (4)

1: Technical University of Denmark;
2: University of Bradford;
3: Technische Universität Ilmenau;
4: Technische Universität Darmstadt

ABSTRACT

Robust Design offers a coherent and widely appreciated approach for the parametric exploration of the design space by means of simulation or experimentation, which is well-established in the quality-by design domain. From the perspective of design research, however, this only addresses a relatively narrow part of the design process and is not fully integrated with other design decisions such as concept exploration, the suitable configuration of system elements, or the design of interfaces. Particularly in light of the growing importance of developing technologically advanced and "smart" systems, it seems that a new methodical perspective on Robust Design is needed. Against this background, this paper consolidates knowledge and insights from different research fields and industry sectors. On this basis, new angles to the discussion on product robustness in different domains are explored in order to suggests directions for action and new research areas, both with respect to a methodical RD approach as well as the question of systematic research procedures.

Keywords: Decision making, Design engineering, Robust design

Contact:
Eifler, Tobias
Technical University of Denmark
Denmark
tobeif@dtu.dk

Cite this article: Eifler, T., Campean, F., Husung, S., Schleich, B. (2023) 'Perspectives on Robust Design – An Overview of Challenges and Research Areas Across Industry Fields', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.289

1 INTRODUCTION

Robust Design (RD) is an engineering approach focusing on the development of products that are insensitive in their behaviour in relation to disturbances from different internal and external sources across the relevant product life phases. Well-established in the quality-by design domain (Clausing, 1994), RD offers a coherent and widely appreciated approach for the parametric exploration of the design space by means of simulation or experimentation (Grove and Davis, 1992). From the perspective of design research, however, this only addresses a relatively narrow part of the design process and is not fully integrated with other design decisions such as concept exploration, the suitable configuration of system elements, or the design of interfaces. Against this background, and particularly in light of recent developments towards technologically advanced and "smart" systems, a new methodical perspective on RD seems needed. For new design tasks associated with the development of cyber-physical systems that rely on sensor data driven controls of the physical product (Welzbacher et al., 2022), AI / machine learning algorithms to provide contextual intelligence, or the management of design trade-offs in multidisciplinary products, the standard parametric robustness approach will not be sufficient. For example, when considering the question of a sensor variation (Juul-Nyholm et al., 2020), the robustness might for example be affected by its mechanical structure, its hardware, or also the chosen software and filtering solutions. Since all of these domains have their own terminology and understanding, and employ different approaches and tools to address variation and/or robustness in design and real time operation, a more systematic and holistic approach is necessary to carefully align all perspectives across different design phases.

A recent review of RD-related publications within the design community (Eifler and Schleich, 2021) has unveiled a largely unstructured research field. Based on a mapping of publications at ICED and Design conferences (in the period from 2011 to 2021), it was shown that the design research perspective on product robustness lacks a consistent terminology and does not provide a systematic view on multidisciplinary product development, with few systematic efforts to show method validation or insights on the actual method implementation and impact in an industry context (e.g., Campean et al., 2022). In other words, current design research on the RD topic falls short on providing clear evidence for the reproducibility and scalability of results or the generalisability of methods and tools beyond simplified, largely contextual academic case examples. Therefore, establishing a direct link between the academic research effort on RD methods and the industry challenges and needs, as well as collaborative efforts to develop and adopt methods in practice, appears as a timely imperative.

For further advancing the field of RD, it is essential to consolidate knowledge and insights from different research fields and industry sectors in order to outline future research challenges related to the field of product robustness. In this context, this paper seeks to explore new angles to the discussion and to suggest directions for action and new research areas, both with respect to the methodical RD approach as well as the question of systematic research procedures. The paper's contribution is threefold:

1. Provide an expert viewpoint on current robustness and RD related challenges in four different industry sectors (automotive, medical device development, precision engineering, and production systems), from the position of academic research groups with longstanding track record of engagement with industry on RD methods research;
2. Present a consolidation of common challenges across industries with consideration of differential contextual requirements for RD methods and tools;
3. Outline future directions for RD research, calling for combined efforts from different design research fields and communities to address the identified challenges.

The remainder of the paper is organised as follows: the paper starts with a brief historical perspective on robustness and RD, followed by a methodical consideration of the challenges in four industry fields. Based on the consideration these insights provided, an analysis is provided, leading to directions and actions for RD research.

2 ROBUST DESIGN – A HISTORICAL PERSPECTIVE

The concept of robustness is widely used across the engineering and non-engineering disciplines, often with variations in definition and understanding, reflecting both contextual purpose and disciplinary viewpoints. From the point of view of the perceived performance, robustness is commonly defined as the ability of a system to maintain its functional performance around the expected level, in the presence of endogenous and exogenous uncertainties and disturbances. The study of robustness is

https://doi.org/10.1017/pds.2023.289 Published online by Cambridge University Press

therefore naturally associated with the study and modelling of uncertainty, both in terms of characterising the sources of uncertainty (associated with either the inputs to the system, internal parameters of the system, or the operating environment), and relating this to the observed variability of the output parameters.

Historically, the concept of robustness is often associated with the work of Taguchi (1986), who has associated the observed variability in the performance output of a system with the perceived quality, via the "quality loss function" concept. He has further proposed an empirical, experimentation-based approach to quantitatively study the relationship between the sources of variability (which he referred to as "noise factors") around the system, either internal or external, and the key output variable via "signal to noise ratios". His practice-oriented framework for detailed product and process design is famously based on "parameter design" (optimal target setting for the system or process parameters to minimise the variation in the output performance) and "tolerance design" (optimal setting of tolerances around the set targets for parameters) aiming at a variability in the output that is within the set tolerance for performance. The work of Taguchi has received attention from academics as well as practitioners and had a significant impact across industries after the 1980s when it was popularised in the US. For example, the "Six Sigma" methodology (Breyfogle, 2003) for product and process improvement had the RD principles and methodology at its core, seeking to systematically identify and quantify the sources of variation and implement effective controls for variability in key output variables.

On this basis, RD research has evolved into a variety of different fields over time, largely benefiting also from incorporating expertise in other long-established research fields such as precision engineering (Hansen, 1970; Höhne et al., 2005, Harfensteller et al., 2022). Examples of this diverse understanding are RD methods for an early assessment of product robustness (Götz et al., 2020), network-topological metrics to describe the robustness of engineering systems (Haley et al., 2015), or the assessment of visual robustness (Forslund and Söderberg, 2010). On the other hand, the limitations of Taguchi's experimental approach have been exposed by many authors (Box, 1988; Davis, 2002), in particular in relation to the analysis of complex systems, where the study of variability transmission through the system is required and a model-based approaches are commonly employed (e.g. Nair et al, 2004). The model-based approach, underpinned by the response surface methodology, has become increasingly commonplace for a variety of RD applications, often used in conjunction with multi-physics simulation in system design. In another direction, Clausing (2005) has made a significant contribution to RD research by explicitly linking "lack of robustness" in the functional performance of a system with system failures, either "hard" (total loss of function and potentially of the system) or "soft" (where the perceived performance of the system falls below the acceptable limit from a user point of view). Clausing has also argued for the "Failure Mode Avoidance" (FMA) paradigm to improve reliability by focussing on selecting design solutions on the basis of the evaluation of likelihood of failure due to lack of robustness at the conceptual design stage. The adoption of the FMA framework within the automotive development (Saxena et al, 2014) has demonstrated the effectiveness of a systematic integration of design processes with methods specific to RD (e.g. the P-Diagram to identify sources of noise; modified DSMs to evaluate propagation of variability) and design assurance approaches, driving the development of robust design verification plans (Henshall and Campean, 2010).

The proliferation of cyber-physical systems (CPS) and their applications across industries has brought prominence to robustness from the viewpoints of other disciplines as well – in particular software engineering, embedded systems and machine learning / AI components. To illustrate the richness of this research, the survey of Shahrokni and Felt (2012) identified over 600 papers dealing with software robustness over a period of two decades. The definitions of CPS robustness emphasize disturbances associated with "unforeseen or erroneous inputs" or "stressful environmental conditions", and modelling of CPS is commonly approached as input-output dynamical stability based on the notions of robustness of control systems (Rungger and Tabuada, 2016). Much of the research in CPS robustness (see for example Hu et al, 2016; Shafique et al, 2020) directly link to vulnerability of the systems resulting from the lack of robustness, and thus robustness is explicitly linked with attributes of the systems such as safety, security, reliability, dependability, etc. A common shortcoming of these approaches is that they concentrate on the uncertainty associated with the intended and unintended inputs (e.g. from the environment), with less attention to the behaviour of the system. CPS robustness has also been discussed in conjunction with systems resilience research (McDermot, 2019; Bagchi et al., 2020), linking with systems adaptability and flexibility as strategies to improve robustness.

3 PERSPECTIVES ON ROBUST DESIGN - CHALLENGES IN FOUR INDUSTRY FIELDS

3.1 Methodology

The authors of this paper have longstanding experience of engagement with product development, robustness and RD research in four industry sectors - automotive, medical device development, precision engineering, and production systems, with track record of industry-academia collaborative research spanning over many years. On this basis, they are positioned as domain experts, providing their insight on current trends in the industry where they have expertise gained from collaborative research projects carried out by the research groups they lead or represent, over the past two decades.

The assessment of the current state of RD across the four industry sectors is based on a common structure that was collaboratively defined by the authors to identify the key drivers for the industry environment dynamics, to derive the corresponding technical challenges for RD, and for an elicitation of the main requirement for RD methodological developments. This review guide was then used individually to identify corresponding challenges in the following four areas based on the authors' experience complemented with additional insights from industry collaborators:

1. *Industry environment drivers* – focussing on market, customers and technology trends that set the priorities for new product development, challenging to the current RD approaches;
2. *PD organisation challenges* – factors that impact on the current effectiveness of the product design and development activities within PD organisations;
3. *Derived technical RD challenges* for the PD organisations to develop robust products that meet the key requirements from the users and industry competitive environment;
4. *Requirements for RD methods*, capturing the methodological developments required to address the current technical challenges, informing on potential research for robustness methods.

On the basis of the information collected, a joint analysis was conducted through several workshops, with the aim of identifying common drivers, organisational and technical challenges across the four industry sectors, and to produce a synthesis of directions for robust design research. It should be noted though that the differentiation of industry sectors is not always unambiguous, as products initially developed in one sector might subsequently find broader implementation in another area (e.g. from precision engineering to the automotive industry).

3.2 Automotive industry

The automotive industry has focussed on robustness since the ‘80s as part of an engineering quality improvement drive for process quality assurance in manufacturing operations, and in the context of large increases in volumes with global distribution and supply chains. By the late 90’s, the increase in complexity of automotive systems brought by the proliferation of electronic and digital controls and mechatronic components, and the challenge of meeting higher demands for quality and reliability from a global customer base with high vehicle usage uncertainties, has shifted the focus of robustness efforts towards the design and development phases. Increasingly, initiatives like Six Sigma and Design for Six Sigma have shifted towards applications to systems design, with focus on analytical approaches for variability reduction and robustness countermeasures by design. The Failure Mode Avoidance framework, adopted by many automotive OEMs, sought to integrate methods and tools that support a systematic approach to robustness across the systems design and development, with a strong focus on function analysis, driving the systems integration and robust verification and validation plans.

The pace of change in automotive systems design and development has significantly accelerated over the past two decades with two main drivers: (i) the proliferation of software and AI / machine learning components in the vehicle architectures to deliver advanced control features for the driver and users comfort and safety, including driving tasks automation; and (ii) the pressure to demonstrate environmental sustainability, with radical implications for rapid technology shifts towards electrification, vehicle light-weighting, while using sustainable materials and components with high recycle/reuse, and significant increase in the required design life (e.g. 15 years for many subsystems).

This brought significant technical challenges (summarised in Table 1) within the automotive PD from the robustness and reliability perspective, many of which have been highlighted by a cross-industry reliability research roadmapping workshop (Campean et al., 2020). From an organisational point of view, the shift towards vehicle architectures underpinned by networks and software defined features,

https://doi.org/10.1017/pds.2023.289 Published online by Cambridge University Press

has brought significant change to the disciplinary mix of engineers involved in automotive PD. Managing a symbiotic integration within the heterogeneous multidisciplinary PD ecosystem has its own, not insignificant, challenges. From the robustness perspective, the plethora of definitions of robustness across the disciplines, as discussed above, is an illustrative example of the disciplinary chasm. Different perspectives lead to communications issues within the systems design process, which are further exacerbated by the incongruent nature of the methods and tools used by different communities to support analysis. While this challenge is not unique to the automotive industry, the case can be made that the interdisciplinary gaps are perhaps deeper than within other industries, given the pace and scale of change and innovation in technologies adopted, and the inherent complex nature of the vehicle systems design. This, in turn, results in a higher urgency for action to develop effective methods to support robust design across disciplines. Table 1 summarises some of the key current methodological requirements for robust design methods from the automotive industry perspective.

Table 1. Robust design challenges for the automotive industry

Industry environment drivers	• Ubiquitous intelligent / interconnected features to provide enhanced user experience, comfort, safety and security (including automated driving) • Accelerated technology shift towards electrification and hydrogen • Sustainability – materials, light-weighting, recycle, remanufacturing, reuse • Increase durability requirements (15 years design life for components)
PD Organizational environment / challenges	• Dynamics of the interdisciplinary mix in the PD organisation - shift from mechanical / electrical to embedded systems, software and networks • Increased supply chain dynamics
Derived technical robust design challenges	• Handle the fast introduction of new technologies (across electrification, light-weighting, ADAS) with legacy systems and architectures, with demonstrated robustness / design assurance for safety and reliability • Proving the long term durability and robustness attributes for new systems, against real world uncertainty, under time and cost constraints • Managing the data-driven continuous product development and release operation for software defined functionality and features • Resilience, robustness and reliability assurance for Mobility as a Service
Requirements for robustness methods	• End-to-end robust feature development process within a digital MBSE-supported environment • Methods for proving robustness of CPS, addressing the uncertainty modelling and propagation across the physical and ML systems • Integrated methodological chain for design assurance of smart data-driven control features, including X-over-the-air • Framework and methodologies for continuous product development process: IVHM, complexity management, obsolescence management • Robust design methods automation – with AI assistance to enhance rigour and productivity, i.e. Robustness Expert-in-the-Loop

3.3 Drug delivery devices

The market for drug delivery systems covers a diverse field of medical devices for the effective and safe provision of medication to patients. Including various routes of administration, injection devices in particular, have been shown to play a vital role in the long-term treatment of diseases. In form of wearable or pen devices, they provide an easily accessible option for medication that cannot be administered otherwise (e.g. orally), which reduces significantly the complication and social embarrassment of a vial-and-syringe approach, improving dosing schedule and medication adherence (Lee et al., 2006).

While the question of robust injection devices has been the authors' main focus, many of the corresponding challenges summarised in Table 2 certainly also apply to other delivery devices. This includes the context of a usually high production volume for a frequently disposable product (in the case of the world's largest insulin care providers several hundred million devices per year), the imperative of safe and accurate medication with drugs that are often concurrently developed, and the enormous user expectations towards discreetness. Furthermore, and in contrast to other medical devices, these

https://doi.org/10.1017/pds.2023.289 Published online by Cambridge University Press

requirements need to be fulfilled in a home use situation, hence outside of controlled procedures and protocols of a professional healthcare setting.

Overall, the above requirements from market and customer side lead, in their combination, to a variety of technical RD challenges. These are, first of all, driven by the high production volume of a safety critical product that is still relatively complex. Particularly adjustable dosing requirements (compared to autoinjectors with fixed dose) come with considerable complexity, including a significant number of individual components. The above, in turn, results in a strong focus on injection moulding as the main production process, a constant pressure to reduce parts and manufacturing costs, and, as a consequence, a high product integration. Sitting at the boundary between medical device and consumer product development, this integration is furthermore expected to increase significantly due to new technologies that promise a better user-device interface.

From a RD perspective, this implies that design decisions play a major role in mitigating the high risks of variation in either production or the little controlled home use environment. In contrast, the specification of tolerances is limited to the main production process, and usually an in-detail process optimisation rather than a tolerance design task. The importance of a predictable RD process is further underlined by the high uncertainty of a concurrent development of devices and drug candidates, treatment regimes respectively. This implies that reusability or adaptability of previous solutions is limited (Sigurdarson, 2022) while there is a high uncertainty given that only 10% of drugs actually reach the market (Lowe, 2019). In this context, a key challenge for design is to systematically manage the increasing level of product integration and interdependencies between different product functions. While connected drug delivery devices, for example, hold a high potential with respect to further improving medical adherence and treatment, new technologies must be carefully fitted into an immensely narrow envelope that is defined by the necessary accuracy and safety of the mechanical functionality, the available size and costs of new technological solutions, and increasing concerns of the environmental footprint. On the other hand, the high production volume also implies that even minor improvements of the product have a substantial impact.

Table 2. Robust design challenges for drug delivery devices

Industry environment drivers	• Safety critical products with hard to predict, uncontrolled use environment; • Strong focus on suitability and new technologies for the user-device interface (relevant for safety and patients' adherence); • Expectations of discreet products (i.e., small, easy to hide); • New requirements for sustainable products/production of disposable device;
PD Organizational environment / challenges	• High degree of documentation to meet regulatory requirements; • Concurrent development of pharmaceuticals and devices; • High annual production volume;
Derived technical robust design challenges	• Static choice of production processes; • High volume production of relatively complex product; • High integration of mechanical solutions (given high production volume, cost pressure, safety requirements, small design envelope, etc.); • Further increasing integration due to new functionality (e.g., connectedness for an improved user-device interface, circularity requirements, etc.);
Requirement for robustness methods	• Low reusability or adaptability of results; • System Design as main variation mitigation strategy (other strategies such as tolerance design/calibration/rework/etc. are largely unsuitable); • Uncertainty of concurrent development process regarding the required dosing requirements and sequence, drug stability, device-user interface, etc; • High product integration (including multidisciplinary technologies); • Even minor improvements to the devices have a substantial impact.

3.4 Precision engineering for special applications

Increasing requirements in the device engineering, electrical and electronics to mobility industries include precise positioning of objects, precise measurements of physical quantities and high quality in realisation of specified transfer functions. In addition, there is an increasing need for miniaturisation and functional integration. These requirements lead to an increasing customer-specific demand for

https://doi.org/10.1017/pds.2023.289 Published online by Cambridge University Press

precision-engineered products that are characterised by the integration of a wide variety of working principles and properties from numerous domains (optics, mechanics, electrics, electronics, microsystems technology, materials technology, etc.) with strong interactions between them. Since physical effects are often fully exploited to realise the properties of precision-engineered products, the elements of the products are usually very sensitive to different external influences (e.g. temperature, air flows, etc.) and internal influences (changes in elements over time - e.g. subsidence effects).
The operating principles used in the products are partly well known (high degree of maturity), but new working principles are constantly being added in order to achieve the precision requirements. These new working principles and their underlying effects, incl. side effects (Schienbein, 2021) that are not wanted but also cannot be prevented, must first be understood so that a maturity growth can be observed (see Table 3). Relevant development decisions are made on the concept level, as the solution principles have a great impact on the robust functional realisation.
The market for precision engineering products is very diverse. High-precision products (such as measuring instruments) are often needed for special applications, so that relatively small quantities are required. For these products, many end customers are well known, so that specific requirements and usage scenarios can be well aligned (Manske, 2021). In contrast, there are mass products (such as sensors or actuators) whose quality requirements are becoming increasingly stringent, but at the same time high quantities are necessary. In the mass market, price pressure is increasing so that, in addition to precision, cost requirements have a very high priority. Mass products will not be considered further here, as these represent the transition to the other industry sectors (see sections 4.1, 4.2 and 4.4).

Table 3. Robust design challenges for precision engineering

Industry environment drivers	• Broad market spectrum from special applications (including ultra-precision measurement technology) with small quantities to the mass market • Market needs products with increasing precision requirements (e.g. in optics, semiconductor industry, etc.)
PD Organizational environment / challenges	• Relevance of the integration of the domains leads to strongly interdisciplinary development processes • Growing markets and expected fast response times require organisational changes
Derived technical robust design challenges	• Properties of the products can only be realised through a coordinated interplay of different physical effects • Physical effects are increasingly being fully exploited in the products, so that supplementary effects have to be taken into account (Schienbein, 2021) • Specific measures have to be implemented to manage the impact of internal and external influences on the product (Brix and Husung, 2022)
Requirement for robustness methods	• RD approaches must comprehensively represent the complex intended and unintended interactions of the products with the environment • RD approaches must comprehensively represent the physical main and side effects as well as the interplay of the different effects (effect chains) at different levels of abstraction (concept to detailed system description) and system levels, also taking into account changes over time. • RD approaches need to support the representation of different maturity levels as well as the maturity growth

3.5 Production systems

In modern international value-added chains with globally distributed production sites, production systems have to fulfil their function and generate parts and products despite harsh and varying environmental conditions, such as high humidity, temperature, and emissions. These varying manufacturing conditions pose important challenges not only on the design and tolerancing of the products that should be manufactured (Spruegel et al., 2014), but also on the robust design of the production systems themselves. Moreover, in the last two decades, production and manufacturing systems have undergone radical change considering the vast developments in the context of industry 4.0 and smart manufacturing. These developments were to a large extent driven by technological advancements regarding data acquisition, such as new sensor technology, data transfer, such as the

https://doi.org/10.1017/pds.2023.289 Published online by Cambridge University Press

industrial internet of things (IIoT), and data processing, such as data mining, big data, and machine learning approaches. However, not only the technological environment of manufacturing and production systems has changed, but also the market and customer requirements of these systems. In this regard, not only fierce requirements on the economic efficiency of manufacturing systems have to be met, but also requirements on their stable and robust connectivity and autonomy, on the ecological sustainability of the manufacturing processes, and on the flexibility and reconfigurability with regard to fluctuating market requirements. Obviously, the fulfilment of these requirements directly relates to the robust design (see Table 3) of such manufacturing and production systems. However, despite this critical link between design and the functionality of manufacturing systems, few research works focus on the application of robust design methods and tools to manufacturing and production systems. In this regard, for example Schleinkofer et al. (2019) present a framework for the robust design of FRUGAL manufacturing systems while Ihueze et al. (2017) focus on the optimization of production wastes using robust design techniques.

Table 4. Robust design challenges related to production systems

Industry environment drivers	• LEAN manufacturing systems (Ihueze et al., 2017) • FRUGAL manufacturing systems (Schleinkofer et al., 2019) • Connectivity in the industry 4.0 context • Autonomy and self-regulation for cyber-physical product systems
PD Organizational environment / challenges	• Increased interdisciplinarity - continuously evolving (shift from mechanical / electrical to embedded systems, software and networks) • Increased supply chain dynamics
Derived technical robust design challenges	• Managing the fast adoption of manufacturing technologies • Proving the long term extended durability and robustness attributes early at the product development stage with limited testing • Harsh operating conditions
Requirement for robustness methods	• Robust feature development process; • Proving robustness of CPPS (Cyber-Physical Production Systems) early in PD • Robustness and reliability of smart data-driven control features, including X-over-the-air / Industry 4.0

4 DISCUSSION AND CONSOLIDATION

First of all, the insight from different industries presented in section 3 illustrates the wide and diverse array of drivers that are shaping the focus on product robustness and the corresponding methodical approaches in different industries. This includes direct influences such as the evolving spectrum of relevant product features, besides the directly related properties such as safety and reliability, and also the production volumes, as well as indirect influences such as small design envelopes and increasing concern with respect to sustainability and circularity. These aspects affect the requirements for robustness methods to different degrees, depending on their combination, as also discussed below. A common theme for all sectors is the accelerated pace of technology change, which has an immense influence on design tasks, and, in turn, the question of assurance of product robustness. The prime example here is the introduction of interconnected, often intelligent solutions, which applies to all areas.
In terms of derived technical challenges for PD organisations, however, the impact of technology changes is different across the discussed industry fields. While the development of autonomous systems plays a major role for both the automotive industry and production systems, the main driver for technology implementation differs in precision engineering (increasing precision requirements in optics, semiconductors, etc.) and drug delivery devices (improvement of the user-device interface for better patient treatment). The same applies for the related method requirements. Addressing the robustness of CPS, both in terms of development and validation, is one of the major emerging topics related to autonomous systems. In other areas, i.e. the electrification of cars or new physical principles for ultra-precision measurements, achieving product robustness is highly influenced by the question of systematic technology maturation, or also by the question of integrating an existing technology in an already challenging and complex assembly. This largely aligns with previous research (Juul-Nyholm, 2021), which has found the same difference between technology maturation and technology integration across domains such as sensor development, consumer electronics, etc. Despite these differences, one key

https://doi.org/10.1017/pds.2023.289 Published online by Cambridge University Press

challenge for developing robust products is definitely the question of multi-disciplinary development processes, and the approach and availability of methods to support cross-disciplinary design work. The question how to integrate knowledge from mechanical, electrical and software engineering as well as from data scientists, including the alignment of terminology, applies to all of the areas and is an imperative research task for the future. The same applies to increasing circularity requirements, i.e. the question of robustness in reuse, remanufacturing, and recycling, particularly in mass production settings. This will certainly widen the range of necessary expertise for the RD tasks even further.

With respect to requirements for development of methodologies and methods to better support RD to address these challenges, a first reflection is that different products are subjected to very different internal and external uncertainties, variables or interactions, which need to be addressed systematically in RD approaches. Taking the automotive and production environment as an example, there are strong variations in the external influencing variables, such as loads, environmental conditions, etc., whereas these effects are usually not present for precision engineering products. The latter also applies for drug delivery devices, even though a largely uncontrolled home use environment still poses an immense threat to an often highly safety critical product. Another challenge, particularly for automotive and production system development is the methodical development of robust control features, which need to be aligned with model-based systems engineering (MBSE) frameworks to cover all aspects of distributed, yet interrelated functionality, and to assure traceability and interoperability. Instead, medical devices require an enormous level of integration due to the high production volume and the small design envelope, all while achieving high accuracy for a product that is usually developed from scratch. This leads to numerous design trade-offs between almost all design objectives that needs to be represented appropriately. In a similar direction, RD methods for precision engineering need to able to successfully address long chains of different physical effects, without which the increasing precision requirements would not be achievable, and the complex interactions of a product with its environment.

5 OUTLOOK AND FUTURE WORK

This paper has provided an up-to-date reflection on industry environment drivers, technical and organisational challenges and associated requirements for methodological developments for robust design. We found that while challenges might have industry specific aspects, there are common trends across the industry sectors. From an RD research point of view, this paper argues for the need to systematize the requirement and boundary conditions in the industrial sectors, while also addressing future demands such as circularity requirements, and to develop consolidated RD approaches based on the results. While generic RD methods are valuable, in particular for educating future engineers, approaches should address specific industry needs, e.g., through context-specific customization options. Similarly, the RD approaches should be described in such an abstracted and structured way that common insights can be extracted across industry sectors. This contribution calls for a broader cross-disciplinary engagement to address these evolving demands in robust design research.

REFERENCES

Bagchi S. et al. (2020), “Vision Paper: Grand Challenges in Resilience: Autonomous System Resilience through Design and Runtime Measures”, *IEEE Open Journal of the Computer Society*, 1, https://doi.org/10.1109/OJCS.2020.3006807.

Box, G. (1988), “Signal-to-noise ratios, performance criteria, and transformations”, *Technometrics*, 30(1),pp.1-40.

Brix, T. and Husung, S. (2022), “Research and Teaching on Robust Design in early Design Phases”, *RD Research Seminar*, https://doi.org/10.17632/n9pjyhxkht.1.

Breyfogle, F.W. (2003), *Implementing Six Sigma*, Second Edition: Smarter Solutions Using Statistical Methods, Productivity Press, ISBN 9780471265726.

Campean, F., Uddin, A., Bridges, J., Fannon, S. and Yildirim and U. (2022), “Evaluation of the Impact of Collaborative Research on Robust Design Methodologies: A Large Scale Empirical Case Study with an Automotive OEM”, *Design Conference* 2022. https://doi.org/10.1017/pds.2022.1.

Clausing, D. (1994), *Total Quality Management - A Step by Step Guide to World Class Concurrent Engineering*, ASME Press. https://doi.org/10.1115/1.800695.

Clausing, D. and Frey, D.D. (2005), “Improving System Reliability by Failure-Mode Avoidance Including Four Concept Design Strategies”, *Systems Engineering*, 8:3:245-262, https://doi.org/10.1002/sys.20034.

Davis, T.P. (2004), “Measuring Robustness as a parameter in a Transfer Function”, *SAE 2004 World Congress & Exhibition*, https://doi.org/10.4271/2004-01-1130.

Eifler, T. and Schleich, B. (2021), "A Robust Design Research Landscape - Review on the Importance of Design Research for Achieving Product Robustness", *ICED conference*, Gothenburg, Cambridge University Press, pp. 211 - 220, https://doi.org/10.1017/pds.2021.22.

Forslund, K., Karlsson, M. and Söderberg, R. (2013), "Impacts of geometrical manufacturing quality on the visual product experience", *International Journal of Design*, 7(1), 69-84.

Götz, S., Schleich, B. and Wartzack, S. (2020), "Integration of robust and tolerance design in early stages of the product development process", *Research in Engineering Design*, 31, pp. 157-173. https://dx.doi.org/10.1007/s00163-019-00328-2.

Harfensteller, F., Henning, S., Zentner, L. and Husung, S. (2022): "Modelling of corner-filleted flexure hinges under various loads", *Mechanism and Machine Theory*, 175.

Henshall, E. and Campean, F. (2010), "Design Verification as a Key Deliverable of Failure Mode Avoidance", *SAE Int. J. Mater. Manuf.* 3(1), https://doi.org/10.4271/2010-01-0708.

Grove, DM. Davis, TP (1992), *Engineering, quality and experimental design*, Longman. ISBN 978-0582066878.

Haley, B., Dong, A. and Tumer, I. (2015), "Measuring functional robustness with network topological robustness metrics", *20th International Conference on Engineering Design (ICED 15)*.

Hansen, F. (1970), *Adjustment of Precision Mechanisms*. Lliffe Books, London.

Höhne, G, Brix, T. and Sperlich, H. (2005), "Learning from design failures - the method of weak point analysis and virtual deviations". *15th International Conference on Engineering Design (ICED 2005)*.

Hu, F., Lu, Y., Vasilakos, A.V., Hao, Q., Ma, R., Patil, Y., Zhang, T., Lu, J, Li, X., Xiong, N.N. (2016), "Robust Cyber–Physical Systems: Concept, models, and implementation". *Future Generation Computer Systems*.

Ihueze, C., Okpala, C.C., Okafor, C. E. and Ogbobe, P. (2017), "Robust Design and Optimization of Production Wastes: An Application for Industries", *World Academy of Science, Engineering and Technology*, 76 2013, Available at SSRN: https://ssrn.com/abstract=2902171.

Juul-Nyholm, H. B., Eifler, T. and Ebro, M. (2020), "Robust Design for IoT - on the relevance of mechanical design for robust sensor integration in connected devices". *DESIGN Conference*, Croatia. https://doi.org/10.1017/dsd.2020.326.

Juul-Nyholm, H. B., Ebro, M. and Eifler, T. (2021), "Barriers for Industrial Sensor Integration Design - An Exploratory Interview Study", *ASME Journal of Mechanical Design*, 143(7), https://doi.org/10.1115/1.4050078.

Lee, W.C., Balu, S., Cobden, D., Joshi, A.V., and Pashos, C.L. (2006), "*Medication adherence and the associated health-economic impact among patients with type 2 diabetes mellitus converting to insulin pen therapy"*, *Clinical Therapeutics*, 28(10), https://doi.org/10.1016/j.clinthera.2006.10.004.

Lowe, D. (2019), "The Latest on Drug Failure and Approval Rates", *Science and Translational Medicine*, URL: https://blogs.sciencemag.org/pipeline/archives/2019/05/09/the-latest-on-drug-failure-and-approval-rates.

Manske, E., Theska, R. and Fröhlich, T. (2021), "Foreword to the Special Issue on Tip- and Laser-Based 3D Nanofabrication in Extended Macroscopic Working Areas". *Nanomanuf Metrol*, 4, 131. https://doi.org/10.1007/s41871-021-00113-7.

McDermott, T.A. (2019), "A Rigorous System Engineering Process for Resilient Cyber-Physical Systems Design". *International Symposium on Systems Engineering (ISSE)*, Edinburgh, UK, 2019, pp. 1-8. https://doi.org/10.1109/ISSE46696.2019.8984569.

Nair, VN., Taam, W., and Ye, KQ. (2002), "Analysis of functional responses from robust design studies", *Journal of Quality Technology*, 34, pp. 355-370.

Rungger, M. and Tabuada, P. (2016), "A Notion of Robustness for Cyber-Physical Systems", *IEEE Trans Automatic Control*, 61(8), https://doi.org/10.1109/TAC.2015.2492438.

Schienbein, R., Fern, F. and Theska, R. (2021), "Fundamental Investigations in the Design of Five-Axis Nanopositioning Machines for Measurement and Fabrication Purposes". *Nanomanuf Metrol*, 4, pp. 156–164. https://doi.org/10.1007/s41871-021-00102-w.

Schleinkofer, U., Dazer, M., Lucan, K., Mannuß, O., Bertsche, B. and Bauernhansl, T. (2019) "Framework for Robust Design and Reliability Methods to Develop Frugal Manufacturing Systems", *Procedia CIRP*, 81:518-523, https://doi.org/10.1016/j.procir.2019.03.148.

Shafique, M et al. (2020), "Robust Machine Learning Systems: Challenges, Current Trends, Perspectives, and the Road Ahead". *IEEE Design and Test*, 37(2), pp. 30-57, https://doi.org/10.1109/MDAT.2020.2971217.

Shahrokni, A. and Feldt, R., (2013), "A systematic review of software robustness". *Information and Software Technology*, 55(1), https://doi.org/10.1016/j.infsof.2012.06.002.

Taguchi, G. (1986), *Introduction to quality engineering – designing quality into products and processes*, Asian Productivity Association. ISBN: 978-9283310846.

Saxena, A., Davis, T. and Jones, J.A. (2015), "A failure mode avoidance approach to reliability". *Annual Reliability and Maintainability Symposium (RAMS)*. https://doi.org/10.1109/RAMS.2015.7105062.

Spruegel ,T.C., Walter, M. and Wartzack, S. (2014), "Robust Tolerance Design of systems with varying ambient temperature influence due to worldwide manufacturing and operation", *Design Conference*, pp. 1189-1198.

Welzbacher, P., Puchtler, S., Geipl, A., Kirchner, E. (2022). Uncertainty Analysis of a Calculation Model for Electric Bearing Impedance". In Design Conference 2022. https://doi.org/10.1017/pds.2022.67.